Master Thesis

An offshore port concept to reduce the construction costs in offshore wind projects

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An offshore port concept to reduce the construction costs in offshore wind

By an analyses on the market developments, workability and financial performances

In partial fulfilment of the requirements for the degree of

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Lincolnshire offshore windfarm, England
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"Those who fail to bet on the green economy,
will be living in a grey future."

Antonio Guterres (United Nations Secretary-General)

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
Civil Engineering and Geosciences

In cooperation with:
Vuyk Engineering Rotterdam

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June 27, 2018

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Abstract

In 1991 Denmark finished the construction of the first offshore wind farm, Vindeby. At the end of 2016 the total installed capacity of offshore wind in Europe was over 14 Gigawatt (GW). In these 25 years the offshore wind market has developed on many aspects, among others the dimension of the turbines and the distance to shore. Nowadays a turbine capacity of 8 GW is installed and it has a turbine height of 110 meter and a rotor diameter of 160 meter. The distance to shore increased from 2 kilometer in 1991 to recently constructed wind farms with a distance to shore of more than a 100 kilometer. The developments of the offshore wind farms increase the requirements for the installation vessels and as a consequence the present day rates can be up to $300.000.

Offshore wind market

The global potential of the offshore wind market is analysed, the two main results are the total installed capacity and distance to shore of an average construction by the year 2030. For Europe this is 60 GW and the US Atlantic coast this is 22 GW. The distance to shore of an average wind farm construction for these two markets by the year 2030 is 65 kilometer. Due to their similar market conditions, which are more challenging for construction than other continental markets, the European and US Atlantic market conditions are leading in this research.

The current logistical strategy for the construction of an offshore wind farm is similar to the strategy applied in 1991. From the manufactory the components are delivered to the onshore port. At the port the turbines are partly pre-assembled and stored near the quay wall. Installation vessels load the foundations and sail to the offshore location, where the installation takes place. Next, the turbines are loaded by the installation vessel and transported offshore after which they are installed.

The developments in the market lead to demands during the construction of offshore wind turbines. Six market demands are derived by interviewing experts from the offshore wind industry. The demand with in potential the highest financial performance, is to decrease the rental costs of the installation vessel. All six demands can be fulfilled by the presence of an offshore port near the offshore wind farm. The offshore port is required to be transportable, so it can be used for the construction of multiple offshore wind farms which increases the financial potential. The potential of an offshore port functioning for the demands of the offshore wind market is unknown in literature and in the industry, this gap can be filled by answering the following research objective:

'Explore the market potential of an offshore port concept to reduce the LCOE for an offshore wind farm, by making analyses on the activities executed during construction and a corresponding technical design of the port concept that shows a financial potential.'

Port concepts

The six demands can be fulfilled by performing four activities at the offshore port. For each activity the maximum allowed conditions are determined. These conditions consist of maximum allowed motions, a minimum surface area and a maximum allowed wind velocity.
Based on the required surface area for five turbines, the environmental conditions and a construction

limitation for the offshore port, five boundary conditions are determined.

The potential of seven support structures that fulfil the boundary conditions for the offshore port are determined. A single support structure is referred to as port component. The port components are a barge, a semi-submersible, a large vessel, a versabuoy, a pneumatic system, a jack-up barge and a jacket. The workability of these port components is calculated and the advantages and disadvantages are indicated. As a result, the barge, the semi-submersible, the versabuoy and the jack-up barge are determined to be a potential port component.
Based on the mobility, motion response and a rough cost indication of the individual port components, seven potential port concepts are determined. Three of these seven port concepts are selected to calculate the financial performance. The selected port concepts are a single barge, a single jack-up barge and a combination of a small jack-up barge and a barge.

Potential savings
The current logistical strategy for construction of an offshore wind farm is compared to various logistical concepts that include an offshore port. The logistical concept with a feeder vessel that sails from the onshore to the offshore port and an installation vessel that sails between the offshore port and the wind farm has the highest potential saving. Taking into account the assumptions made throughout this research, for each executed project by the offshore port the savings are expected to be €23.000.000. These savings consist of €6.000.000 by a sooner generation of energy and of €17.000.000 by savings on the construction of an offshore wind farm.

The financial performance of the three offshore port concepts are evaluated. The discounted cash flows are determined throughout the lifetime of the offshore port. The net present value, internal rate of return and payback time for the three port concepts are shown in table 1. The financial results are most sensitive to the ratio between wind farm capacity and the turbine capacity, also the market share that is interest in applying the offshore port and the day rate of the vessels have a substantial influence on the three performance indicators.

Table 1: Financial results of the three offshore port concepts

	Large jack-up barge	**Barge**	**Barge & small jack-up barge**
NPV (Million euro)	52.0	215.5	75.0
IRR (%)	11.1	50.0	13.9
Payback time (Years)	12.9	2.3	9.7

Conclusion
When the offshore wind market follows the tendency of developments of the last years, there is a market potential for an offshore port concept to reduce the construction costs. All three port concepts that are taken into account are expected to be profitable. However, based on the boundary conditions of this research the port concept of a barge has most potential.
The main recommendations are to analyse the interest of potential port owners, perform a motion response into more detail and validate the financial assumptions concerning the profit of sooner energy generation.

Preface

This study is carried out in order to obtain the degree of Master of Science in Civil Engineering at the Delft University of Technology. The research is established under the supervision of the Hydraulic Engineering department of the Delft University of Technology and in close cooperation with Vuyk Engineering.

The approach, used methods and final results of the exploring study are described in this report. The final result consist of approximations of the financial performance of a new construction concept for the offshore wind market. These results can function as a basis for further research into the feasibility of a new construction concept.

This research has embodied a selection of my personal interests and has driven my passion for the subject of offshore wind development. During the research I was introduced to the challenges that are faced by the offshore wind industry. I believe this study can be a small step to embrace the opportunities within the offshore wind market and hopefully it encourages the enhancement of innovative concepts to reduce the costs for offshore wind.

An overview of the structure of this thesis and introduction to the thesis topic can be found in chapter 1. Readers that are particularly interested in the future market development of offshore wind are referred to chapter 2. The possible port concepts that fulfil the demands in the offshore wind market and their calculated workability can be found in chapter 6. In chapter 8 the financial performance of the port concepts are discussed. References to the bibliography are split up into two groups. The references that include the letter *W* are not derived from literature, but are retrieved from websites and solely used for visualisation of the description.

Acknowledgements

This research could not have been completed without the participation and support of numerous people. These people and their contributions are greatly appreciated and gratefully acknowledged. Most of all I would like to express my gratitude to the graduation committee for their guidance and enthusiasm during the performance of this research. I would like to thank Chairman Prof. Ir. T. Vellinga for the encouragements and supervision during this research. Dr. Ir. J.C.M. van Dorsser is acknowledged for his great suggestions ans sharp comments during the meetings, it contributed largely to the final result. Further I would like to thank Ir. W.F. Molenaar for finding the balance between theory and practice and the feedback on the structure of the report.

A special debt of gratitude is owed to Vuyk Engineering and in particular Ir. A.M. Damen, for providing me the opportunity to work in a professional environment and introduce me to the world of marine operations and in particular the hydrodynamics. Ir. A.M. Damen deserves my gratitude for her motivational comments, comprehensive feedback and support during the thesis, specifically when the deadline approached. Finally I owe a special word of thanks to the employees of Vuyk Engineering, in specific Ir. K. van den Berg and Ir. M. van Vooren for sharing their view on certain thesis topics.

In addition I would like to express my appreciation to my family and friends who supported me during my time as a student. This increased my motivation to finalise this research.

Martijn Scheltes
Rotterdam, June 2018

List of abbreviations

AGV	Automatic guided vehicle
BM	Centre of buoyancy to metacentre
CAPEX	Capital expenditures
CG	Centre of gravity
EPS	Expanded polystyrene
EU	European Union
GHG	Greenhouse gas
GM	Metacentric height
GW	Gigawatt
Hs	Significant wave height
IRR	Internal rate of return
JUB	Jack-up barge
JUV	Jack-up vessel
KB	Keel to centre of buoyancy
KG	Keel to centre of gravity
kWh	Kilo Watt hour
LCOE	Levelised cost of energy
LNG	Liquified natural gas
LPG	Liquified petroleum gas
MPM	Most probable maximum
MW	Megawatt
NPV	Net present value
OCSLA	Outer continental shelf lands act
OPEX	Operational expenditures
PSS	Pneumatic stabilised structure
RES	Renewable energy sources
SLS	Serviceability limit state
Tp	Peak period
VLCC	Very large crude carrier
US	United States
WACC	Weighted average cost of capital

Table of contents

1. Introduction

This chapter introduces the thesis topic: *'A new port concept for the construction of an offshore wind farm'*. The developments in the offshore energy market are explained in section 1.1, the research motivation is set out in section 1.2, the research approach is discussed in section 1.3 and the report layout is provided in the section 1.4.

1.1 Offshore wind energy development

The Climate Agreement of Paris at the end of 2015 (COP21) confirmed the intention of almost 200 countries all around the world to limit climate change. The major goal is to keep the average temperature rise well below 2°Celsius average in this century, preferably no more than 1.5°Celsius. This goal has serious consequences for the global energy system. Renewable energy sources (RES) are expected to continue their increase in energy generation share. For example, since 2008 the annual installed capacity of wind is highest for all power stations in Europe [110]. Apart from that, the offshore wind capacity however, is still a small percentage of the worldwide wind capacity. Where the worldwide wind capacity is just 4% of the total generated energy in 2016 as can be seen in figure 1.1.

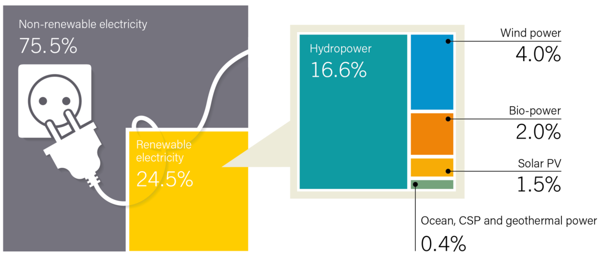


Figure 1.1: Worldwide energy generation at the end of 2016 [W10]

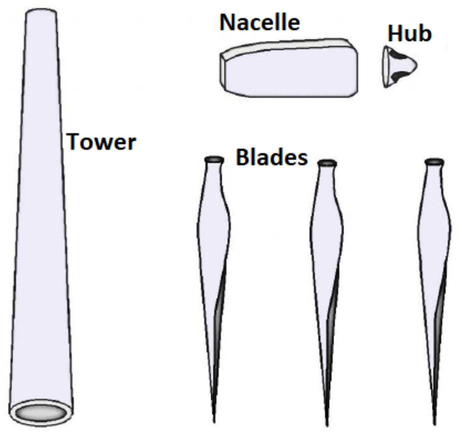
In 1991 Denmark finished the construction of the first offshore wind farm, Vindeby. Since 1991 the offshore wind industry has grown on average 52% each year [165]. Three important developments in the offshore wind market are discussed in the next paragraphs. These are the capacity of the turbines, the distance to shore and the key market players.

1.1.1 Wind turbine structures

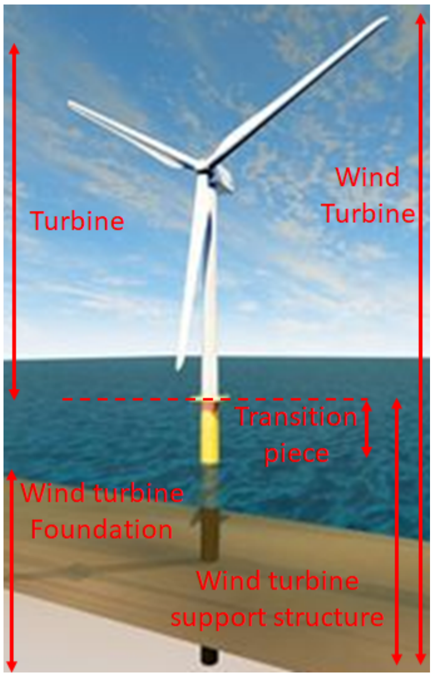
Transport and installation of the turbine and the foundation is 18% of the capital expenditures (CAPEX)[160] [18]. The capital expenditures are the total costs at the time of delivery of a structure. This share depends on the type and dimension of the wind turbines that have to be transported. These type and dimensions are discussed in this paragraph.

Turbine

Structurally a turbine consists of six main components: a tower, a nacelle, a hub and three blades, as can be seen in figure 1.2a. The wind turbine support structure consist of a foundation and a transition piece. The foundation is embedded into the seabed and links to the transition piece [126]. This is visualised in figure 1.2b. The largest currently available turbines, have a rotor diameter of 164 meters and a capacity of 8 megawatt (MW) [8]. The company General Electric, announced in the first months of 2018 to start a pilot with a 12 MW turbine by 2019. The evolution of the last 25 years is displayed in figure 1.3 and shows a steady trend to further increase of the rotor diameter, hub height and capacity. It is expected that the commercialisation of 20 MW turbines takes place before 2030 [17] [157]. This corresponds to a rotor diameter of 250 meter.



(a) Main parts of a turbine [192]



(b) Definitions of the wind turbine

Figure 1.2: Wind turbine components and definitions

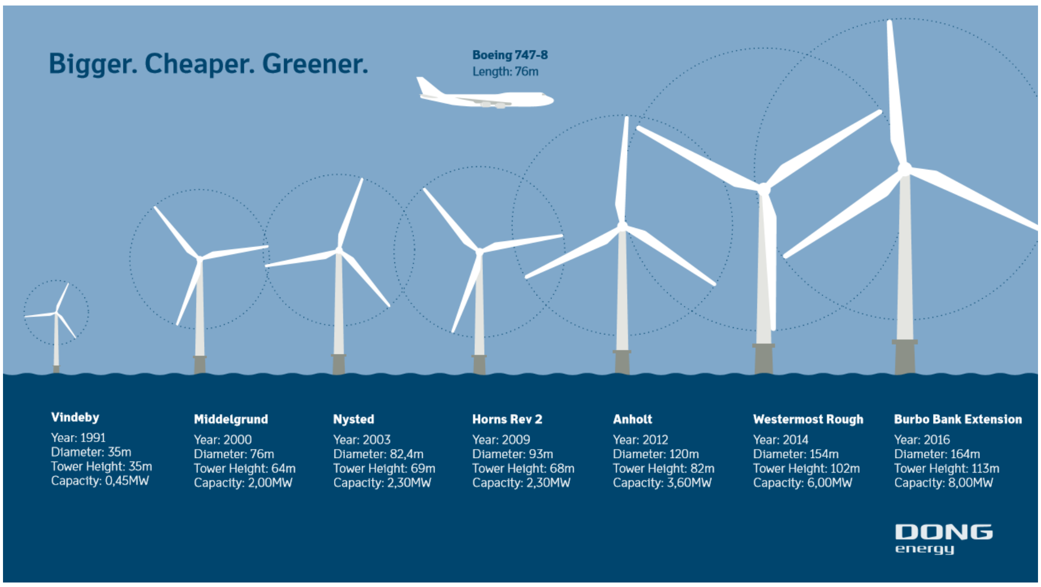


Figure 1.3: Turbine development the past 25 years [W9]

Wind turbine foundation

80% of the commissioned offshore wind turbine foundations are monopiles. A monopile foundation is limited to approximately 30 meter water depth. At water depths larger than 30 meter, tripod, gravity based and jacket foundations are usually deployed [206] [90]. The selection of the foundation is based on site-specific conditions such as: water depth, wind/wave conditions, currents, seabed properties and access requirements [46]. An overview of multiple wind turbine foundations is presented in figure 1.4. A more extensive overview of fixed and floating foundations is displayed in appendix B.

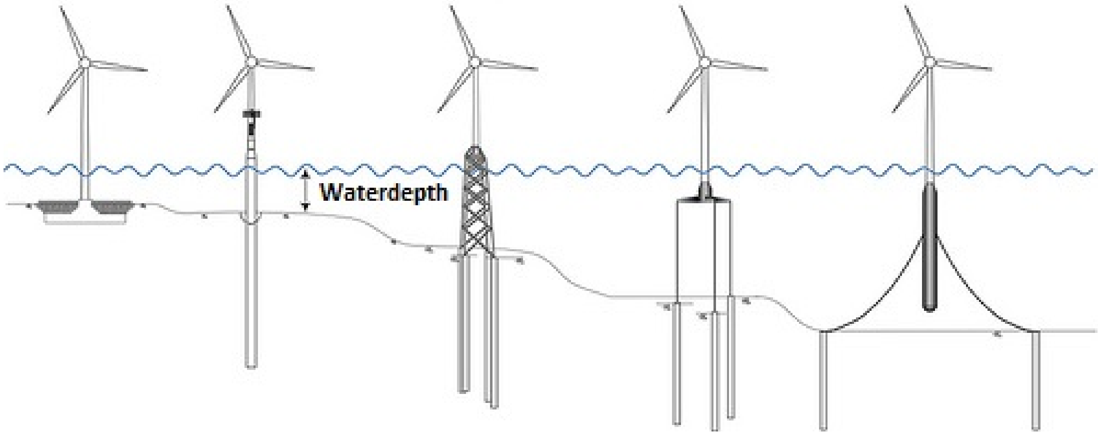


Figure 1.4: Multiple wind turbine foundations. From left to right: gravity based, monopile, jacket, tension-leg platform, spar-buoy [W36]

In 2017 Statoil realised the first operational floating wind farm in Scotland[179]. Six more projects of floating foundations will be commissioned in Europe before 2021 [210]. These structures ease the installation by avoiding heavy-lift vessels and can be installed in areas with poor seabed conditions. It also allows for potential recycling by their ease of transport. Floating foundations provide possibilities for countries with high water depths near the shore.

There are currently four foundation designs for floating offshore wind: semi-submersible, spar-buoy, barge and tension leg platform [210]. The semi-submersible and the barge platform are buoyancy stabilised while the tension-leg platform is mooring line stabilised and the spar bouy is ballast stabilised. A minimum water depth of 50 meter is required for floating foundations to be cost effective [5]. A brief overview of the wind turbine foundations and the appropriate water depths for installation are provided in table 1.1.

Table 1.1: Wind turbine foundation overview [141] [5] [23]

		Fixed				**Floating**			
		Monopile	Jacket	Tripod	Gravity based	Semi-submersible	Tension-leg platform	Spar bouy	Barge
Water depth	0 - 30 m	X			X				
	30 - 50 m	X*	X	X	X**				
	>50 m					X	X		X
	>100 m					X	X	X	X

X*: Nowadays 'XL monopiles' of over 1000 tons are produced with a diameter up to 8 meters for water depths up to 35 meters. There are preliminary studies that show current manufacturing capabilities can be applied until a water depth of 50 meter. A higher water depth increases the probability of buckling failure. [88].

X**: Deep water gravity based foundations have a different design than shallow water gravity based foundations. Shallow water gravity based are feasible in water depths until 10 meter [141]. Deep water gravity based foundations are already installed at a water depth of 30 meter and can be installed up to a water depth of 50 meter [167].

1.1.2 Water depth and distance to shore

If the wind energy sector wants to achieve its significant future opportunities, wind farms must be constructed increasingly farther off the coast. This is a technological and economic challenge. Farther off the coast means deeper water, rougher conditions and tougher accessibility. These three complications mean higher costs, although the energy generation is higher thanks to the stronger winds that is more consistent. Wind blows significantly stronger at sea, which results in an energy generation that is twice as high as on land. As there is plenty of space to develop wind farms offshore, this is very attractive[41]. Figure 1.5 displays the increase in water depth, distance to shore and wind farm capacity over the past 20 years[1].

As can be seen in figure 1.5 the distance to shore increased nearly exponentially. Germany is ahead concerning the distance to shore and water depth of wind farms. In 2016 the average distance from shore for new wind turbine installation was 40 kilometres, where the average distance from shore for new wind turbine installation in 2017 was 90 kilometres. In Germany there are three wind farms operational with a distance to shore of more than 100 kilometer: Global Tech 1, Bard offshore and Veja mate. England is making progress as well, the proposed Doggersbank Teesside A and B will set a new record with a distance to shore of more than 200 kilometer [55].

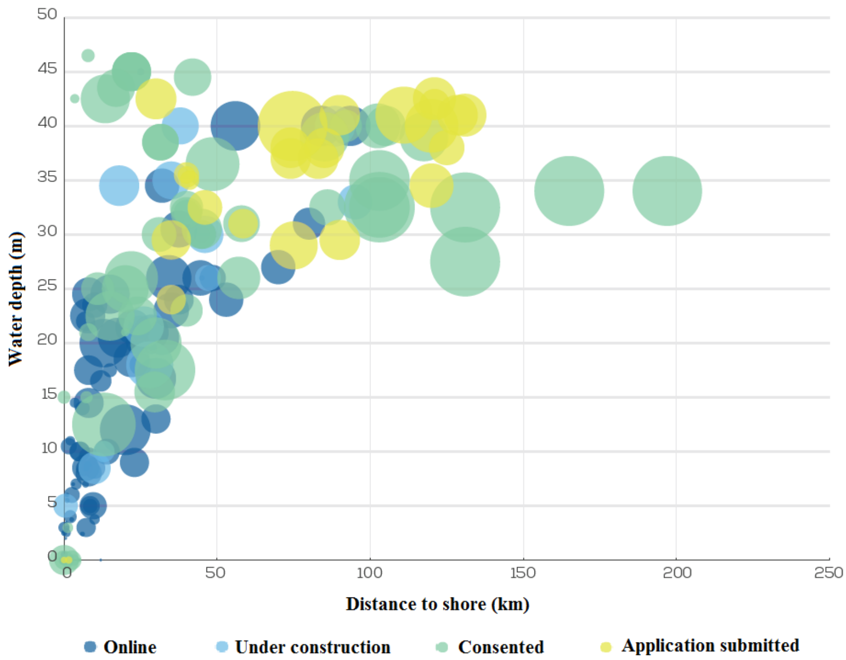


Figure 1.5: European (fixed) wind farms at the end of 2015 [91]

1.1.3 Key players

Offshore wind energy technology is a lot younger than onshore wind energy, the offshore wind capacity is increasing worldwide as the market is developing. A cumulative overview can be seen in figure 1.6[2].

[1] In which consented means approved for construction and the capacity is indicated by the size of the bubbles

[2] RoE is an abbreviation for: Rest of Europe and RoW is an abbreviation for Rest of World

Countries which currently have a low market share in the offshore wind industry will emerge as key players. Two main reasons for these shifts are: wind farms tend to be constructed in deeper waters and the growing interest in renewable energy. Figure 1.7 shows the total offshore wind power capacity of the main world players in the future. Where China and the United States (US) are expected to excel outside Europe.
A shift in market share can be seen when comparing figure 1.6 and figure 1.7. A clear shift towards China, the US and Brazil can be seen, though the values in figure 1.7 can deviate in the future since the planned tenders are uncertain to be commissioned. Currently, the US depends on individual states to install offshore wind. More information on this is provided in section 2.4.

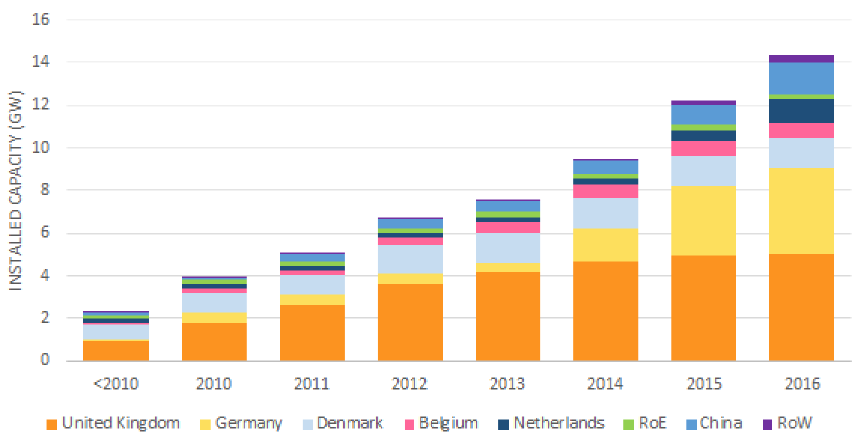


Figure 1.6: Cumulative overview of commissioned offshore wind energy [89] [149]

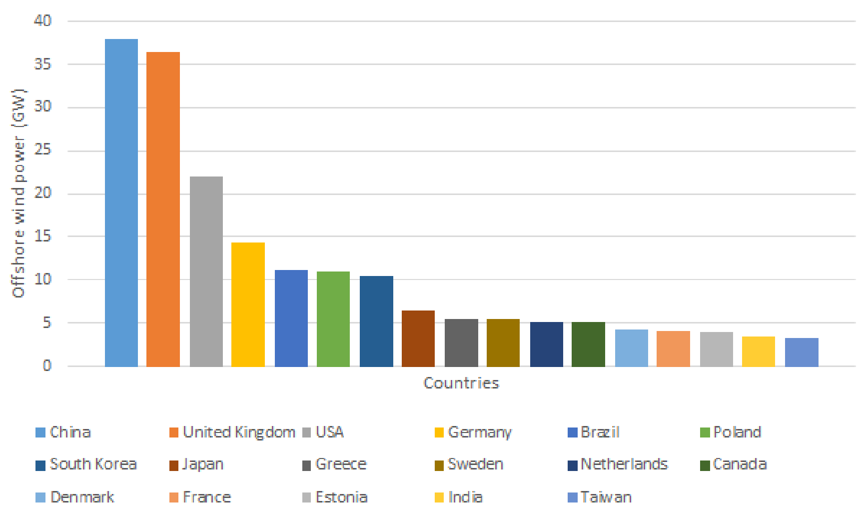


Figure 1.7: Aggregated offshore wind capacity for the main world players in gigawatt (GW) (commissioned, under construction, approved and planned tenders at 24-10-2017) [158]

1.2 Motivation for research

The offshore wind market has been increasing each year from 1991 on, since then a lot of research is carried out to optimise the turbines, grid connections, installation vessels and other aspects of the construction phase. These are all optimisations that contribute to the efficiency of an individual phase of the construction phase. However, only a few papers are published on optimising the logistics of the construction. The construction phase consist of:

Manufacturing the wind turbine, transport to the offshore site and the installation of the wind turbine.

Academic works that address the logistics of the construction phase discuss the effective storage layout for the turbine components on the installation vessel [192] [131]. Other papers that consider the overall construction phase discuss the potential of the pre-assembled installation method, for the installation of offshore turbines. Component-wise installation method requires more time to install the turbines than the pre-assemble method [199] [198].
The market potential and technical feasibility of certain pre-assemble methods is not specified within these researches. Figure 1.5 shows the development of market conditions and table 1.2 emphasizes that these conditions lead to an increase of costs. Combining the potential of the pre-assemble installation methods with papers that discuss the cost increase when moving the deeper water, farther from the shore. Results in a market demand and a literature gap for a new innovative construction concept for the offshore wind market.

Table 1.2: Impact of dwater epth and distance on CAPEX [77] [160]

Water depth (m)	**Distance from shore (m)**							
	0-10	10-20	20-30	30-40	40-50	50-100	100-200	>200
10-20	1	1.02	1.04	1.07	1.09	1.18	1.41	1.60
20-30	1.07	1.09	1.11	1.14	1.16	1.26	1.50	1.71
30-40	1.24	1.26	1.29	1.32	1.34	1.4	1.74	1.98
40-50	1.40	1.43	1.46	1.49	1.52	1.65	1.97	2.23

However, there is just one research that discusses the potential of a new logistic approach to reduce the construction costs in the offshore wind market [46]. The results are promising, the installation time per turbine is decreased with nearly 500%. Though, technical and financial feasibility is not taken into account. More information on this research can be found in appendix A.

The installation of a wind farm requires several vessel types. The surface area and carrying capacity of these vessels are essential parameters determining the costs of transport according to Vuyk. At present the day rates for installation jack ups range between \$50.000 and \$300.000. The precise day rate is project dependent since it depends on parameters like: water depth, rental period and seasonal availability [36] [107] [2]. The sailing distance, water depth and wind farm capacity are increasing in the future, so the construction costs will also increase [160] [18].
A new concept that fulfills the demands in the offshore wind market could reduce the levelised cost of energy (LCOE). The LCOE is determined by dividing the total costs over the lifetime, by the total energy output over the lifetime [87]. This research focuses on the consisting market gap in literature and in practice, on a construction concept to reduce the LCOE of an offshore wind farm. If a new construction concept works out to be technical and financial feasible under certain conditions, this concept could be used in future offshore wind farm projects.

1.3 Research approach

The literature gap on a new construction concept to reduce the construction costs of an offshore wind farm, is verified in the offshore wind industry. The market demands during the construction phase are made insightful and these are compared with each other. If a new construction concept can contribute to multiple demands, there is a potential for this concept. Prior to requesting the demands in the market, it should be known how the offshore wind market looks like. Topics as market players, market developments and market techniques have to be understood. Depending on the demands in the market, a new construction concept can be created and consequently multiple phases of the construction can be improved. This new construction concept is explored by a technical and financial study.

1.4 Report outline

This chapter introduced the thesis topic on the construction of an offshore wind farm. The second chapter elaborates into more detail about the current offshore wind market and the forecast of this market. Chapter 3 explains the construction strategies that are applied in the offshore wind market. A reference case is formed, which is based on the most common applied construction strategy. Chapter 4 presents the demands in the offshore wind market during the construction of an offshore wind farm. Chapter 5, determines the maximum conditions for the workability of the new construction concept. The next chapter explores the potential of several concepts and this is followed by chapter 7 which indicates the potential savings of these concept. A financial balance and sensitivity analysis on the market conditions and assumptions made is performed in chapter 8. This report outline is visualised in figure 1.8.

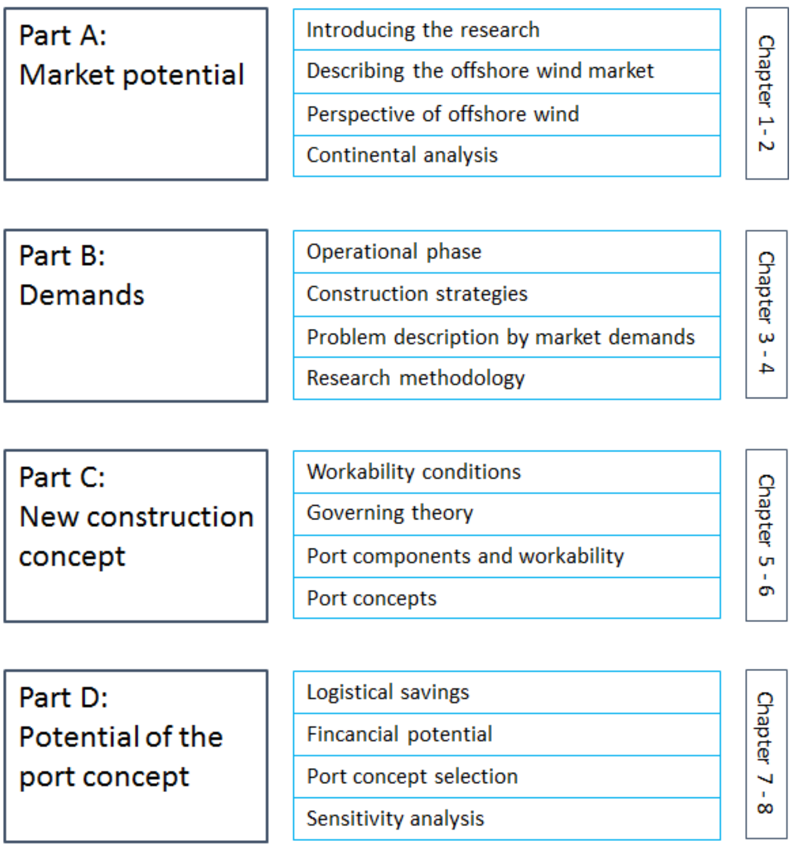


Figure 1.8: Framework of the report outline

2. Market potential of offshore wind

Offshore wind is compared to other competitive energy sources. This is followed by an analysis on the potential of offshore wind for all continents in section 2.2 until section 2.6. In section 2.7 for each continent the offshore wind capacity and the offshore wind conditions are extrapolated to the year 2030. A conclusion on the potential of offshore wind is drawn in section 2.8.

2.1 Offshore wind competitiveness

Wind blows a lot stronger at sea, up to one and a half times as strong as on the nearest coast. Which results in a wind generation in the offshore field that is twice as high as on land [41]. This is very attractive, as there is plenty of space to develop wind farms at sea. But at the same time, the condition offshore are much more challenging than onshore. The LCOE value determines the degree of competitiveness of offshore wind to other energy sources, it is expressed in euro per kilo watt hour (€/kWh). In 2017 the LCOE of offshore wind ranged between 0.04 €/kWh and 0.13 €/kWh [95].

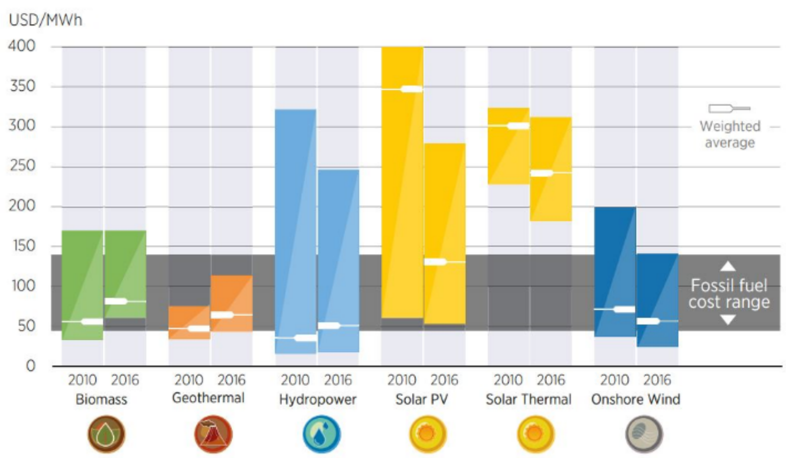


Figure 2.1: Worldwide development of RES and their LCEO [64]

Renewable energy sources (RES) are currently more cost comparative to fossil fuels, where the LCOE of RES will decrease and of fossil fuels will rise in the next decade. In 2017 the electricity cost for fossil fuels ranged between 0.04 €/kWh and 0.15 €/kWh [64].

In Germany zero subsidy bids have won in april 2017 and in the Netherlands this is achieved in march 2018 [52]. For other bids only a small percentage of the prospected subsidies for offshore wind is still required, though this also holds for other RES. When the offshore wind market aims to compete with other RES, cost reductions are a need. Solar power and offshore wind are difficult to compare, since the potential of the RES can be different within a similar region. The LCOE of offshore wind projects has come down significantly over the last ten years. The reduction has been steep and non-linear, due to some rapid changes in project finance costs, turbine technologies, supply chain capability and competitive auctions that have had an impact alongside the learning effect of larger volumes. This also holds for the generation of solar power as can be seen in figure 2.1.

For offshore wind and solar power, the LCOE price of the bids decreased drastically. The lowest cost price for onshore solar power is a bid in november 2017 in Mexico at 0.0015 €/kWh [57]. For offshore

wind energy this is a bid in november 2016 by Vattenfall, who won a tender with a new record price of 0.05 €/kWh [209]. These two RES are outstanding all other types of energy sources with the current cost price of the bids. This is presented in figure 2.2.
The largest future decrease in LCOE will come from lower financing costs, due to a reduction in perceived risk. The second largest reduction is due to turbine technology innovations that will enable greater power output and higher reliability without increasing the cost per MW of capacity.

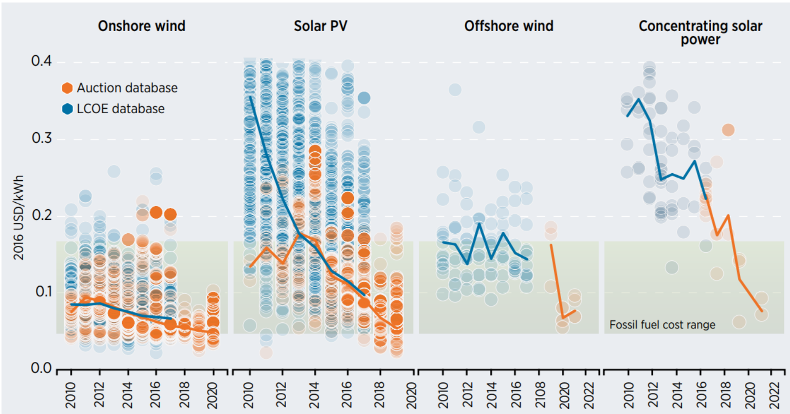


Figure 2.2: Auction price trends [98]

2.2 Climate targets

The energy system is expected to crucially change over the next decades due to a shift from fossil fuels to renewable energy sources (RES). The United Nations Framework Convention on Climate Change (1994) was the first step to prevent dangerous anthropogenic interference with the climate system. This was followed by the Kyoto Protocol (2005) and the Paris Agreement (2016). The latter confirmed the intention of almost 200 countries all around the world to limit temperature rise to well below 2°Celsius this century, preferably no more than 1.5°Celsius. These climate agreements are translated to targets by country to reduce a percentage of their greenhouse gas (GHG) emissions in 2030, in which the European Union (EU) has one shared target.
To achieve these targets the energy sources shift to renewable energies, one of these RES is offshore wind. An important note to be made is that this intention concerns no legally binding consequences. The RES targets of a country provide an indication of the level of intention in which a country wants to increase the share of RES. When the current RES share is high and they already joined the offshore wind market. It is plausible that the country will increase their offshore wind capacity or achieve the capacity indications.

2.3 Europe

When comparing all the continents, the offshore wind market is furthest developed in Europe. In this paragraph it will be studied if Europe continues to be the market leader by the year 2030. All countries in Europe are considered to have the same climate targets as presented by the European Union, including the United Kingdom.

Climate targets

The EU has translated the intention of the Paris Agreement into targets. Because a high share of RES in the energy consumption provides better opportunities for the offshore wind market to grow.

They are analysed and displayed in table 2.1. A comment has to be made that there is no punishment for countries that fail to meet the targets. Since each country is allowed to determine the distribution within the RES generation themselves, the EU targets do not provide a clear indication of the amount of offshore wind capacity in 2020 or 2030.

Table 2.1: EU climate targets, compared to levels of 1990 [60]

	Targets	Sub-targets
2020	20% reduction in GHG emissions	20% share of renewable energy in final energy consumption
		20% reduction in energy consumption
2030	40% reduction in GHG emissions	At least 27% renewable energy in final energy consumption
		At least 27% reduction in energy consumption
2050	80-95% reduction GHG emissions	

Offshore wind capacity

To determine the capacity potential of offshore wind in Europe and the conditions that come along with this, it is analysed how much wind farms are in the pipeline. Figure 1.7 shows the potential future offshore wind market including the planned tenders, this uncertain share contributes largely to the total potential capacity. In 2015 a research was conducted using the same source as in figure 1.7. The values of potential capacity between this research in 2015 and the values available at the moment of this research deviate 90% on average [158] [166]. The reason for this is the high amount of cancellations of planned wind farms.

Concerning the offshore wind energy potential in 2030, recent reports are published by several organisations. Reports by Windeurope[3] [147], the IEA[4][96] and the European Commission [28] have the highest reliability. Their offshore wind scenario analyses have a higher reliability, since it only changed by 12% on average over the past two years[5]. Therefore, the market capacity potential of offshore wind will be based on indications provided by several organisations that are active in the offshore wind market and not by an overview of commissioned and potential wind farms.

The offshore wind potential capacity as forecasted by these three organisations are shown in figure 2.3. The forecasts are extrapolated to the year 2040 as indicated by the dotted line. Based on the three determinative arguments below, an average of the Windeurope low and Windeurope central scenario is selected:

- In January 2017, there was 42 GW offshore wind capacity operational, under construction and consented in Europe [91]. This 42 GW excludes the planned tenders and the projects under

[3]Windeurope, previously EWEA, is the voice of the wind industry, it has over 450 members with headquarters in more than 40 countries.

[4]International Energy Association, publishes a World Energy Outlook every year. In the report of 2016 Offshore wind accounts for 10% of total wind, this share is assumed similar in 2013.

[5]EWEA 08-2015 vs Windeurope 09-2017 varied 5% in their scenario on offshore energy in 2030, the world energy outlook of 2014 vs world energy outlook of 2016 published by IEA varied 20% in a combined wind and solar scenario for 2030, EC reference scenario 2013 [27] vs 2016 varied 10% in the wind scenario for 2030.

consenting procedure, the 42 GW will be delivered in 2025. The Windeurope central scenario reaches 42 GW in 2023, and the Windeurope low scenario reaches 42 GW in 2027.

- The reports of the IEA and the EC make assumptions that are not based on recent policies and developments of the market but on values and trends in 2014. The increase of announced projects by market leaders and also by countries joining the offshore wind market was not taken into account.
- The interviewed persons were unanimously positively concerning the future potential of offshore wind. A list of interviewed companies can be found in appendix D. The main reasons for this positive view are: multinationals joining the offshore wind market which lowers the price of €/kWh, the increasing demand on renewable energy and the gained experience over the past years. Though it also commented that most countries in the world will not join the offshore wind market, since they have other RES that suits them better due to their geographical location.

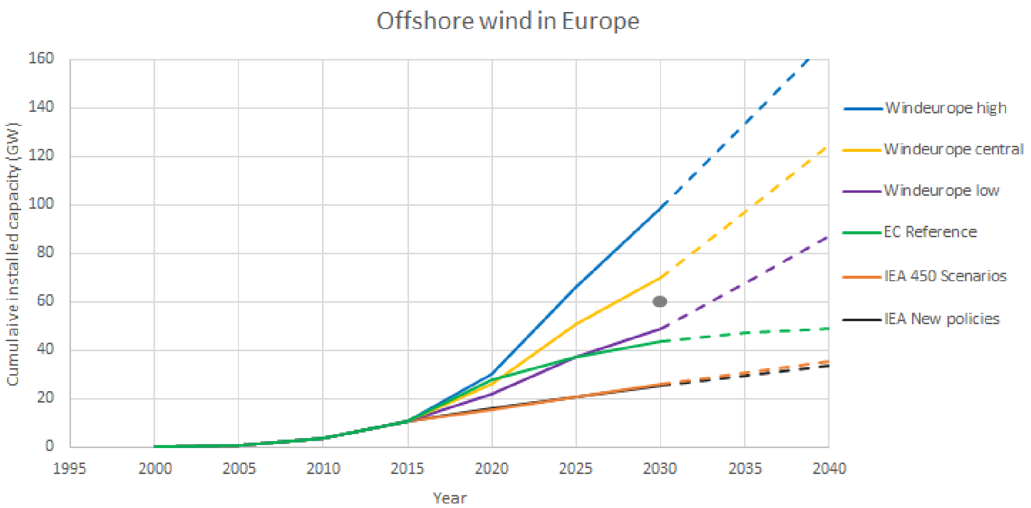


Figure 2.3: EU offshore wind potential capacity

The installed capacity of offshore wind in Europe is 60 GW in 2030, as is displayed by the grey dot in figure 2.3. 60 GW can fulfil 8% of the European energy demand in 2030. Where the total installed onshore and offshore wind capacity fulfils 26% of the European energy demand in 2030 [147] [28].

Offshore wind conditions

Besides by how much there will be installed, the market potential of a new construction concept is influenced by what type of wind turbine is going to be installed and where the sites will be located. Therefore the analysed offshore wind conditions concern the location, size of the turbines and type of foundations of future wind farms. To determine the distance to shore and the water depth of the offshore wind farms in Europe that become operational in 2018 or later, 4COffshore is used as a source[6].

[6]This database contains information on the design and environment of the commissioned and key potential wind farms. It is not an open source, a paid subscription is required. Since [158] concerns the capacity of all the commissioned and potential offshore wind farms, it is used as a source for figure 1.7. However, the database of 4COffshore available for this research, provides more detailed information.

Recently published reports only provide indications with graphs similar to figure 1.5 and there is no open source that provides specific information on potential wind farms and their location, wind turbine size and type of foundation. Potential wind farms are wind farms that are under construction, consented and planned. Even though not all of the potential offshore wind farms will be constructed, it provides a clear indication of the future conditions.

Locations

There are four countries that have a 80% share of the cumulative installed capacity of offshore wind in Europe by 2030. These countries are: United Kingdom, Germany, the Netherlands and France [95]. The current share of 2/3 of the wind farms in the North Sea and 1/3 of the installation in the Baltic Sea, Atlantic Ocean and Irish Sea will be uphold for the year 2030 [147].

An overview of the offshore wind farms at the end of 2015 in the Southern area of the North sea is provided in figure 2.4. A more detailed and recent map of offshore wind farms in the UK, Germany and the Netherlands can be found in appendix C.1.

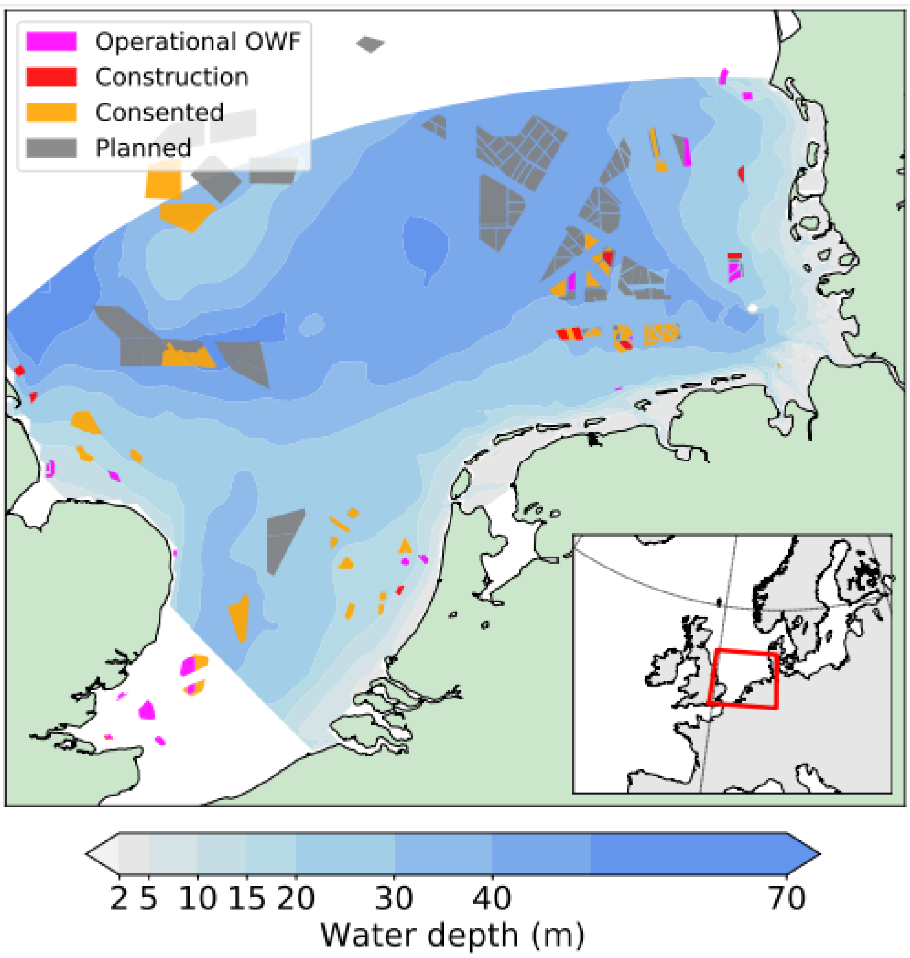


Figure 2.4: Southern North Sea wind farm overview [176]

The average distance to shore of the potential wind farms, is weighted to the related capacity installed. The same approach is applied for the average water depth. The average distance to shore for potential wind farms in Europe is calculated to be 63 km and the average water depth is 32 m [1]. The highest 5% of distance to shore for the potential wind farms is 153 km on average, the largest 5% of the water depths for the potential wind farms with a fixed foundation is 46 m on average. These numbers provide an insight in the variation of offshore wind farm conditions.

Turbines and foundations
The capacity of turbines increased significantly over the past years as was seen in figure 1.3, the average turbine capacity of potential offshore wind farms in Europe is calculated to be 11.3 MW. Though the average wind farm size has increased even more, from 5 MW in 1991 to 380 MW in 2016. The 1.2 GW Hornsea One project, operational in 2020 will be the largest offshore wind farm in the near future. The average wind farm size of potential offshore wind farms built from 2018 on in Europe, is calculated to be 570 MW.
In paragraph 1.1.1 it is stated that 80% of the commissioned offshore wind foundations are monopiles. Despite that for most of the potential offshore wind farms it is undecided yet what type of foundation will be used, it is provided whether the foundation will be fixed or floating [1]. Only 1% of the potential wind farm capacity will be floating, this includes one planned tender of 500 MW in France that accounts for 80% of the floating capacity[7].

The outlook for floating foundations in Europe faces a low potential. This is due to three main conditions, these are listed below and elaborated in appendix C.2.

- The costparity between fixed and floating foundations at a water depth of 60 meter, in combination with the potential resource area of fixed foundations nearly satisfying the European electricity consuption.
- Currently there are only five spar-buoy foundations operational with a total capacity of 30 MW.
- Competitive RES for geographically unfavorable countries.

2.4 North America

The potential offshore wind market of this continent is dominated by the United States (US) though forecasts are uncertain due to recent developments in politics. In response to federal disruption of the climate progress, states step up to fill the gap. The Jones Act makes the forecast on offshore wind even more challenging. An overview of the current holding climate targets and the potential of offshore wind is provided below. The approach for the capacity and the conditions is similar as for the European market.

Climate targets

Despite that this continent consist of 23 independent countries, only the United States and Canada have plans to join the offshore wind market. Since these countries have separate climate targets they will be treated individually. In June 2013, President Obama launched a series of policies and measures to reduce GHG emissions in the United States [38]. The targets are to reduce net GHG emissions by 17% in 2020 and by 26–28% in 2025, relative to 2005 emission levels. However on August 2017, the US formally communicated its intent to withdraw from the Paris Agreement and the corresponding

[7] Therefore, the floating foundations are neglected in determining the average water depth. Including these water depths would lead to a distorted indication

climate targets.
At present, 14 states have vowed to continue upholding the Paris Agreement and press ahead with policies to fight global warming [26]. Because these states only represent 36% of the nation's population, the United States as a whole is still expected to fall short on the initial policies by President Obama. The states of New York and California are large states that show their sustainable leadership by requiring 50% of the electricity generation in 2030 by RES. Though there are smaller states who have already set higher specific targets. Hawaii has set a goal of 100% of RES by 2045 and Vermont 75% by 2032.

In the Paris climate conference, the government of Canada made a political commitment to attain a 30% reduction of GHG emissions from 2005 levels by 2030 [127]. Canada currently already produces 68% of its electricity from RES, of which 60% is produced by hydro power. Onshore wind energy represents about 5% of Canada's current electricity generation capacity [125]. Ontario and Nova Scotia, representing half of the population in Canada, have announced that they will increase that share to 20% by 2030 [127]. No clear indications are provided concerning offshore wind targets in Canada.

Offshore wind capacity
The Block Island Wind Farm is the first and so far, the only offshore wind farm in the United States. To determine the growth of the offshore wind market, reports of the Department of Energy and of the National Renewable Energy laboratory are leading by their indications, since no offshore wind targets are set. As stated before in paragraph 2.3, the offshore wind farm databases which include planned offshore wind farms are not reliable for a future capacity indication. Reports of these two organisations provide well argued indications on the future potential of offshore wind in the United States.
Currently there is only 30 MW of offshore wind operation in the U.S., however it is expected that 22 GW will be operational by 2030 and 85 GW by 2050 [43]. Since the offshore wind industry is in an early phase of development in the US, critical notes can be placed by the reliability of these indications. However, the main driver of the huge potential in the United States is that the largest part of the population lives in an overcrowded coastal zone. This leads to opportunities for offshore wind because a short distance limits the energy losses of transport.
There are no reports available that provide an indication on the amount of offshore wind in Canada by 2030. Due to the competitiveness of other RES in Canada, it is assumed that the future potential in Canada is negligible for the year 2030.

The Jones Act
A condition that influences the potential of offshore wind in the United States is the legislation. The Merchant Marine Act of 1920 in particular, this is commonly known as the Jones Act. Section 27 of the Jones Act deals with coastwise trade and requires that all goods transported by waters between United States ports, shall be carried on a United States flag ship. In virtue, a vessel being built in or documented under the laws of the United States and owned by persons who are citizens of the United States [35].
The Jones Act applies to US Waters three nautical miles wide, seaward of the territorial sea baseline. The territorial sea baseline is located at 12 miles from the coastline. However, the 1978 enactment of the Outer Continental Shelf Lands Act (OCSLA), extended United States jurisdiction to the full expanse of its 200 nautical mile Exclusive Economic Zone [53]. Whether and how the laws apply to

offshore wind will remain uncertain until a design of a project is proposed to court.

If an offshore point is not a coastwise point than it is not binded by the OCSLA. To represent a coastwise point the attachment to the bottom must be physical and tangible. An offshore wind farm outside the 200 miles range is not cost competitive and is not likely to occur by 2030 or 2050. The Jones Act increases the transport costs since the ship design and building industry is not on the required level. For the Block Island Wind Farm, United States-flagged vessels had to transport equipment from the site to the installation vessel, adding additional cost to the installation of the project.

Offshore wind conditions

Besides the legislation, there are other conditions that influence the potential of an offshore port concept. These conditions include the locations where the wind farms will be build and the components that are used.

Locations

The site specific information of potential wind farms in the U.S. is based on recent reports concerning all the projects that are in the pipeline [43] [140]. The main projects by 2030 are concentrated in the Atlantic Ocean, approximately 15 % of the future sites is the other areas like: the Pacific Ocean, Gulf of Mexico or in large lakes. Excluding the states of California and Hawaii, which are located at the Pacific Ocean, 98% of the projects in the pipeline are at the Atlantic Coast.

The same approach as for Europe is applied to calculate the site specific information. Considering the 22 GW of installed capacity by 2030, the average distance to shore is 46 km and the average water depth is equal to 85 meter. For the Atlantic Ocean this is just 46 km and a water depth of 33 meter. This difference is caused by the Pacific Ocean projects who rely heavily on floating foundations.The Pacific Ocean faces more technical challenges and uncertainties than wind farm projects at the Atlantic coast and they only account for 13% of the potential projects, these projects at the Pacific Ocean are not taken into account.

The highest 5% of distance to shore for the potential wind farms at the US Atlantic is 75 km on average, the largest 5% of the water depths for the potential wind farms with a fixed foundation is 48 meter on average.

Wind turbines and foundations

The average capacity of the offshore wind turbine size for the potential projects in the United States is 10,6 MW and the average wind farm size is 470 MW [140]. In figure 2.5 the United States is displayed with the corresponding potential area for floating and fixed foundations. The separation line is based on the required depth of at least 60 meter for floating foundations. Hawaii is displayed in the left bottom corner. It clearly shows that the Pacific Ocean relies on the floating foundation development. The Atlantic coast that contains the large majority of the potential wind farms, can develop a lot of fixed foundations as a starting point.

2.5 Asia

This continent contains six countries that have plans to join the offshore wind market. The approach to determine the climate targets, offshore wind capacity and offshore wind conditions is similar as for the previous continents. So the detailed analysis on the climate targets, offshore wind capacity

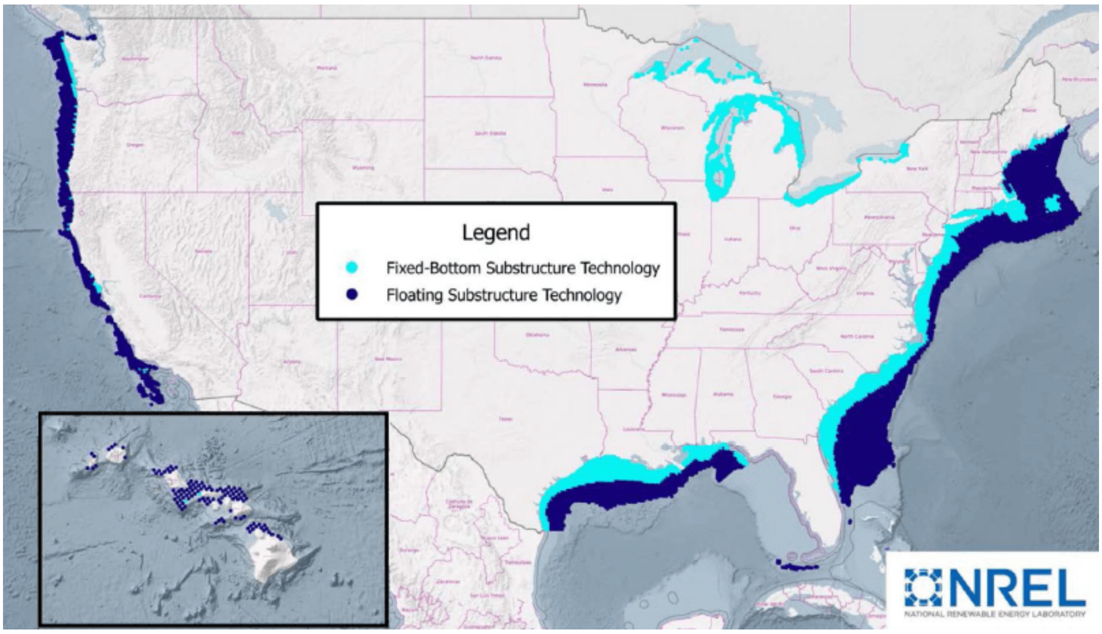


Figure 2.5: Fixed and floating wind resource areas [140]

and the offshore wind conditions can be found in appendix C.3, a summary is provided in table 2.2. Vietnam, Taiwan, South Korea and India are discussed as one country, since their individual offshore wind potential by 2030 is a maximum of 4 GW. China and Japan are the key players in the Asian offshore wind market.

2.6 All continents

Outside Europe, North America and Asia, there are no countries listed in the several reports that show offshore wind capacity indications by 2030. However Brazil and Australia, both have one large offshore wind farm in the pipeline [1]. As a result of continued delays, lack of an established supply chain and the non availability of vessels and components, the perspective for offshore wind is challenging. Therefore, these two markets are not taken into account. More information on these offshore markets can be found in appendix C.4.

2.7 Extrapolation conditions to 2030

Not all the commissioned offshore wind farms by 2030 are currently announced, the conditions have to be extrapolated to the year 2030. The distance to shore, water depth, wind farm size and wind turbine size of wind farm projects from 2018 and ahead are derived in the previous four sections. The average year of commissioning of the potential wind farm projects is calculated and extrapolated to the year 2030.

For Europe and China a similar approach is applied, these are the only countries that currently have a representative amount of installed capacity of offshore wind. In Europe, all the commissioned wind farms before 2018, were on average commissioned in 2010. The average commissioned wind farm in 2018 and ahead will be commissioned in 2022. This difference in 12 years is multiplied by 1,67. However a linear relation is not expected, because the amount of suitable areas increase when the conditions increase.
As a consequence, the difference between 2022 and 2010 is divided by 1.2. This outcome is added to

the conditions in 2010. As a result the four conditions are extrapolated to the year 2030. Equation 1 represents the applied formula for the European extrapolation. A similar approach is applied to China, although the numbers 1,2 and 1,67 are different in the corresponding equation.

$$C = \left(\frac{(B - A) * 1,67}{1,2} \right) + A \tag{1}$$

In which:
A = Market conditions in 2010
B = Market conditions in 2022
C = Market conditions in 2030

The other three markets have a negligible commissioned capacity before 2018. Their average commissioned project after 2018 is simply extended to the year 2030 by a linear extrapolation between 2018 and the average commissioned year of the potential wind farms. A summary of the extrapolation method is provided in table 2.2.

Table 2.2: Extrapolation to the average commissioned conditions in 2030

		Distance to shore (km)	Water depth (m)	Wind farm size (MW)	Wind turbine size (MW)	Installed capacity (GW)
2018 and ahead	EU	63	32	570	11	
	China	22	14	300	10	
	Japan	7	17	180	8	
	Asia clustered	23	28	230	6	
	US Atlantic	46	33	470	11	
Before 2018	EU	37	24	180	4	
	China	20	11	160	4	
2030	EU	73	35	723	14	60
	China	23	15	375	13	65
	Japan	8	20	216	10	10
	Asia clustered	28	34	276	7	13,5
	US Atlantic	55	40	564	13	22

2.8 Market conclusion

The average construction conditions of projects from 2018 and ahead can be seen in figure C.3 and the average market conditions by the year 2030 are presented in figure 2.6. Considering the water depth in this figure, a group of China and Japan is formed at about 20 meter and the remaining three groups form a group at about 35 meter. Considering the distance to shore, one group is composed at about 25 kilometer offshore, while another group is formed at about 70 kilometer offshore.
When taking the complete graph into account a group is established at the right top by Europe and the US Atlantic. The other group is established at the left bottom by Japan, China and the clustered group of Asia. From the average market conditions by 2030 as displayed in figure 2.6 it can be concluded that there are two separate groups concerning the market conditions by 2030. The capacity installed is represented by the size of the bubble.

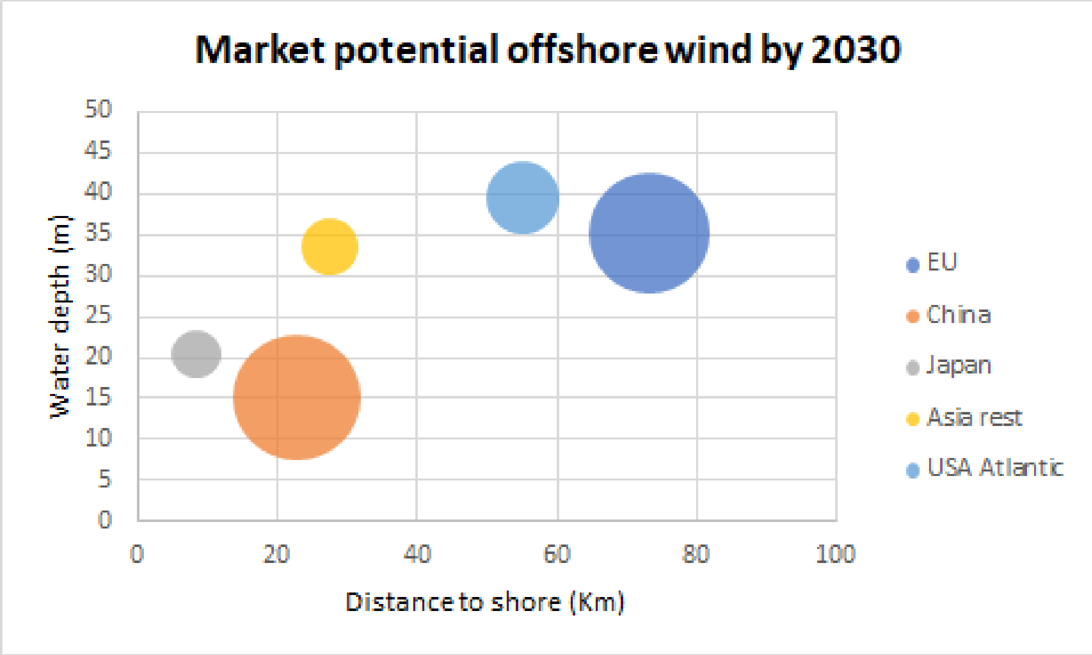


Figure 2.6: Average market construction conditions by 2030

3. Construction strategies

Several strategies are possible for the construction of an offshore wind farm. The applied strategy depends on the location, season, capacity and companies involved. The most common strategy applied in practice, is used as a reference case in this research. This allows for a comparison between the new construction concept and this reference case. Another reason to analyse the current construction strategy, is to determine the adjustments required for future construction strategies. Since it is a developing market, the future strategies can deviate from the currently applied construction strategies.

3.1 Offshore wind industry

The current and future demands in the market are not described in the literature, therefore interviews are a valuable contribution to this research. The interviewed companies are dominant players in the offshore wind market and except an explanation on the demands in the market, they can also elaborate on current strategies and developments in the market.

Recent literature is in most cases already outdated since the market is rapidly changing. An example is the full pre-assembling onshore, of the offshore turbines. Recent literature suggests a pre-assembling method comprised of a minimum number of components to be loaded on an installation vessel. This reduces the number of lifts onshore and decreases the installation time [199] [198] [117].

However, the companies in the market unanimous agree that this method is not feasible to conduct in the near and long future, because the size of the turbines is increasing and this development is expected to continue. This leads to technical difficulties to conduct a single lift, furthermore this is financially not feasible. To execute a single lift, a new type of vessel would be required with a higher lifting payload, reach and lifting height. These are not attractive to be constructed since in a few years time, a new lifting requirement will be demanded from the vessels. Therefore, it is technically and financially more reasonable to carry out multiple lifts to install the future turbines.

Three topics are discussed during the interviews. The precise topics discussed deviate between the different companies. First the current construction strategy in their field is discussed, which is followed by a discussion on how possible developments in the market can influence the construction strategies. The third topic is about the market demands during construction. Interviews are chosen above a survey, since an interview encourages more complete and interpretable answers. It also provides the possibility to respond to incomplete answers [47]. Most qualitative in-depth interviews are semi-structured [24]. It provides some structure based on the research interests, but also possibilities for the respondent's spontaneous description.

Together, the interviewed companies represent all the separate phases in the life cycle of an offshore wind farm, starting at the design & engineering phase. The phases are listed vertically whereas the components are listed horizontally in figure 3.1, these are also covered by the interviewed companies. A reference to the view of the interviewed companies is noted as 'market', since the current and future construction strategies of the companies can not be mentioned. The names of the companies interviewed can be found in appendix D, as well as the number of projects in which they were responsible for the installation. Due to the reasons mentioned in this paragraph, the interviews are the dominant guidance in this chapter to understand the strategies and demands in the market.

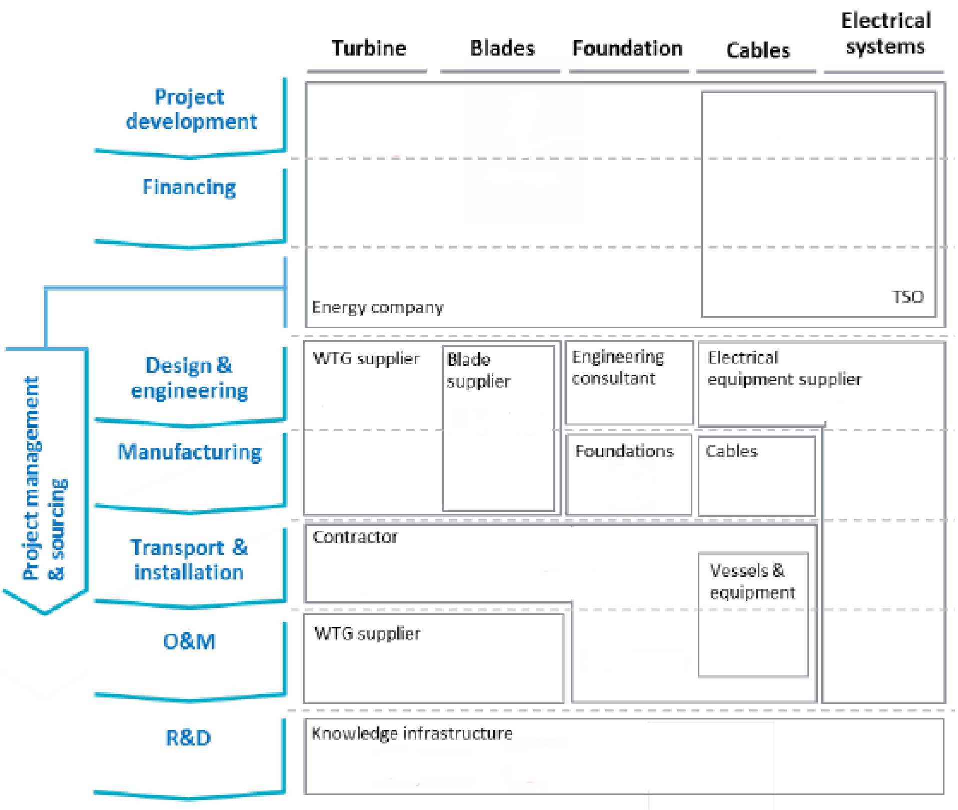


Figure 3.1: Aspects of an offshore wind farm life cycle[8] [195]

3.2 Operational phase

During the operational phase of an offshore wind farm the energy is generated. For a typical offshore wind turbine, the life span is about twenty-five years. To achieve this life span a wind turbine needs maintenance, which consist of preventative and corrective maintenance. The operation and maintenance costs account for about 20-25% of the overall life cycle costs [109] [45], where the costs for corrective maintenance are a factor of two higher than those of preventative maintenance [164]. In most preventative maintenance strategies the wind turbine is visited about twice a year for maintenance [193] [197].

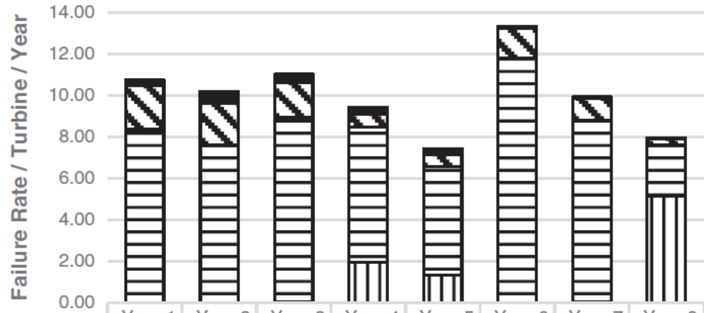
Based on 350 offshore wind turbines throughout Europe, the failure rates by year of operation are displayed in figure 3.2. This figure clearly shows that minor repairs are dominant throughout the operational phase of an offshore wind turbine.

Similar relations between minor and major replacements are found for onshore wind turbines [29], but also for other offshore wind farms [178] [48]. A minor repair is any failure with a total repair material cost of less than €1000, between €1000 and €10.000 is a major repair and material repair costs above €10.000 are a major replacement.

The blades, hub and gearbox have the highest repair costs and downtime per reparation [30] [44]. However, the major replacement failure rate is very low for the hub and blades, they do not contribute much to the overall operation and maintenance costs. Smaller components like the gearbox and generator with a high repair dominance have a higher share on the operation and maintenance costs.

Maintenance on small components has a limited influence on the costs of either: manufacturing, trans-

[8] TSO is an abbreviation of transmission system operator



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Major Replacment	0.28	0.56	0.39	0.34	0.31	0.09	0.05	0.03
Major Repair	2.13	2.02	1.70	0.62	0.56	1.43	1.07	0.32
Minor Repair	8.34	7.60	8.89	6.50	5.24	11.80	8.76	2.45
No Cost Data	0.00	0.00	0.03	1.95	1.33	0.00	0.03	5.14

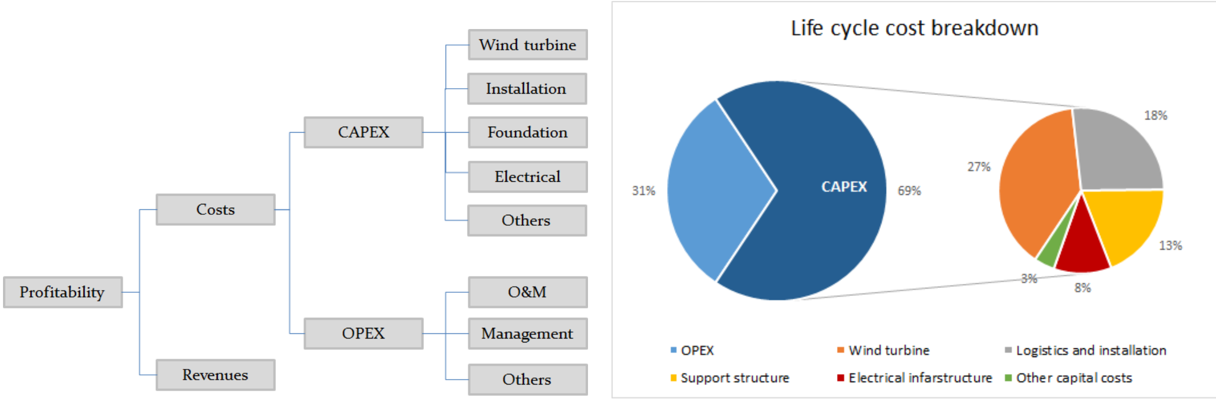
Figure 3.2: Failure rate and failure category per year of operation [30]

port or installation. Though, applying the right maintenance strategy is a challenge for the offshore wind industry. Possibilities are: a workboat operating form a port base, a workboat with support from helicopters, a service operation vessel, a permanent offshore accommodation or wind farms who share their logistics [45] [188]. A new maintenance strategy is not considered in this research due to the dominance of small components in the costs of repair.

3.3 Construction

The cost drivers for an offshore wind farm project are presented in figure 3.3a. The influence of each cost driver on the life cycle costs is presented in figure 3.3b. The vessel chartering costs contribute the highest portion to the logistics and installation costs [100] [77]. Accurate percentages depend on for example, a specific project, the country of a project, the available infrastructure and the distance to shore. Because when the distance increases, the electrical infrastructure costs are driven upwards. A longer distance to the shore normally also involves higher water depths, which requires a more complex installation procedures and more expensive equipment.
The market could only provide project specific information on the cost breakdown, so literature is used to determine the generalised percentages in figure 3.3b. The life cycle costs are split up between operational expenditures (OPEX) and CAPEX and averaged over the sources [142] [109] [42]. The OPEX are the ongoing costs for having a structure, examples are: maintenance, insurance or property fees. The CAPEX consists of multiple drivers, with a deviation between sources on the aspects a driver covers. Therefore a source is only taken into account, when it generally mentions at least the four most influential cost drivers [160] [18] [163].
The percentages in figure 3.3b represent a monopile as foundation. Since the operation and maintenance phase is placed outside the scope, this research focuses on the manufacturing, transport and installation phases. The cost distribution of these three phases are provided in figure 3.3b.

The current construction strategy is elaborated in the following paragraphs. It functions as the reference case of this research project. However, there is not one universally applied installation strategy for all offshore wind farms. This depends among others on the site, company, seasonal and installed capacity. The most common strategy that is currently applied and the corresponding equipments and components used for construction, determines the reference case used in this research. In the



(a) Cost drivers (b) Life cycle cost and CAPEX breakdown

Figure 3.3: Influential cost drivers in the life cycle

remaining of this research this reference case is a constant and does not show deviations, in practice this is of course different due to different conditions. This reference case is subdivided into four phases representing the reference case, and elaborated in the next paragraphs.

3.3.1 Delivery of components

The offshore turbine components and the type of foundations are discussed in paragraph 1.1.1. Manufacturing the turbine and in lesser extent the foundation, requires a lot of equipment. The manufacturing of the monopile and the tower of the turbine are approximately similar process. Steel plates are rolled to form cans and cones, tese are then welded longitudinal. The cans and cones of the monopiles are shipped by barges to a manufactory near the port, where they are assembled by welding machines and inspected by a third party. In some cases, the components are transported from the manufactory by truck or by rail. The last step is the coating and load out to the quayside of the port.
The welding and coating of the tower of the turbine takes place at the same manufactory as the rolling process. From here the tower sections are transported to the quayside of the port where the full pre-assembling takes place. Manufacturing the transition piece comprises more processes, though they are in line with the latter explanation.
For all three components it holds that the transport to the quayside can be a long sailing distance. The manufacturing of the blades and nacelle is technically more difficult and not elaborated. They are transported to the quayside by rail, truck, vessel or a combination.
Currently, the largest capacity installed is a turbine of 8 MW at the Buro Bank wind farm. An average installation in 2017 comprises 6 MW. Cable laying vessels do not require a delivery to the port, since the vessels load the cables at a quayside elsewhere, the same accounts for the scour protection. Additionally a substation is directly delivered to the installation location. It should be noted that there is no need for delivery of all the components at the same time.

3.3.2 Onshore assembling

Depending on the manufacturing location, monopiles and transition pieces can directly be transferred to the offshore wind farm site, since they do not require assembling. In the reference case the manufactory for welding and coating is adjacent to the port, so the monopiles can be loaded to the quayside of the port. Assembling at the port only applies to the turbine components, the possible assembling methods are discussed in paragraph 3.3.4. The most common method is to assemble a bunny ear and

have a separate third blade and tower. A bunny ear represents an assembled: nacelle, hub and two blades.
A crane with a capacity of 500 tonnage is required to lift the tower, additional cranes with nearly as much capacity are used for the assembling. A strong quayside is required for the weight of the cranes and all the components of a turbine, the latter accounting for 1000 tonnage.

Figure 3.4: Onshore assembling of the turbine at Eemshaven [W5]

The installation of the turbines provides various numbers of pre-assembly methods and when considering that the tower is transported in one piece, there are currently three possible methods [61] [105]. These are listed below:

- Tower + pre-assembled nacelle and hub + pre assembled blades
- Tower + "bunny ear"+ seperate third blade
- Tower + pre-assembled nacelle and hub + three seperate blades

Another method than the component-wise installation is the fully pre-assembled method. The main advantage of this method is that it only requires a single lift to install a turbine on the transition piece. At the time of this writing, this method has only been applied twice. This is in the Beatrice Demonstrator Project and in the Donghai Bridge project [215]. However, as described in section 3.1 a single lift is technically and financially not feasible for future turbines.

3.3.3 Offshore transport

For each offshore wind project the installation vessels are reconfigured, so the project specific components can be placed efficiently. A jack-up vessel or jack-up barge, is used for the transportation of the foundation and also for the transportation of the pre-assembled turbines. The number of monopiles transported by the jack-up vessel is very dependent on the project specifications to be cost efficient. For the reference case this number is not fixed, on average this is about 4 to 8 monopiles.
The inter array cables are transported by a cable laying vessel. The required equipment and manpower to install the cable at the wind turbine support structure are transported by an installation support vessel.

The substation is transported by a heavy lift vessel and the scour protection is transported by a fall pipe vessel. The turbines are transported from the port to the wind farm location by the jack-up. During each trip, about 4 to 8 turbines are transported. The bunny ear method is most widely applied, though the pre assembling method depends on the vessel. The tower of the turbine can be installed by a single lift or in multiple lifts when not fully assembled before transportation. In this reference case, the tower of the turbine is fully assembled onshore.

In section 1.1.1 it is stated that the transport and installation is on average 18% of the CAPEX. This percentage excludes the electrical infrastructure. Of this 18%, the vessel chartering costs contribute the biggest portion [100] [18]. The precise contribution of the vessel costs is project dependent. But to understand the dimensions, as stated in section 1.2 the jack up day rates range between $50.000 and $300.000. These numbers are confirmed by a jack up rental company.

The six most common type of installation vessels are shown in figure 3.5. All six types of installation vessels are discussed in this paragraph. A jack-up vessel is a popular installation vessel. It combines the self-lifting and stabilising features with a self-propelling system. They are limited by water depths of 50 to 60 meter. They can be used for multi purpose roles. A jack-up barge has a lower deck area and has a low sailing speed or is non self-propelling. The shape of the hull is a barge, which makes them less favorable as a jack-up vessel for longer sailing distances.
A heavy lift vessel is shown in figure 3.5c, it has a higher crane capacity as the jack-up vessel or jack-up barge. Also it is not limited by water depth, since it does not elevate itself above the water surface. A disadvantage is the susceptibility to waves and the limited availability in the market.
A cable vessel installs the inter array cable and the export cable. An inevitable property of a cable laying vessel is the carousel, this stores the cable without bending it too much. A fall pipe vessel places the rock armour around the foundation, an example is provided in figure 3.5e. Deviations of vessels used for the scour protection are a rock dumping vessel, which is less accurate, or a vessel with a smaller fall pipe which is more accurate. The fall pipe vessel places the rocks more accurate by using an under water camera.
The support vessel assist the inter array cable vessel and the survey before installation takes place. It is capable of lifting equipment with a low weight on the transition piece and it functions as a hotel for the offshore crew. This can be seen in figure 3.5f.

3.3.4 Offshore installation

The five main steps of installation and their consecutive order are listed below [3][9].

1. Installation of the foundation
2. Placement of the scour protection
3. Cable laying process
4. Installation of the offshore substation
5. Installation of the turbines

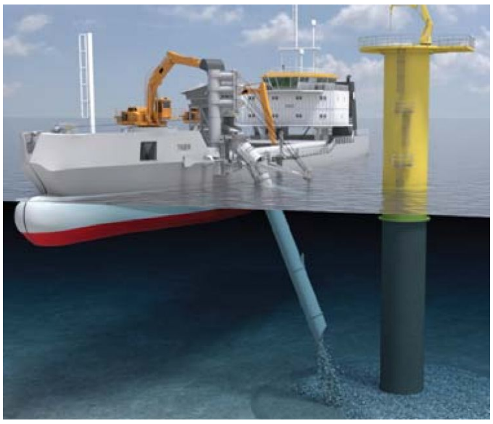
[9] Some literature shows deviations, primarily because of project specific conditions. This consecutive order for monopile installation is derived by a literature study and confirmed by the interviewed companies.

(a) Jack up vessel at Gemini wind farm [W21]

(b) Turbine installation by jack up barge[10]

(c) Heavy lift vessel installing a jacket[10]

(d) Inter array cable vessel[10]



(e) Fall pipe vessel [W4]

(f) Installation support vessel[10]

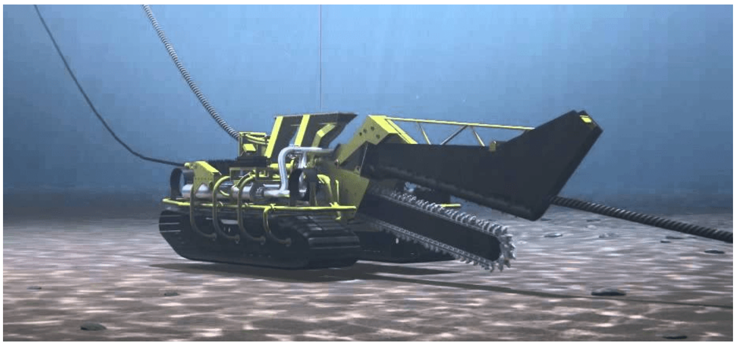
Figure 3.5: The six most common installation vessels

Weather conditions influence the workability and can cause delays in the project. Therefore the summertime is a favorable period for offshore wind farm installation, but due to limited availability of equipment there are also installations in wintertime. When the weather conditions impede the installation for a few days, the jack-ups sail to the port and load to full capacity. Obviously the installation takes place from bottom to the top, but there are more aspects to be taken into account. The sequence of installation is of critical importance, it needs to be conducted efficiently to reduce

[10]Vuyk database

the costs as much as possible.
Depending on the current, a scour protection is required. A filter layer consisting of small rocks is placed at the location of the foundation. The foundation is installed by driving the pile, or alternatively drilling the pile into the ground. When the foundation is installed, the transition piece is placed on the top and the space between them is grouted. This installation is displayed in figure 3.6a.
The function of the transition piece is to correct the misalignment of the pile on the seabed. It also creates a stable base for positioning the turbine. When the installation vessel is finished, the fall pipe arrives for a second time. In some cases a side dumping barge is used, but this is less accurate and has a higher probability of damaging the monopile. The scour protection is finished when the armour layour of rocks is placed. This is shown in figure 3.5e. An alternative strategy is to place nonwoven geotextiles, that are filled with sand and function as an armour layer.

(a) Lifting of the transition piece at Anholt wind farm [W2]

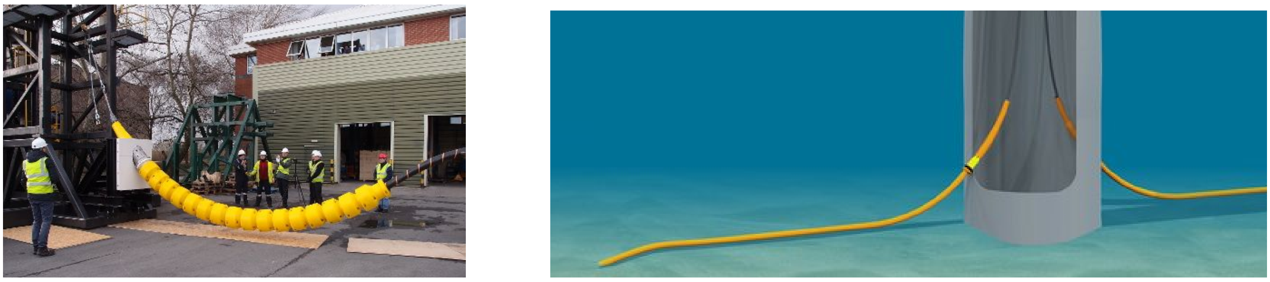


(b) Trench machine [W33]

Figure 3.6: Installation of transition piece and inter array cable

The installation support vessel drops the required equipment for the cable installation on the transition piece. The inter array cable is connected to the J tube in the monopile, which is monitored by an under water camera. When the cable is connected, it is manually pulled above to the transition piece. Next, the installation vessel sails to the second monopile and the same process takes place. So between two monopiles there is one inter array cable. A few circled loops of monopiles are created and each circle is prepared to be connected to the offshore substation. Circles are created for when failure in one inter array cable occurs, so the direction of the current can be switched.
The inter array cable is buried into the seabed by a machine that uses a water jet. A part of the inter array cable is protected by a tube, this is the yellow part in figure 3.7a and the orange part in figure 3.7b. In some projects the opening of the J tube is connected to the monopile at a level under the seabed. When the turbine is installed, the cable will be connected to the nacelle. The export cable is connected to an onshore and offshore substation and by the use of a cable trencher the cable is buried approximately 3 meter under the seabed.

The inter array cable is installed after the scour protection, so the cable is not damaged. Depending on the type of scour protection, this sequence could be turned around. Though the cables are always installed before the substation and the turbines are installed. With no turbine present, the pulling of the cable is a lot easier. The installation of the substation is after the cable installation because it this is an expensive operation. This operation should not be influenced by failure or delay of the cable installation.



(a) Cable protection system [W11]

(b) Connection to monopile, in no scour protection case [W26]

Figure 3.7: Inter array cable installation

The substation is installed before the turbines, because as soon as one loop of wind turbines is installed it costs money when they do not generate energy. In most projects, the substation is installed by a heavy lift vessel. The turbines are installed by a jack up vessel or jack up barge. These vessels have a high day rate and therefor these processes take place at the end of the installation cycle. So failure or delay of previous processes does not affect the rental period of these vessels.
There is also a technical argumentation to install the turbine as last. It is not possible that the blades stop moving for a long period of time, this leads to a possible failure of blade bearing. First the tower is installed, then the pre-assembled nacelle and hub are installed and the installation of the three separate blades mark the end of the installation of the wind turbine.

3.4 Future trends in construction

Due to the rapid developments and changes within the industry this is difficult to predict. For example GROW, which is an ambitious program by 20 leaders in offshore wind, developed a target in the summer of 2016 to have a cost price of 7 cent per kWh by 2030. However at the end of 2016 the winning offer for the first wind farm at Borssele was 7.27 cent per kWh and a few months later the second wind farm at Borssele was sold for a cost price of 5.45 cent per kWh.
Future construction strategies that are likely to occur are based on the interviews and confirmation by multiple persons. The future construction strategies are subdivided into three categories: foundations, vessels and turbine assembling. These are taken into account because they influence the construction by the year 2030.

Foundations

A monopile foundation is currently limited to approximately 35 meter water depth for design reasons. However, preliminary designs show that the current manufacturing capabilities can be applied until a water depth of 50 meter and the monopile will keep the largest share of the annual installed foundation type. This is because its manufacturing costs are relatively low and the manufacturing and assemling is fast and a proven technique.
However, the share of jackets as a foundation will increase, they are applicable in water depths up to 60 meter and can deal with a wider range of soil and weather conditions than the monopile. The

expectations on floating foundations show a low potential due to a number of reasons:

- The number of lifts to place the turbine components on top of the transition piece should be minimised, because installation on a floating foundation is very sensitive to waves. The remaining weather window that allows for installation is very small. This also holds for the anchoring of the foundation.
- Ports do not have the required facilities like water depth, crane capacity and appropriate quayside. The turbines have to be fully assembled onshore to reduce the number of lifts on a floating foundation.
- Floating foundations will remain more expensive than fixed foundations at water depths below 60 meter. When a country does not have a favorable offshore wind region, other RES can be more cost effective.

Vessels
Currently the main vessel type used for installation of the foundation and turbine is the jack-up vessel or jack-up barge. The water depths of the wind farms are increasing, this makes installation by a heavy lift vessel more attractive. Besides higher water depths, also the distances to shore increase. A jack-up is not ideal to sail long distances. It carries three or four legs, this together is comparable to the weight of a tower of a turbine.
Heavy lift vessels are more costly than a jack up, mainly due to the motion compensated cranes and the higher lifting capacity than a jack up. Installation of a turbine by a heavy-lift vessel is more difficult than the installation of a foundation by a heavy-lift vessel.

Turbine assembling
An example of offshore installation with fully pre-assembled turbines, is the Donghai Bridge project. The 3 MW turbines are pre-assembled onshore and installed with a single lift, as can be seen in figure 3.8a. Capacities of 12 MW are currently developed and achieved by increasing the efficiency of the turbine, but also by increasing its size. Despite that a single lift has a shorter installation time, it is technically not feasible to conduct this for large future turbines. This is due to the fact that turbines have to be made a lot stronger to handle a single lift, but because the turbine already amounts for 30% of the capital costs [20] the manufacturers refuse to increase the costs of the turbine by making them stronger.
The heavy-lift vessels that are currently able of installing large turbines have a very low availability. With the rapid development of the turbine size, the available vessels that can handle a single lift will decrease even more. Another disadvantage is that the installation has a very small weather window.

A pre-assembled tower with nacelle and hub is a plausible future strategy. The blades will be installed separately, this is partly due to the length of the blades and the available space on the vessel. The structural forces on the lifting blade yoke, caused by the blades catching wind, is more limiting than the wave forces during the installation for a jacked situation. Currently turbines are assembled at 14 m/s, though the tools are already certified to 19 m/s. When the traverse system that catches these forces is developed further, the maximum installation wind speed will increase in the future.

To decrease the costs of transport, onshore wind farms have an innovative solution that is already in serial production. A bolted steel shell tower consists of multiple tower sections, mounted on top of each other. Each section is made out of steel shells which are assembled together on site. The steel shells are produced from bended steel plates and require less steel compared to the tubular steel towers. They can easily be transported to the site, though it still asks for optimisation. When applying this installation technique offshore, the crane capacity of the vessel can be decrease.

(a) Full pre-assembled turbine [W6]

(b) Steel shell tower concept [W29]

Figure 3.8: Turbine assembling possibilities

4. Demands and objective

Demands in the offshore wind market that lead to an improvement in the construction phase, could reduce the levelised cost of energy. Dominant companies in the offshore wind market are asked for improvements during construction. The main demands are listed in section 4.1. This is followed by the problem description, research objective and applied methodology.

4.1 Demands in the market

An important development in the competitiveness of offshore wind to other renewable energy sources, is to reduce the construction costs. The most expensive required element for construction is the jack-up vessel, the high day rates are described in paragraph 3.3.3. However, the construction phase has multiple cost elements like equipment, components to install and manpower, that could all be reduced. Demands like cheaper raw materials, more vessels available or a more effective turbine can not be improved by the construction phase and are therefore not taken into account.
Another example is that a specific type of turbine is used for multiple wind farms. But because each wind farm has another contractor to install the turbines, the contractors all have adjusted their own fleet or build a new vessel to install the specific turbine for one wind farm. However, the demand of a turbine manufacturer having his own installation vessel can not be solved by considering the three construction phases.

The demands are referred to as: "the market", specific company names are not used in this report, an overview of all the companies interviewed can be found in appendix D. Not all interviews led to specific demands, some interviewed persons explained their applied strategy and by listening critically a demand could be derived. For example, it was described that during the transport of the tower of the turbine some fatigue life is lost. However, after the interview it was calculated that only a negligible percentage of the fatigue is lost during the life time of the turbine[11]. When this percentage would be higher, this demand could be taken into account, due to this small loss of fatigue life it is not included as a demand. The demands are listed below and an elaboration is provided on why this demand is required.

Demand 1: Deep water port near the wind farm

A deep water port is demanded for the placement of the turbine on the spar buoy foundation. The deep draft of the spar buoy provides stability, so that a fully assembled wind turbine foundation can be towed in an upright position. This brings field work down to an absolute minimum. However, there are only a few fjords with a water depth of more than 40 meter.

Due to weather sensitivity and the lack of deep water ports, it is preferred to tow a fully assembled spar buoy horizontally. At the offshore site it is flipped by adding ballast. Next, the fully assembled turbine is placed on top of it at the offshore wind farm location.
The weather conditions have to be favorable to prevent delays in the towing and installation of the assembled wind turbine foundation. To increase the potential of this substructure, this barrier of a

[11] Using the Palmgren-Miner's rule and the hydrodynamic load equation of Bernoulli on the installation vessel [177].

low sailing workability can be removed by a port near the wind farm.

In section 3.4 it has been explained why the potential of floating wind is low. Although, this potential could be increased when the demand of a deep water port near the wind farm is fulfilled.
There are currently four substructure designs for floating offshore wind, as stated in paragraph 1.1.1. The spar buoy substructure is in operation at the Hywind project, the single other substructure with a technology readiness level appropriate for launch is the semi-submersible.
The continental shelf has a gentle slope, so countries with a long continental shelf have a shallow water area in which fixed foundations can be installed to generate wind energy. Countries who have a short continental shelf, rely on floating substructures to generate offshore wind energy. Floating substructures are mainly of interest for those countries. Examples are: Norway, Portugal and the US Pacific coast. For water depths of more than 100 meter, the spar buoy foundation is the most appropriate. Other advantages of the spar buoy are the low sensitivity to waves and the manufacturing cost.

Demand 2: Decrease rental costs of the installation vessel
The day rate of a jack-up vessel multiplied by the rental period determines the rental costs for the jack up vessel. A rule of thumb applied in the vessel industry for the day rate of a jack-up, is about 0.1% of the CAPEX of a jack-up for a charter period of approximately 1 year. A larger distance to shore requires a longer rental period so the rental costs increase. When the water depth increases, the jack up needs heavier legs which increases the CAPEX. The jack up vessel requires a higher capacity for longer sailing distances to become more cost effective. This increases the day rate, but here is a trade-off between day rate and rental period.
The jack up vessel is inefficient for sailing since its main task is to conduct the installation. Since the day rate of the jack-up has a substantial share on the construction costs, the rental costs have to be reduced.
When the installation is executed with a heavy-lift vessel, the day rates are higher than for a jack-up vessel. This is mainly due to the motion compensated crane and the higher lifting and carrying capacity of the heavy-lift vessel. They are more suitable in deeper waters, which is usually in alignment with a long distance to shore. When a heavy-lift vessel is used, the rental costs are demanded to be reduced as well.

Demand 3: Usage of one installation vessel and a cheap feeder system
This demand holds for the US offshore wind market. The demand is nearly similar to demand two, though the motivation is different. The installation vessel is the most expensive share of the construction. When using an additional feeder vessel to supply the installation vessel as conducted in the US, the feeder vessel can not be an installation vessel. Because a lifting capability increases the day rate of the vessel substantially.
The Block Island wind farm was installed in 2016 by the Brave Tern vessel from Malta. Due to the Jones-Act, the Brave Tern was not permitted to touch the shore. Meaning that a US-flagged feeder vessel had to transport the partly pre assembled turbine components, from the US coast to the Brave Tern vessel located offshore. This added high costs to the installation of the project because this US feeder vessel was expensive. This installation method was applied for the first time which led to high costs. The installation of the blades for a turbine in the Block Island wind farm requiring two jack-ups,

is displayed in figure 4.1a.

Demand 4: A shelter with loading facilities
The workability of cable laying is in most cases limited by a wave height of 3 meter. At least once a month during the summer period this condition occurs and the two vessels will return to the shore where loading takes place. When the sailing distance increases, a longer period of bad weather is required to make the return to the shore effective. When there is a shelter near the wind farm site, loading of food, drinking water or a cable protection system can take place. This decreases the cycle time of loading and the construction can be conducted in a shorter period of time. A similar demand of loading at a shelter holds for the scour protection installation vessel.

Demand 5: A smaller installation support vessel
The offshore installation continues all day, there are two shift of twelve hours for the crew. Besides transporting equipment, the major function of the installation support vessel is to provide about 60 sleeping places. The size and costs of the cable laying support vessel can be decreased when the crew does not have to sleep on the vessel. Figure 4.1b shows the two vessels used for the inter-array cable installation.

(a) Installation of blades at a US wind farm [W8]

(b) Cable laying vessel and the support vessel (top) [W28]

Figure 4.1: Installation of blades and inter array cable

Demand 6: Ease the transport of the tower
The rolling, welding and coating of the tower of the turbine, are processes conducted in countries with low-costs for labor and raw material. The sections of the tower sails a long distance to the marshalling port, where the assembling and vertical lifting of the tower takes place. From here the full assembled tower is sailed to the offshore wind farm location.
The demand is to optimise this transport of the tower, for example by sailing a shorter distance with a fully pre-assembled tower or not visiting the onshore port. This does not hold for the foundation, since this is coated after the onshore assembling and coating does not take place at the onshore port but in the manufactory.

The conclusion of the demands in the offshore wind market during construction is as follows:

All demands can be fulfilled when an offshore port near the wind farm would be available. This is the most important conclusion of the market demands. Other new construction concepts with less focus on a new logistical construction concept are maybe able to fulfil single, multiple and perhaps all demands as well. But in the remaining of this research, the feasibility and opportunities of an offshore port concept are analysed. It is a new construction concept that has the potential to fulfil all six demands.

Though it could be questioned whether the demand of using one installation vessel is fulfilled. When the port would be floating, it is nearly a vessel. An improvement in the onshore ports is not a demand, mainly because most of the onshore ports used for offshore wind farm construction are recently build. To take a demand into account it has to be a useful contribution to the current construction strategy. When it creates new additional profits, the demand is more relevant to take into account than when it does not create additional profits. An indication of the effect that a demand has on the profits is based on the expected influence of the demand on the cost reduction. When a demand could gain a high theoretical profit, it also has to be feasible to fulfil this demand.
A high technical, ecological, cultural or legislation challenge has less potential to be integrated by the industry and the governments than a small adjustment in the standard strategy.
The demands are prioritised based on the positive effect on the profits and the expected integration by the industry and governments, as is shown in the figure below. A high value on both axises means a favorable value and a higher priority to be taken into account in the design. An elaboration on the location of a demand within the graph is provided in appendix E. They are ranked relatively to each other, so there are no units on the axis.

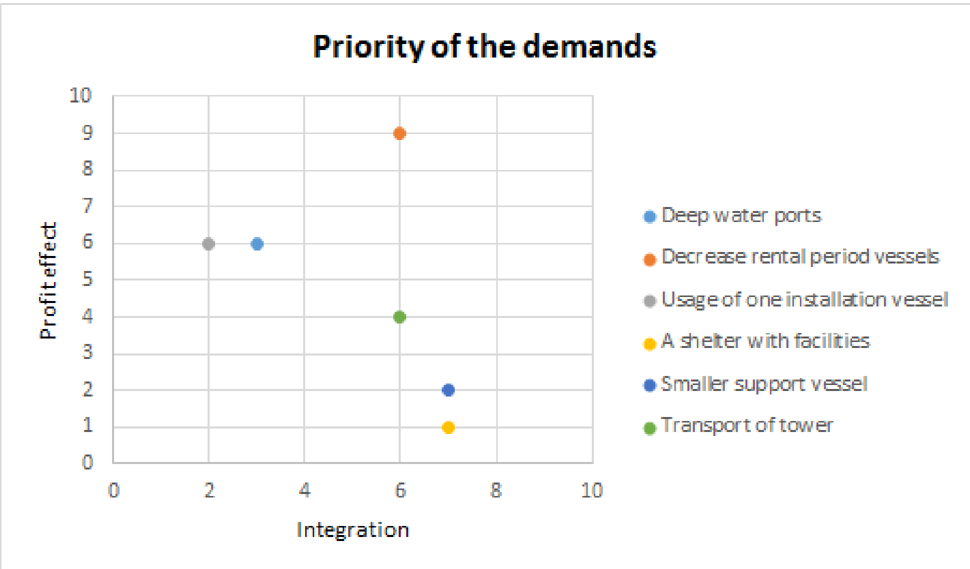


Figure 4.2: The demands in the market ranked to priority

4.2 Problem description

The offshore wind market has six demands during construction, when a demand is fulfilled the levelised cost of energy (LCOE) for wind farm projects could be lowered. An offshore port concept could fulfil all the demands, though the potential is uncertain. This is because no research considered the opportunity of an offshore port designed for the construction phase of an offshore wind farm yet. As stated in paragraph 1.2, just one research considered the possibility of an offshore port that is located

near the offshore wind farm. Though this research only considered the logistical profit in time and does not pay attention to financial or technical feasibility.
It is unknown whether an offshore port is logistical, technical and financial a valuable contribution to the onshore activities of the offshore wind farm construction.

Problem statement

A new port concept could provide opportunities during construction, to decrease the LCOE for offshore wind. When an offshore port concept has a market potential, it is uncertain under which conditions it is technically and financially feasible to have such a port.

4.3 Research objective

The offshore wind market is developing into deeper waters and at a farther distance to shore. These and other developments will continue in the next decades. It is questionable whether the current approach regarding construction is the most effective one. The market is interested in the opportunities that could be generated by an offshore port. This can be an alternatives for the onshore marshalling port concept and be applied as offshore port to multiple offshore wind farm projects. In future this port can be engineered when it is a technical and financial feasible concept. The research objective is defined as follows:

'Explore the market potential of an offshore port concept to reduce the LCOE for an offshore wind farm, by making analyses on the activities executed during construction and a technical design of the port concept with the corresponding financial performance.'

4.3.1 Scope

To answer the research objective, the complexity of certain minor parts have to be reduced. For this purpose a number of well thought out and simplifying assumptions are discussed and decisions are made. These assumptions and decisions are elaborated in the bullet points below.

- As explained in paragraph 3.2, maintenance is dominated by minor repairs. Suitable solutions for maintenance have different demands than improvements for the construction phase, consisting of manufacturing, transport and installation. Therefore, the operation and maintenance phase is placed outside the scope.
- The design of the port is created for the year 2030. A constructed offshore port for offshore wind, is assumed not to be feasible before 2030. The outlooks for 2050 show, that there is still an offshore wind market potential between 2030 and 2050[12]. This makes an operational offshore port by 2030 interesting as well.
- The offshore port is designed to fulfil demands during construction. When the port is used for multiple projects, the financial feasibility increases. This requires the port to be transportable, it could be self propelled, towed or transported by vessels.
- The offshore port should be feasible for all construction conditions by 2030. The owner of the offshore port should not reject offshore wind farm projects because the offshore port can not

[12]Same sources used for the analyses in chapter 2

handle the environmental construction conditions. The North Sea and US Atlantic coast are the selected regions, more information on this is provided in section 5.2.

The market potential of a movable offshore port that is used throughout the construction of an offshore wind farm is explored during this research. A fixed offshore port near multiple future wind farms is not. This concept could also be an opportunity to reduce the LCOE. However based on fewer wind farms construction that can be supported, the existing plans by TenneT to create an offshore hub at the Doggersbank and the difficult phasing of multiple wind farms in a nearby area, this concept is not analysed within this research.

4.4 Research methodology

Four main steps are taken to explore the feasibility of an offshore port concept. These four steps are indicated by the green circles in figure 4.3. Step one is elaborated in chapter 5 and step two represents chapter 6. In this chapter also step three is elaborated and step four consist of chapter 7 and 8. The four main steps can be summarized as follows:

1. The demands are translated to activities that have to be executed at the offshore port, to fulfil a specific demand. The maximum workability condition for each activity and the environmental conditions have to be determined as well.
2. Port components are potential type of foundations for the offshore port. A port component is taken into account when it can fulfill the boundary conditions of the required activities to fulfil the demands.
3. The port components are analysed on the degree in which they satisfy the workability conditions. For floating port components this is calculated by a motion response analyses, the workability of fixed port components is based on limitations of the construction. As a result not all port components can be used as a port concept. Taking into account the advantages and disadvantages of each port components and an indication of the investment costs, three port concepts are selected.
4. A logistical model can be used to indicate the savings on construction when applying an offshore port concept. In combination with the costs a financial potential can be determined for the selected port concepts. As a result one port concept is selected proposed to develop into more detail.

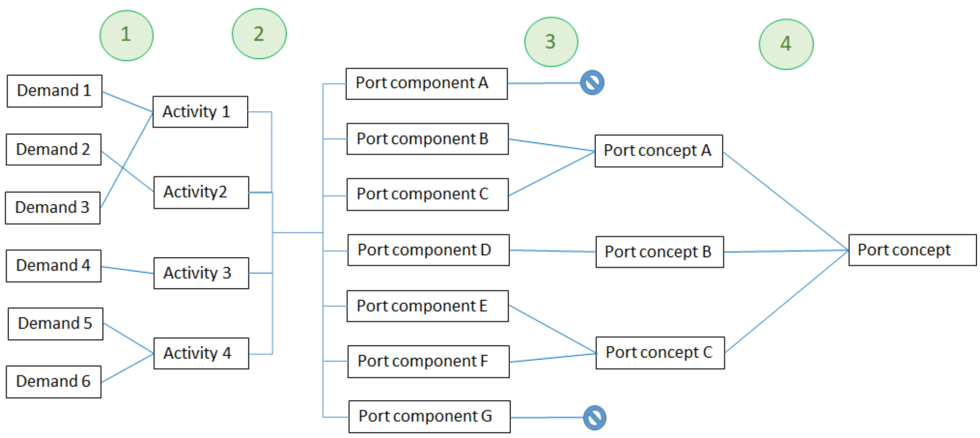


Figure 4.3: Research methodology from demands to offshore port concept

5. Workability conditions

Conducting an activity offshore is in principal more expensive than conducting it onshore. When activities in the offshore port are a serviceable addition to the construction process, the potential of an offshore port grows. The required activities are derived from the demands in section 4.1 and their workability is determined. The workability depends on the environmental conditions, these are elaborated in section 5.3.

5.1 Current state offshore ports

For this research it is important to determine if it is feasible to use an offshore port for the offshore wind market. Only one research has been performed that takes into account an offshore port near an offshore wind farm. This research only considered the logistical profit in time and does not pay attention to financial or technical feasibility. The result of this research carried out by ECN shows a huge potential for offshore ports, for more information on this research see appendix A. Though the possibility of using the offshore port for multiple wind farm installation projects was not considered. There are no existing ports located near offshore wind farms, this was the result of a literature review and a short interview with two experts[13] in the offshore wind field.

Currently there are offshore ports with container terminals operational, however these ports are connected to land via causeways [152]. In 2018 the construction of an offshore port at Venice will mark the first offshore (container) terminal without a connection to the shore. Recent developments and announced offshore port projects that have no connection to the shore are: the project Portunus and the Louisiana terminal in the US and the Hon Khoai port in Vietnam [152]. So offshore ports can be taken into account when they are constructed as an artificial island made by reclamation sand.
Possible advantages of a floating terminal are a movable terminal when severe weather conditions take place, no foundation issues with a steep drop of the ocean floor just offshore and less dredging activities when the terminal is located just offshore. A transportable port, floating or fixed, is not planned for construction. However, researches are performed to look at the feasibility of a floating terminal for container transshipment or for the cruise industry. These terminals consist of large pontoons, nonetheless in the shipping industry these are only engineered and are not planned for construction or yet constructed [4] [79].

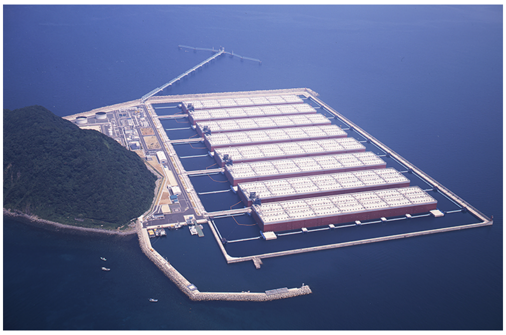
Considering other industries like the oil and gas, platforms are used which could act as a port. Fixed structures like jack ups, gravity based or guyed towers which act as a platform [32]. But there are also floating alternatives used in the oil and gas industry. Floating liquified natural gas and floating production storage and offloading are examples of floating vessels which are able to act as a transshipment, import or export terminal. In the oil and gas industry there are also very large floating structures used that are no vessels but can act as a terminal. Examples are: the spar, semi-submersible vessel or a tension-leg platform [32].
Considering markets with less relation to the shipping industry, there are very large floating structures

[13] An assistant Professor in engineering dynamics of offshore structures and a PhD candidate on offshore wind support structures

functioning for different purposes. These structures are for example used as an airport runway (figure 5.1a), floating oil storage bases (figure 5.1b) and there are floating performance stages [201].

Relevant current and future research on offshore ports are taken into account. There are currently two noticeable and closely related researches. In July 2017 MARIN tested a concept for a floating mega island as an alternative for ports and cities. The second noticeable research is the aimed development of a large European electricity system in the North Sea by TenneT. MARIN is visited for additional explanation and the idea of TenneT is discussed during the conducted interviews. This provided insights in the difficulties that come along, like: legislation, ownership, logistics and technical barriers.

(a) Airport runway, Tokyo [201]



(b) Oil storage base at Kamigoto Island [201]

Figure 5.1: Floating offshore constructions

5.2 Offshore port specification

The demands gathered in paragraph 4.1 are translated to activities that could be conducted at the offshore port. To carry out the activities, equipment, labour and other facilities are needed. The activities can only function when certain preconditions and requirements are fulfilled. When the design of the port concept is known, the amount or intensity of the activities could be increased or when needed decreased.

From figure 2.6 it can be concluded that a group is established at the right top, by Europe and the US Atlantic coast. This group is the potential market in the remaining of this research, for using an offshore port during the construction of an offshore wind farm. The related conditions to this group are more favorable for the offshore port concept, in comparison to the conditions corresponding to the other group at the left bottom of the figure. Since a large distance to shore seems advantageous for a new port concept, because of the high day rates of the jack ups.

Developments in the US offshore wind market should be followed closely in the next decade. Because of the Jones Act, the market could develop less than forecasted. The Jones Act could be troublesome to locate a temporary offshore port at the US Atlantic coast. The offshore wind market can have the same destination as the European dredging industry in the US. Which was unable to set foot on the ground in the US.

Due to the global growing importance of RES and no suitable RES alternative for the US Atlantic coast. The Jones Act might be bypassed on its application to offshore wind, this mainly depends on the government policy that is elected. Also it could be considered to design, build and own the offshore port by an US company. Another reason to prefer these markets over the Asian market is due to interview responses. It is hard to set a foot on the ground in Asia for the European offshore wind market.

5.2.1 Offshore port activities

Each demand could be fulfilled by activities conducted at the offshore port. These activities take only place offshore, when this is more favorable than conducting them onshore. The analyses on the added value of an offshore activity, in relation to the same activity conducted onshore, is provided in paragraph 7. The activities required to accomplish a single demand are listed below. The desires for each demand are listed as well, these could have an added value to the offshore port but are not required by the demand.

1. **Deep water port near the wind farm:** For this demand it is required to fully assemble the turbine at the offshore port and place it on top of the spar buoy foundation. Also vessels should be able to berth and be unloaded and loaded at the port.
   It is desired to assemble the spar buoy foundation at the offshore port so it does not have to be towed horizontally and flipped near the offshore port.

2. **Decrease rental costs of installation vessel:** The required activities are unloading the feeder vessel and the loading of the installation vessel. With an offshore port the sailing distance for the installation vessel can be reduced to a minimum, this decreases the rental period. The day rate of the jack up vessel can be dropped drastically with an offshore port. The carrying capacity of the installation vessel has to satisfy for one turbine instead of 4-8 as applied in the reference case. This is possible because the distance is shorter and the flexibility of the installation vessel increases, also the maximum sailing speed can be substantially reduced.
   The desired activity is the partly pre-assembling of the turbine components. A full assembly of the turbine is not desired since the installation of a full turbine is technically difficult. The degree of assembling will be discussed in chapter 7. When the pre-assembling can be carried out at the offshore port, the feeder vessels can transport separate components instead of a partly pre-assembled turbine. This leads to a lower day rate for the feeder vessel. The pre-assemble method at the offshore port could include more components than the pre-assemble method onshore. This influences the installation time, although a trade off has to be made between installation time and a higher day rate for the installation vessel due to a more assembled turbine.

3. **Usage of one installation vessel and a cheap feeder system:** Vessel costs are by far the largest contributors to the costs for installation and logistics. There is no required or desired activity that corresponds with this demand. No specifications stated on how a cheaper alternative to the current installation method in the US should be achieved, but it makes sense that the vessel costs have to be reduced. So the required and desired activities are similar to demand number two.

4. **A shelter with loading facilities:** All vessels used during construction should be able to load and unload at a shelter. It is required to have a storage area and that berthing takes place in a sheltered environment.
   A desire is that besides food and clean water, the crew transfer can take place at the offshore port. Another desire is that heavier equipment like: stones, cables and transition pieces can be

loaded and unloaded at the offshore port. Also maintenance on the vessel could be a conducted activity, this could be explored in a later stadium.

5. **A smaller installation support vessel:** Sleeping places are required at the offshore port, as is the possibility to berth. If the cable laying vessel increases its capabilities, the support vessel can be eliminated.
   A desire for the offshore port that comes along with this, is storage area and lifting possibilities for the equipment, used to install the inter array cable.

6. **Ease the transport of the tower:** It is required to assemble the tower at the offshore port. This reduces the sailing distance with a full assembled tower and less capacity is required.
   It is desired to sail directly from low-costs labour countries to the offshore port. No berthing and transfer at the onshore port desires more berthing space at the offshore port, although this eases the transport of the tower.

<table>
<tr><th></th><th colspan="4">Required activities</th><th colspan="6">Desired activitities</th></tr>
<tr><th>Demands</th><th>Assemble turbine</th><th>(un)loading</th><th>Storage use</th><th>Sleeping and crew transfer</th><th>Assemble foundation</th><th>Assemble turbine</th><th>Sleeping and crew transfer</th><th>(un)loading</th><th>Storage use</th><th>More berthing</th></tr>
<tr><td>Deep water port near wind farm</td><td>|X|</td><td>|X|</td><td>X</td><td>X</td><td>|X|</td><td></td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>Decrease costs installation vessel</td><td></td><td>|X|</td><td>X</td><td>X</td><td></td><td>|X|</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>Usage of one installation vessel</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>A shelter with loading facilities</td><td></td><td>|X|</td><td>|X|</td><td>X</td><td></td><td></td><td>|X|</td><td></td><td></td><td></td></tr>
<tr><td>A smaller installation support vessel</td><td></td><td></td><td></td><td>|X|</td><td></td><td></td><td>X</td><td>|X|</td><td>|X|</td><td></td></tr>
<tr><td>Ease the transport of the tower</td><td>|X|</td><td>X</td><td>X</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td>|X|</td></tr>
<tr><td>Total</td><td>2</td><td>4</td><td>4</td><td>5</td><td>1</td><td>1</td><td>4</td><td>3</td><td>3</td><td>1</td></tr>
</table>

Figure 5.2: Activities required and desired for each demand

There are activities that represent some secondary activities as well. When turbine assembling is a required activity, it directly includes the use of storage and sleeping facilities as well. Because the assembling process is not executable without a storage area and multiple working shifts. This holds for several activities listed above and therefore figure 5.2 does not coincide with the activities mentioned in the above. These main activities are expressed by the absolute sign in figure 5.2. The demand created for the US market is not specified into activities, as explained above. Though it can be assumed that the activities are similar to demand number two.

An important analysis is that four activities cover eight out of the ten, required and desired activities as can be seen in figure 5.2. These four activities are:

- Assembling the turbine
- (Un)loading the cargo
- Usage of storage area
- Sleep accomodation with crew transfer

Only the desired activities of assembling the foundation and more berth space, are not included within the four activities. The activity of assembling the foundation is related to a demand with a low priority, as can be seen in figure 4.2. So the desired activity of this demand is not of crucial importance to take into account. The demand of easing the transport of the tower scores just above average, regarding the priority of the demands. When the port concept with highest potential is determined, the requirements can be calibrated and the two desired activities could be integrated in the design. But the port concepts are not based on these two desired activities.

5.2.2 Offshore port preconditions

The required and desired activities have some necessities that are expressed in preconditions. The preconditions are the equipment, labour and facilities needed to carry out the activities. For all four activities an overview is created, an example of the activities turbine assembling and (un)loading is presented in table 5.1. The activities of more berth space and sleeping and crew transfer can be found in table 5.2.

Table 5.1: Preconditions for two activities with highest priority

	Activity: (Un)loading	**Activity: Turbine assembling**
Equipment	Quaywall for the feeder vessel Crane for unloading Trailers for transport of the components	Crane for assembling foundation Quaywall for the installation vessel Trailers for transport of the components
Labour	Medium intensity	High intensity
Facilities	Storage area turbine components Sleep facility and crew transfer	Storage area for partly assembled turbine Sleep facility and crew transfer

Table 5.2: Preconditions for a smaller installation support vessel

	Activity: Sleeping and crew transfer	**Activity: More berth space**
Equipment	Quaywall for the additional feeder vessel Crane for unloading	Quaywall for the feeder vessel A crane available for unloading
Labor	Low intensity	Low intensity
Facilities	Sleeping accommodation	Storage for tower components

5.2.3 Workability activities

The selection of the most appropriate port concept is partly based on the consequence of downtime. The downtime of the port is not required to be 0%, the workability of the port has to be approximately equal to the vessels that supply the port and the vessels that install the turbines. The workability criteria of the activities have to be determined, to compare it with the workability of the vessels. For the workability of the port it is assumed that the port does not fail. Motions by the port are an influential factor on the workability when the port is floating, the six type of modes are displayed in figure 5.3.

When the port is floating, the motions are a determinative aspect for the workability. Certain combinations of wave period and wave amplitude may result in unacceptable motions. Large wave heights, but also long waves at low wave heights can incite motion. When the frequency is close to the natural frequency of the port, large motions can occur. These are not determined in this section but are discussed in section 5.4.

- Surge (x): movement in the x-direction
- Sway (y): movement in the y-direction
- Heave (z): movement in the z-direction
- Roll (ϕ): rotation around x-axis
- Pitch (θ): rotation around y-axis
- Yaw (Ψ): rotation around z-axis

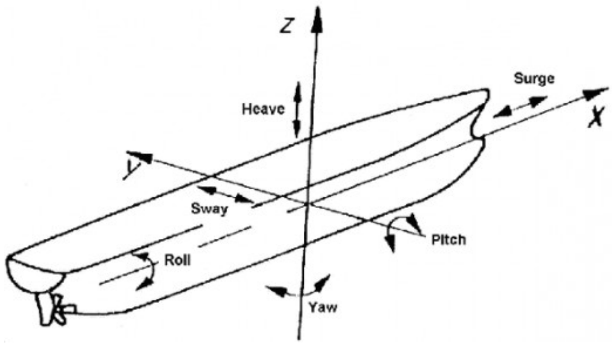


Figure 5.3: Six degrees of freedom of a vessel [124]

The workability of all four activities are elaborated in the following sections. All activities include a certain degree of manual labour, although this is only taken into account by the activity of storage use, since most labour is comprised to this activity. The workability of an activity is based on the serviceability limit state (SLS), which is directly related to the impact on the components transferred, equipment and crew.

The workability of the vessels that cooperate with the offshore port have to be determined. This determines the required workability of the offshore port. When a feeder vessel is used to supply the offshore port, the workability is not of interest. The day rates are lower than for installation vessels, when increasing the sailing speed of the feeder or when using two feeder vessels, the storage just has to be increased. So the workability of the jack-up is leading, this is elaborated in chapter 7. A workability wave spectrum for the installation jack-up is not taken into account yet. This depends on the design of the port and the corresponding activities. When the design of the port is known, the workability of the jack-up used for installation of the turbines is analysed.

(Un)loading of turbine components and lighter cargo

When the feeder vessel finishes berthing, the crane at the port unloads the cargo of the feeder vessel. Cargo can be turbine components, but also lighter cargo like drinking water, food and cable protection systems. The unloading of turbine components is more restricting in comparison to other unloading types of cargo. The loading of assembled turbine components is executed using the crane of the installation vessel. Due to the size of the turbine components, lifting this type of cargo is assumed to have the lowest workability of all (un)loading operations.

The installation vessels can be closely classified to multi purpose vessels[14]. The berthing criteria depend on the type of feeder vessels used for supply of the components and installation. This is discussed at the end of this paragraph. Motion criteria are available for (un)loading general cargo onshore. The safe (un)loading criteria are as shown in table 5.3. When one criteria is exceeded, the (un)loading is discontinued.

[14] Motion criteria for safe loading operations are published for multiple vessel types. However, not for installation vessels. Therefor the criteria of multi purpose vessels are applied. Large multi purpose vessels have a length of 175 meter and a width of 30 meter [124].

Table 5.3: Motion criteria for safe loading operations [189]

Surge (m)	Sway (m)	Heave (m)	Roll(°)	Pitch (°)	Yaw (°)
2.0	1.5	1.0	5	2	3

When the port is floating, the installation vessel and the port have influence on this workability, since both are susceptible to motion. The port concept and its interaction with the installation vessel is unknown and depends on properties of the wave, vessel and port. For large wave periods, the reaction of a vessel and a floating port is simultaneous [66]. A visualisation is provided by the right picture in figure 5.4. A smaller wave period causes a motion on the vessel, but not on the floating port. An example is shown in the left picture of figure 5.4.
The motion criteria as shown in table 5.3 holds for relative motion between the vessel and the port. The most unfavorable situation is when the port and the vessel are 180°out of phase. When modelling the floating port and vessel separately, their phase lag is unknown. Modelling a coupled motion of two floating bodies is a complex derivation and not within the scope of this research. Therefore, an assumption is made to compensate for this uncertainty. The motion criteria as shown in table 5.4 are multiplied by 0.75.

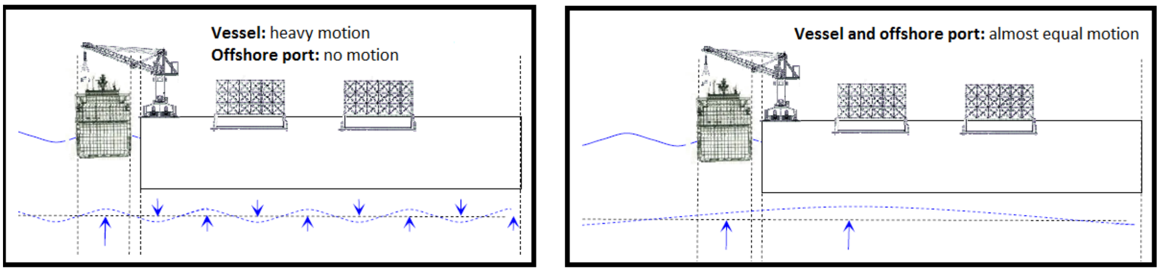


Figure 5.4: Mutual motion of vessel and offshore port [66]

When none of the criteria in table 5.3 are exceeded the cargo handling efficiency is 100%. In figure 5.5 this is indicated between level A and B. Between level B and C cargo handling rates are reduced due to increased ship motions, though non of the criteria in table 5.3 is achieved. When at least one of the motions exceeds the criteria in table 5.3, level C in figure 5.5 is reached and the operations are stopped. The unsafe berthing limit is reached at stage D, safe mooring limits are exceeded. The vessel has to leave the berth in order to prevent damage to the ship and to the quay:

Partly pre-assembling of the turbine

A required activity as explained in paragraph 5.2.1 is: the tower components are assembled and the nacelle with hub is assembled to two blades. The degree of assembling is determined in chapter 7. Wave height and wind velocity are correlated, since wind most commonly generates waves. For installation of the turbines it is shown in practice and in literature, that the wind velocity limit is reached earlier than that of wave height[15] [199]. Installation of the turbine takes place at the hub height, which is shown in figure B.3. For a 12 MW this is about 120 meter above sea level and the limiting wind speed for installation is currently 19 m/s or higher[15]. A hub height of 120 meter is

[15]Confirmed by the interviewed parties that install the turbine, it is in the nearby future still executed with a jack-up.

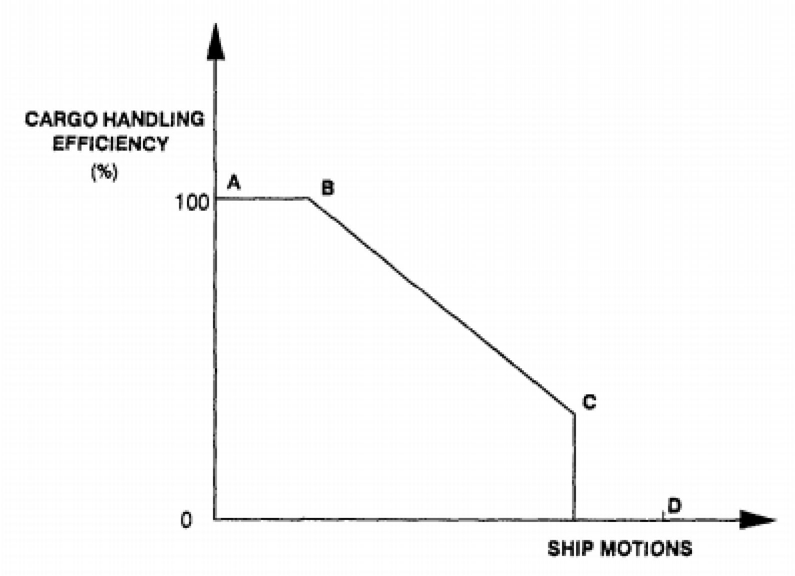


Figure 5.5: Relation cargo handling efficiency and ship motions [58]

related to a 12 MW wind turbine, as derived in chapter 2 this is the expected turbine capacity by the year 2030 in the European and US Atlantic market. 19 m/s is the wind velocity measured at the hub height, for which the tools are currently certified. Looking at the improvements made on the installation tools the last years, it is a conservative assumption that this maximum wind velocity is 10% higher in 2030. This equals a maximum wind velocity of 20,9 m/s at a height of approximately 120 meter above sea level. With the following equation the wind velocity at 10 meters above sea level is determined [137]:

$$V_{w10} = U_w * \left(\frac{10}{h}\right)^{(1/7)} \tag{2}$$

In which:
U_w (m/s) = wind velocity at elevation h above water surface

With a wind velocity at 120 meter above the water surface of 20,9 m/s, the wind velocity at 10 meters above the water surface is calculated to be 14,7 m/s. Since the components catch a lot of wind during installation, generally the installation is constrained by wind speed limits. Because this holds for jack up vessels and heavy lift vessels, it is assumed that the assembling of turbines is also limited by wind and not by waves. The assembling takes place a few meters above the deck surface of the offshore port and the deck surface is a few meters above the water surface of the sea. It can be concluded that the workability limit for assembling is a wind velocity of 14,7 m/s.

Usage of storage area

This activity comprises the internal transport of all cargo and the usage of storage. There are three types of cargo that use the storage area of the offshore port. Turbine components are stored before they are assembled. The partly assembled turbines are stored before they are loaded on the installation vessel. The third type of cargo is general cargo like food, drink water, stones and cable protection systems. Besides trailers for transporting these products, manual labour is required for monitoring and executing these processes. The cranes on the port are only used for unloading the vessels and to assemble the turbine, they are not involved in the storage of components. When the port is a floating concept, motions of the port should remain limited to guarantee safe operation. Nordforsk and PIANC both determined motion criteria for manual work on a floating structure. Since the criteria of Nordforsk are more strict, these will be leading for this study [112] [213]. Light manual work carried out by people adapted to ship motions has the criteria as shown in table 5.4.

Table 5.4: Light manual work criteria for safe working conditions

Vertical acceleration	Lateral acceleration	Roll (°)
0.2 g	0.1 g	6.0

Where g is equal to 9.81 m/s^2. Motions of the structure is not the only criterion for safe conditions for the employees who work in the storage area. When the wind velocity is too high or the deck is to slippery due to a spray or splash of seawater on the deck, the working conditions can become unsafe. For a floating structure the amplitude of vertical relative motion should not exceed the freeboard. The deck wetness is expressed into the following probability [102]:

$$P_{deckwetness} = e^{\frac{-f_x^2}{2m_{0s}}} \tag{3}$$

In which:
m_{0s} (m^2) = zero spectral moment of relative motion, including the dynamic swell-up
f_x (m) = freeboard on section x of the floating structure

The commonly applied limiting value for deck wetness, is a probability of 0.05 [112] [139]. The formulae on deck wetness do not distinguish different degrees, it is from spray to green water. Green water occurs when the waves and ship motions can become so large that water flows onto the deck of a ship. However, ship motions as displayed in table 5.4 are exceeded before the probability of 0.05 on deck wetness is achieved [139]. An elaboration on the overtopping criteria for a fixed structure is provided in appendix G.2.

The third and last aspect to guarantee a safe working environment for the employees in the storage area, is the wind criterion. However, the cranes used for (un)loading and assembling of the turbine are more susceptible to wind than the crew. When these two activities are not in operation, the storage area is not required to be operational either.

Next to a safe operation, there are two more SLS defined for the usage of storage. There should be sufficient surface area available and the components have to stay chained. A 12 MW turbine requires the following surface area[145] [159]:

- Blade[16]: length * width = 105 * 7 = 735 m^2
- Nacelle with hub: length * width = 15 * 10 = 150 m^2
- Tower[16]: length * width = 150 * 9 = 1.350 m^2

[16] Widest part of the component is used and dimensions are a compromise of extrapolation of constructed wind turbines and the announced 12 MW turbine by General Electric

The blades can be stacked into a bladerack, a conservative and reasonable approach is a stacking height of four blades. Therefore the required available surface area after unloading three blades, one tower and one nacelle with hub is 2.235 m^2. The determined dimensions of the three bullet points, are a conservative extrapolation of manufactured dimensions. Though this is balanced, by not including an additional area for the multiple components of the tower. Since before the assembly of the tower, it requires more surface area than after the assembly.

Figure 5.6: Blade rack on the Aeolus jack up vessel [W32]

Blade racks similar to figure 5.6, are placed on the port. They are located near the assembling crane, so this crane can lift the blades in and out of the rack. The assembled tower and the nacelle with hub are also raised off the ground during storage, although they are not stacked. This enables the self-propelled modular transport trailers to manoeuvre underneath. They can jack up to take the mass of the component and transit it. A typical method to achieve this, is to use baulk timbers to distribute the load to the ground [72]. This method is elaborated in appendix G.3.

The required storage area for four turbines is 8.205 m^2, This area consists of: three blade racks, four towers and four nacelles with hub. After pre-assembling, the required surface area is a little less. So no additional surface area is required for the assembled turbines. To keep the costs low, the surface area should be as small as possible. Therefore it is important to assemble the components as soon as possible after arrival at the port. Also a parallel execution of the processes can contribute to a smaller required surface area. It is assumed that as a maximum five turbines are stored at the port. This requires an area of nearly 10.000 m^2.
Based on the dimension of two cranes with a lifting capacity of 1.300 ton[17] ton and an accommodation with a surface area of 1.000 m^2. A total surface area of 12.500 m^2 is required, when stored tight. An area of 5.000 m^2 is added for pathways and comfortable spacing and another 2.500 m^2 is added for assembling the turbine. So the minimum surface area for the port is 20.000 m^2. However, the blades and the towers can be placed partly outside the area of the port. An example of overhanging blades is shown in figure 5.6. It is assumed that this reduces the required surface area by 2.500 m^2. Therefore, the minimum surface areas taken into account for the port is 17.500 m^2.

Onshore the blades are secured with heavy concrete blocks, during sailing they are placed in a blader-

[17] Elaborated in paragraph 6.2.1

ack. The latter is preferred at the offshore port due to weight and surface limitations. The standard trailers have to be adjusted, or the bladerack could be modified by a belt system. This detailed analysis is not carried out in this research. A bladerack provides sufficient stability and protection for the blades during storage.

Sleep accommodation and crew transfer

There are no motion criteria for sleeping conditions for a fixed port. When the port is floating, there are motion criteria required. Research shows that motion sickness and sopite syndrome contribute to sleep disruption [135] [54]. Motion sickness at sea occurs when a vessel is rotating on its width and length axes and therefore they are in most cases the cause of seasickness [181] [22]. Table 5.5 shows the motion sickness criteria, when one or multiple criteria is exceeded for a period longer than 4 hours, 20% of the crew experiences a motion sickness. Sopite syndrom[18] could be experienced by the crew when prolonged exposed to periods of motion, these criteria are also displayed in table 5.5.

Table 5.5: Motion criteria for the crew [181] [112]

	Vertical acceleration	Lateral acceleration	Pitch (°)	Roll (°)
Motion sickness	0.2 g	0.1 g	1.5	4.0
Long term tolerable for the crew	0.1 g	0.05 g		3.0

For a sleeping accommodation on the port, multiple requirements have to be fulfilled according the maritime labour convention drafted in 2006. The most relevant requirements for the design of the port are listed below:

- The dimensions of a berth shall be at least 198 centimetres by 80 centimetres
- Separate sleeping rooms shall be provided for men and for women

The third important aspect for the required surface area of the sleeping accommodation, is the duration of working shifts. A 12 hour shift is commonly applied[19] and the processes continue 24 hours a day. This leads to twice the amount of crew per activity and more berths in the sleeping accommodation.

The crew transfers take place when the feeder vessel is unloading and when the installation vessel is loading. The offshore crew that is accommodated at the offshore port works at the port or at the installation vessels. So no crew boat is used for offshore transfer but the crew transfer takes place from larger vessels. Larger vessels require long bridges for the transfer of personnel. These equipment can be hydraulically controlled [99] and therefor the workability will not be a limitation.

5.3 Environmental conditions

The offshore port has to be suitable to the environmental conditions of its location. For the European market the destination of the offshore port is the North Sea. As explained in section 2.3, this upholds

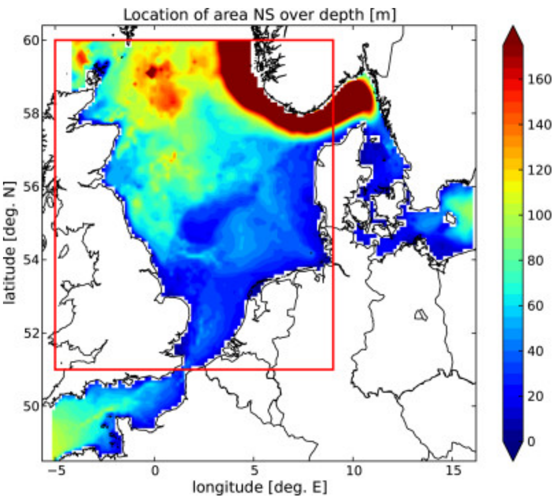
[18] Relates to symptoms of fatigue, a strong desire for sleep and mood changes.

[19] Confirmed by multiple companies active in the offshore wind industry and also healthier than a 6 or 8 hour sleeping shift due to less sleep disturbance [81]

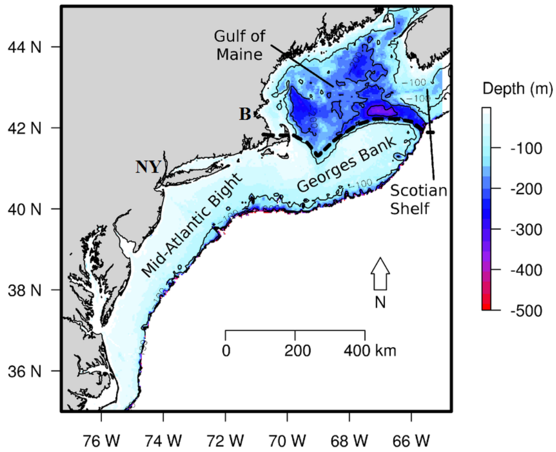
for 67% of the offshore wind farm projects. For the US Atlantic coast the focus is at the latitude of New York and Boston, because in this area the majority of offshore wind farms are planned. The environmental conditions of these two areas, influence the potential of the port components in section 6.2.

Bathymetry

The continental shelf of the US Atlantic coast has a length of 100 to 200 kilometers. This area is appropiate for fixed offshore wind foundations. The continental slope is steep and the water depth increases fast. A large area in the North sea is also suitable for fixed foundations, this area is indicated by blue in figure 5.7a. As can be seen in figure 5.7, the continental shelf of the US has on average a larger water depth than the North Sea.



(a) North Sea indicated by red rectangle [194]



(b) US Atlantic coast, NY represents the city of New York and B represents Boston [W23]

Figure 5.7: Bathymetry of areas of interest, colors indicating the depth in meters

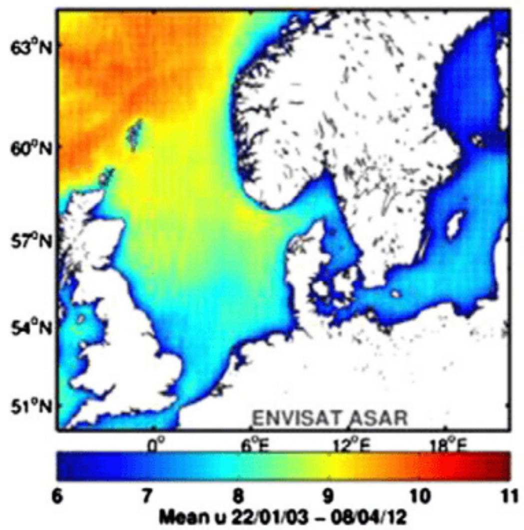
Soil conditions

This variable influences the possibility of a fixed foundation. A soil consisting of a large clay layer does not provide sufficient bearing capacity, on the other hand a soil consisting of rock is susceptible to cracking. Most of the soil conditions in the North Sea can be represented by a stratum of dense sand at the seafloor, underlaid by strong clay [186]. In the northern North Sea it is more common that a rocky sea floor is present. Although this area has the least potential as a location for the offshore port due to the high water depths [154].
Most of the continental shelf at the US Atlantic coast is mantled with sand, only the Gulf of Maine is not. In the central area of the gulf, the sand is mixed with silt, clay and gravel [170] [180]. In the considered two areas there are two locations not suitable for a fixed foundation. This is the Gulf of Maine and the northern part of the North Sea. Since this is only a small percentage of the potential area, a fixed foundation can be considered as a port component in section 6.2.

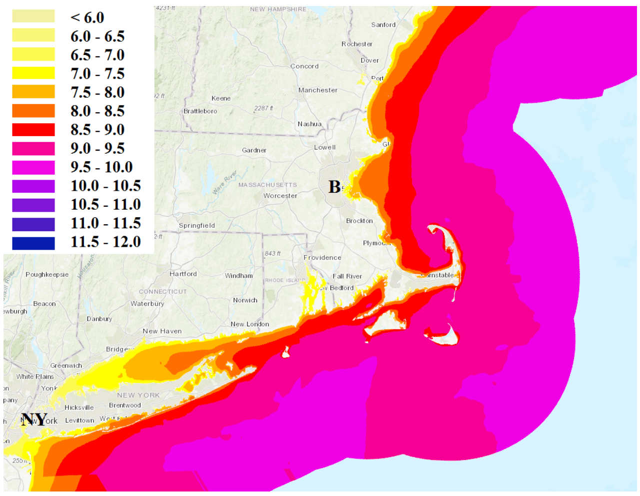
Wind velocity

There are two reasons for analysing the wind velocity. The assembling process is limited by the wind velocity and wind increases the motion of the port that is additional to the motion induced by the waves. The dominant wind direction for the major area of the North Sea is South to North West [162] [74], the corresponding mean wind velocity is displayed in figure 5.8a.

The mean wind velocity at the US Atlantic coast is a little lower than in the North Sea. Figure 5.8b represents the wind speed in the area of interest at an altitude of 90 meter. No clear wind map of the commonly applied 10 meter altitude is available. With equation 2 it is calculated that 9 m/s at this altitude corresponds to a mean wind speed of 6.6 m/s at a height of 10 meter. The offshore winds are, for the most part, higher than from onshore direction. However, the dominant direction is from onshore [150] [173].



(a) North Sea wind map [82]



(b) US Atlantic coast, NY represents the city of New York and B represents Boston [W7]

Figure 5.8: Wind velocity at 10 meter above mean sea level, colors indicate the wind velocity in m/s

Surface current

Whether the considered port concept is floating or fixed, in both cases the tide does not have a direct influence on the structure. When it is floating, it will move along with the tide and when it is fixed there is no displacement due to the tide, though the loads on the port change. Currents can affect the orientation of the offshore port and directly affect the loads imposed. There are multiple currents, but the surface current affects the port the most. For the North Sea the 1 year return period of the surface current is 0,9 m/s [153] [59]. The mean annual current in the North Sea deviates between specific locations, though it is in the range of 2 to 8 cm/s [162].
The Gulf stream system is a thermal ocean current and stretches from the Florida Straits up to halfway the Mid-Atlantic Bright (see figure 5.7b). The width of this system is approximately 80 km near Florida and it slowly increases to a width of 145 km. The current velocity is fastest near the surface, with a mean speed of 1.5 m/s. [34]. However, a few hundred kilometers south of New York the stream system flows away from the coast. Therefor it does not influence the surface current in the considered area. The mean surface current in the area of Boston and New York is in a range between 2.5 - 5 cm/s. Though during a hurricane this can increase to 0.8 m/s [132]. So for the design of the port, the North Sea surface currents are leading.

Wave spectrum

The wave energy causes fatigue on the offshore port and when the port is floating the wave energy also causes a motion response. A wave spectrum consists of the joint distribution of the wave amplitude and the wave period. The wave spectrum contains two types of energy, wind waves and swell. Wind waves are locally generated and have a lower wave period, but a higher wave amplitude than swell waves. It should be noted that there is a range where wind waves and swell waves overlap. Swell waves are long, small-amplitude waves with longer periods. They have a higher potential of leading to dynamic responses. The wave period is expressed as the peak period (Tp), this corresponds with the period oat which the most energy is found. The significant wave height (Hs) is commonly applied, to express the wave height of a wave. This is the average of the largest third of the recorded wave heights.

Frequency and directional dispersion of waves implies that each location in the North Sea, has an unique wave spectrum. The wave spectrum variety within the North Sea is large. Small amplitude and periods are dominant near the coast of Belgium, while in the northern area of the North Sea these values are doubled [13] [83]. There is no source that supplies a wave spectrum that covers the entire North Sea, this is only available for the Northern area [84]. Fortunately, there are sufficient buoys in the North Sea that provide this information and the amount of buoys in the US area is even higher.

One buoy is selected with similar conditions as for the average construction of a wind farm by 2030. In an area nearby, a wind farm is planned for construction. Therefore this buoy is stated as the area with the highest potential for an offshore port. Eight years of data are analysed from this buoy at the location 53.480°N 2.405°E [74]. This location is on a straight line between Newcastle and Den Helder, it is 180 km from Den Helder. The measurements of this buoy are translated to relative occurrence. The wave spectrum of this buoy can be seen in figure 5.9.

Significant wave height (m)	Peak period (s)																Cumulative
7.5																	100
7									0.02								100
6.5									0.04	0.01							100
6									0.04	0.03	0.02						100
5.5								0.01	0.07	0.10	0.02						100
5								0.01	0.13	0.13	0.04						99
4.5								0.03	0.27	0.15	0.08	0.01					99
4							0.02	0.57	0.73	0.10	0.00	0.01					99
3.5							0.04	2.02	0.55	0.04	0.02						97
3						0.01	1.60	2.84	0.22	0.01	0.01						94
2.5					0.01	0.23	6.48	1.81	0.15	0.02	0.01						90
2					0.08	6.22	7.05	1.43	0.10	0.01	0.01	0.01					81
1.5				0.07	5.13	14.16	5.65	1.72	0.13	0.03	0.01	0.01	0.01		0.01		66
1				4.37	13.08	9.76	4.13	0.61	0.04	0.03	0.02	0.02		0.01	0.00	0.01	39
0.5			0.17	3.77	1.96	0.94	0.13	0.06	0.05	0.02	0.01	0.00	0.02				7
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Cumulative	0	0	0	8	29	60	85	96	99	99	100	100	100	100	100	100	

Figure 5.9: Wave spectrum of buoy number 15512 in the North Sea

Nine other buoys in several North Sea areas are analysed as well. An overview of these locations can be found in appendix G.4. All spectra are taken into account when determining the workability of the port. When analysing buoys at the US Atlantic coast, it can be concluded that the wave spectrum of the North Sea is leading for the design [184] [146]. Since the US Atlantic coast wave spectrum is not leading, the buoys are not integrated in the workability analysis.

5.4 Boundary conditions

The average construction conditions of the offshore wind market by 2030 are determined in chapter 2. One of the market conditions is an average water depth of 40 meter, this leads to a boundary condition for the offshore port. Besides the water depth condition, there are four boundary conditions that have to be fulfilled by the offshore port at all times.

The minimum surface area is determined in paragraph 5.2.3. The minimum buoyancy that the port should withstand is equal to 12.600 ton, equal to 123.606 kN. An elaboration on this buoyancy can be found in appendix G.5. The fourth boundary condition is a minimum feeboard. To prevent overtopping by a significant wave height of 5 meter, the freeboard should be at least 10 meter[20]. The offshore port is not bounded to consist of one structure, a combination of several structures is a variant as well. However, the maximum number of port components that create a port concept is two. This is assumed because of technical challenges and to improve the financial feasibility. The five boundary conditions for the design of an offshore port are:

1. The offshore structure has to be at least suitable for a water depth range of 30 to 50 meter
2. A minimum surface area of 17.500 m^2, equivalent to 175 x 100 meter.
3. A minimum buoyancy of 12.600 ton, to sustain an uniformly distributed load.
4. A freeboard between five and ten meter[21].
5. A port concept can consist of a maximum of two port components.

5.5 Workability offshore port

The five boundary conditions listed above have to be satisfied at all times. This is different for the workability conditions of the four main activities on the offshore port. These activities can only be performed on the offshore port when there are workable conditions. So the maximum allowed conditions have to be met with the lowest possible frequency. The motion criteria for safe loading operations are most limiting for a floating port foundation. In comparison to the motion criteria of light manual work and the motion criteria for the crew, the minimum duration of an exceedance of the motion is short for a loading operation. These are as follows:

Surge (m)	Sway (m)	Heave (m)	Roll(°)	Pitch (°)	Yaw (°)
2.0	1.5	1.0	5	2	3

The maximum allowed wind velocity of 14,7 m/s determines the workability for assembling and (un)loading of turbine components. The offshore port limiting value for deck wetness is a probability of 0.05, if this value is higher there is on average to much seawater on the deck.

When the motion response of the offshore port is determined. The wind velocity, surface current and wave spectrum of the offshore locations determine the workability of the offshore port. For fixed foundations also the soil conditions are important to determine the workability.

[20] Maximum wave height is approximately equal to two times the significant wave height [92]. A significant wave height of 5 meter has a probability of 0.005% to be exceeded, see figure 5.9.

[21] The freeboard should be at least five meter to prevent overtopping. The freeboard of a potential installation jack-up also has a freeboard of approximately five meter. Cargo is lifted to and from the port, to ease the crew transfer, lifting and perhaps the sliding of cargo, the maximum freeboard is set to ten meter.

6. Port concepts

There are no offshore ports at a large distance to shore, therefore the type of support structure has to be determined in this research. The characteristics, applications and technical behaviour of potential port components that function as the support structure are described in this chapter. The technical behaviour of floating port components is described by a static stability and a wave susceptibility analysis. To determine the wave susceptibility, the natural oscillation period is calculated. Dimensions of the floating structures are varied to derive the influence of the dimension on the oscillation period. Also fixed port components are analysed concerning their technical behaviour. All potential port components are compared in paragraph 6.2.8. How the static stability and wave susceptibility for floating port components are derived is explained in the first section.

6.1 Governing theory

The workability of a floating port depends highly on the motion response of the port, as is shown in paragraph 5.2.3. The motion response depends on the wave susceptibility of a floating port component. Also the static stability for each port component is calculated and the governing formula's are explained in this section. The static stability is the capability of a structure to return to its equilibrium situation. If the static stability of a port component is low, the motion response of a port is strengthened because the port only returns slowly to its equilibrium. To make sure the terminology used in this research is clear for multiple fields of work, a visualisation is provided in figure 6.1.

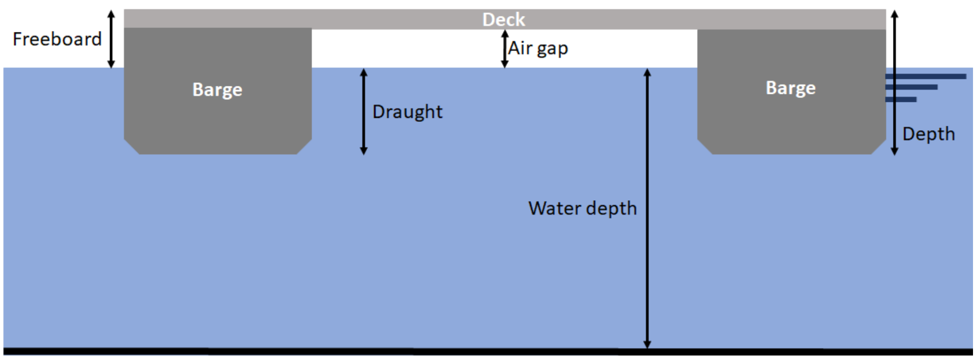


Figure 6.1: Overview of terminology

6.1.1 Static stability

A floating body is statically stable when a floating body experiences a roll, pitch or yaw motion and it will get back to its initial position. For static stability the tilting should be compensated by a couple of the buoyant force and the weight of the structure. When the length of G to M is larger than 0,5 meter it is considered stable [137].

A measure for the resistance to tilting is given by the 'metacentric height'. M is the metacentre, this is the point of intersection between the z-axis and the action line of the buoyant force in tilted position. G is the centre of gravity and B is the centre of buoyancy. The fourth relevant parameter in figure 6.2 is K, this is the bottom of the port component.

There are three lengths that determine the static stability, since GM = KB+BM-KG. The parameter T is the draught, I_{xx} is the transverse moment of inertia and $\bigtriangledown$ is the submerged volume. The moment of inertia presented below is for a transverse symmetrically shaped port component. A coefficient for the shape of the hull is presented by cb. Most port components have a vertical asymmetric shape, since the lightweight of the port is not distributed uniformly over the depth. So to determine KG, the structure is split into elements as is shown by the third bullet point below. When the port component has no keel and no flat shaped bottom, a similar approach as for KG is used to determine KB. At the bullet point below, KB is determined for a barge type of structure which has a flat bottom.

- **KB:** Distance between the bottom (K) of structure and centre of buoyance (B).

$$KB = 0.5 * T$$

- **BM:** Distance between centre of buoyance (G) and the metacentre (M).

$$BM(t) = \frac{I_{xx}}{\bigtriangledown} = \frac{\frac{1}{12} * l * b^3}{l * b * T * cb}$$

- **KG:** Distance between the bottom (K) of the structure and the centre of gravity of the structure (G).

$$KG = \frac{\Sigma V_i * Y_i * e_i}{\Sigma V_i * Y_i}$$

  In which:
  V_i (m^3) = Volume of element i
  Y_i (ton/m^3) = specific weight of element i
  e_i (m) = distance between reference level and gravity center of element i

- **GM:** Distance between centre of gravity (G) and the metacentre (M). The transverse GM is used for the roll motion and the longitudinal GM is used for the pitch motion in the next paragraph.

- **CG:** Calculated similarly to KG, but the load and its distance to the reference level is added. So the distance between the bottom (K) of the structure and the centre of gravity of the total weight. This is used as input for the motion response simulation in AQWA, explained in paragraph 6.1.2.

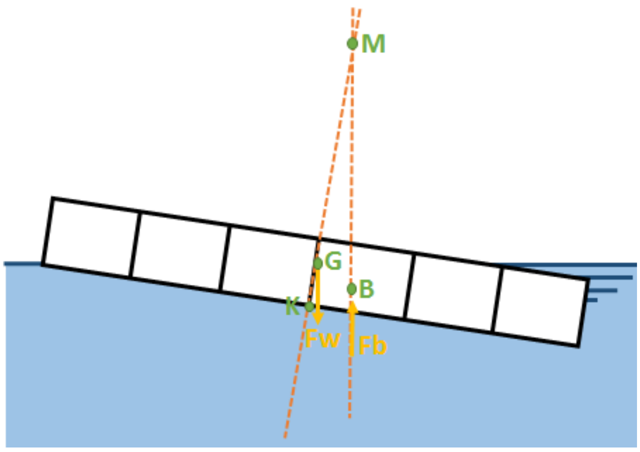


Figure 6.2: Principle of static stability (angle exaggerated)

6.1.2 Motion analysis port components

Besides static stability, also the motion response should be verified. Motion response is the movement or tilting of a floating body caused by environmental conditions. The affect of waves on a structure are the major contribution to a motion response. When the wave climate moves to the natural oscillation period (eigenperiod) of the structure, a higher motion response is created [137] [79]. So a sea state in the right top of figure 5.9, is not directly a cause of a high motion response.
An explanation on the derivation of the eigenperiod is provided in this section. The eigenperiod for the structure is used to indicate the motion response for deviating dimensions of the port components. This derivation also contains several aspects that are required as input for the motion analysis in AQWA. Dynamic motions of a vessel are governed by Newton's second law, which states: Force = mass x acceleration [73]. When applied to a vessel, the following uncoupled equation can be used:

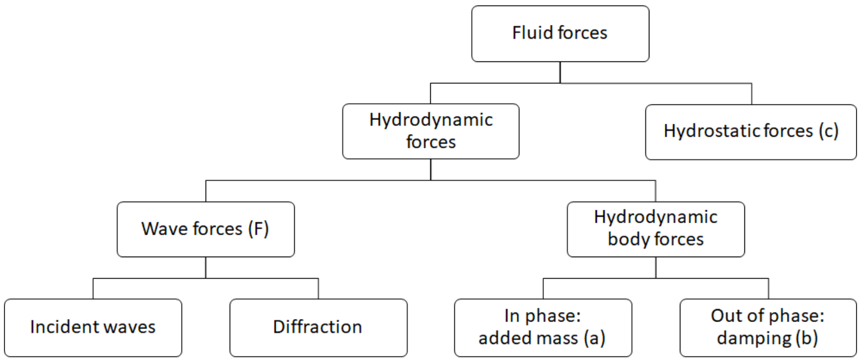


Figure 6.3: Overview of the several types of fluid forces [79]

$$F(t) = (m + a)\ddot{x} + b\dot{x} + cx \quad (4)$$

In which:
m = mass of the ship
a,b,c = coefficients representing the added mass, damping coefficient and stiffness.
x = displacement
F(t) = time varying applied force, e.g. wave forces

The first order wave forces that cause the vessel to keep moving or rotating in the surge, sway and yaw direction are large forces because there are no restoring 'spring' terms present in these directions. The second order wave forces in these directions are prevented by the moorings [103]. As a consequence to the absence of restoring force for stiffness in the surge, sway and yaw direction, these eigenperiods can not be determined.
Damping does not affect the eigenperiod of a floating structure. It does influence the motion response, because it damps the response. The hydrodynamic properties of the floating port components in the heave, roll and pitch direction are derived from a single linear mass spring damper system, as can be seen in figure 6.4.

The motions are assumed to occur only in the considered degree of freedom, so the motions of the structure are uncoupled. For a manual calculation this is justified, because the amplitude and displacement during workable conditions of the port are small [183] [115]. A higher wave frequency leads

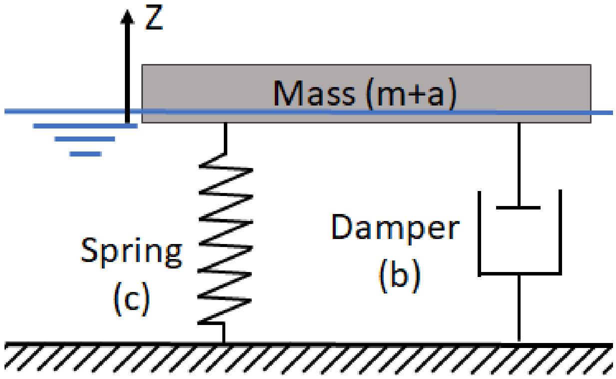


Figure 6.4: Schematic representation of the spring mass system

to a higher error for this assumption [103]. For the three degrees of interest, only pitch and heave are coupled. This is a non-linear coupled vibration that only start to play a role for large amplitudes [103]. The individual directional movements for a floating structure are presented in the following paragraph. The natural oscillation period is derived from equation 4. This equation represents a horizontal displacement in the x direction. However surge is not of interest, while heave, roll and pitch are. These equations of motion are presented in equation 5, in comparison with equation 4 the damping coefficient b_{ij} is not included.

$$\begin{bmatrix} F_{33}(t) \\ M_{44}(t) \\ M_{55}(t) \end{bmatrix} = \begin{bmatrix} m+a_{33} & & \\ & I_{44}+a_{44} & \\ & & I_{55}+a_{55} \end{bmatrix} * \begin{bmatrix} \ddot{z(t)} \\ \ddot{\phi(t)} \\ \ddot{\theta(t)} \end{bmatrix} + \begin{bmatrix} c_{33} & & \\ & c_{44} & \\ & & c_{55} \end{bmatrix} * \begin{bmatrix} z(t) \\ \phi(t) \\ \theta(t) \end{bmatrix} \tag{5}$$

In which:
z = heave direction (m)
ϕ = roll direction (rad)
θ = pitch direction (rad)
I_{ij} = mass moment of inertia in direction i due to a motion in direction j (t m^2)
F_{ij} = excitation force in direction i due to a motion in direction j (kN)
M_{ij} = excitation moment in direction i due to a motion in direction j (kN m)

The natural oscillation frequency can be determined by looking at the movement and motions of the floating structure in still water. Therefore, the natural frequency can be derived by solving the equation of motion without excitation force, meaning equating the right hand side to zero [103]. This is shown in equation 6. The natural frequency of heave is derived by considering the wave motions as is shown in equation 7 [11] [103]. The natural frequency of roll and pitch is determined by a similar approach.

$$(m+a)\ddot{z} + cz = 0 \tag{6}$$

$$\begin{aligned} z(t) &= z_a sin(\omega t) \\ \ddot{z}(t) &= -z_a \omega^2 sin(\omega t) \end{aligned} \tag{7}$$

In the above equation, z_a is equal to the (maximum) amplitude displacement. By substituting equation 7 into equation 6, the undamped natural frequency can be determined. For heave this is displayed by equation 8, for pitch and roll this is presented by equation 9. From these equations it can be seen that the natural frequency depends on the mass *m*, mass moment of inertia *I*, added mass *a* and the hydrostatic stiffness *c*. The derivation of these parameters is explained in the next paragraphs. The natural oscillation period is determined by dividing 2π by the natural frequency.

$$\omega_0 = \sqrt{\frac{c}{m+a}} \tag{8}$$

$$\omega_0 = \sqrt{\frac{c}{I+a}} \tag{9}$$

Hydrostatic stiffness

This parameter is also called, the restoring spring term. When the structure is freely floating, a stiffness exists in the heave, roll and pitch direction. This is due to the buoyancy, which prevents submergence of the structure. The three spring terms can be calculated by the following three equations below [103]. in which $\bigtriangledown$ represents the water displacement in cubic meter.

$$Heave, c_{33} = \rho g * A_{wl} \tag{10}$$

$$Roll, c_{44} = \rho g * \bigtriangledown GM_t \tag{11}$$

$$Pitch, c_{55} = \rho g * \bigtriangledown GM_l \tag{12}$$

Mass and Inertia

For the heave motion, the mass is required to determine the natural frequency. The mass is equal to weight of the structure including the added water and its additional loads. The total volume of concrete is calculated after the wall thickness iteration, this is multiplied by a density of 2,4 t/m^3 and by the gravitational constant. For the roll and pitch motion, the mass moment of inertia is required to determine the natural frequency. These two motions can also be schematised by a spring mass (damper) system, as shown in figure 6.4. But for roll and pitch the amount of displacement z, is the amount of rotation.

The shape of the structure influences the inertia and together with the mass it determines how easily the structure is rotated. For a structure that can be schematised as a squared or rectangular box, the mass moment of inertia is calculated as follows [172]:

$$Roll, I_{44} = \frac{m*(b^2+h^2)}{12} \tag{13}$$

$$Pitch, I_{55} = \frac{m*(l^2+h^2)}{12} \tag{14}$$

In which *b* is the width, *l* is the length and *h* is the depth of the structure.

Added mass

The hydrodynamic mass is generally known is the added mass term. The mass in the spring (damper) system is the mass of the floating structure, plus the mass of the along moving water. The determination of the added mass for heave and roll is shown in figure 6.5. The equation on the bottom of this figure hold for a semi-submerged situation. The added mass as shown in figure 6.5 has to be multiplied by the length of the structure when calculating the roll added mass. The added mass of pitch, can be represented in the same way as for roll. However, the length and width are switched in the equations. The derived added mass formula for catamaran type of structures can be found in

appendix H.6.
A validation of this approach is conducted by another estimation method for the added mass, provided by Journée (2001) [103]. The result for the added mass for pitch is similar and for roll the deviation is smaller than 10%. Since the derivation of the formulas in figure 6.5 is more clearly elaborated in the corresponding book, this approach is applied.

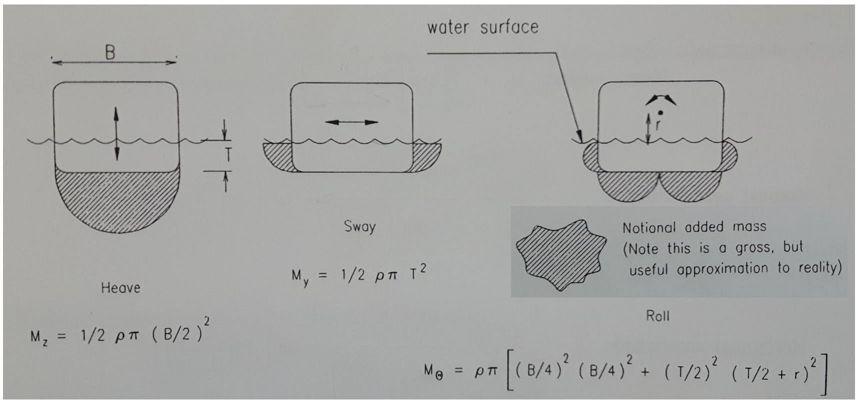


Figure 6.5: Estimate of the added mass per unit length [11]

Damping coefficient
Motion damping is caused by the generated wave, which dissipate energy from the moving structure. The major part of the damping is caused by the viscous damping of the waves [103]. Viscous effects are neglected in the heave and pitch direction. Viscous damping can be significant for rolling ships. This is because the wave potential damping for roll is generally relatively small itself. The "Ikeda method" is an empirical method that estimates the viscous roll damping contributions.
The damping coefficient has to be determined by a computational model. The results of AQWA as shown in this report take this viscous damping into account and this is elaborated in appendix H.1. The motion damping depends on the total moving mass and on the shape of the structure. When the roll motion is critical, a passive free-surface tank can be a good tool to reduce this motion [103]. The tanks are designed such, that sloshing of water can not occur.

AQWA
A hydrodynamic simulation is carried out with the software product AQWA. There are two main reasons why this simulation is conducted:

- Determining the motions response for the selected dimension of a floating port component. The eigenperiods are calculated as explained before, however the workability of a floating structure can only be derived by the heave movement and a motion response for the roll and pitch direction. Also the horizontal and vertical accelerations are of importance because they could be a limiting aspect.
- AQWA also provides output concerning the eigenperiod and the GM value of the structure. When using the same dimensions, the applied methodology in this research to determine the preferred dimension of the structure can be validated.

It should be noted that the results of the simulation depend on the dimensions of the port component. A more elaborated explanation regarding the methodology of the motion response calculation, can be found in appendix H.1. A drawing of the floating port components is made in the program: Rhino. This drawing is exported to Ansys, which transforms the drawing to finite elements. AQWA imports the drawing from Ansys, after which the hydrodynamic simulation can start. An example of the drawing is displayed by a visualisation of in appendix H.1.

Analysing the ten wave spectra as determined in section 5.3, a Hs of 4,5 meter is required for a high workability. So the Hs within the simulations is set to 4.5 meter and AQWA produces motion response for the floating structure, taking into account multiple wave directions and wave periods. AQWA simulates a three hour period for each wave direction. Therefore a most probable maximum (MPM) factor of 1,86 is applied to this motion responses[22]. The AQWA response results are damped by the Ikeda formula, which is discussed into more detail in appendix H.1.

6.1.3 Allowed motions

The allowed motions as determined in paragraph 5.2.3, are compared to the motion response results from AQWA. The determined allowed motions are for an onshore port and a multi purpose vessel. The multi purpose vessel represents the offshore port. By multiplying the allowed motions determined in paragraph 5.5 with 0,75, the relative motion between the berthing vessels and offshore port are taken into account. This leads to the following maximum motions:

Table 6.1: Allowed relative motions for unloading offshore port and vessel

Surge (m)	Sway (m)	Heave (m)	Roll(°)	Pitch (°)	Yaw (°)
1.5	1.3	0.75	3.75	1.5	2.3

A multi purpose vessel has a length of 175 meter and a maximum width of 30 meter [124]. When the offshore port has different dimensions in the length and width, the allowed motions in the roll and pitch direction deviate from the values in table 6.1. The motion combined with a certain length and width of the offshore floating port creates an amplitude at the edge of the port. The amplitude at the edges of the offshore port should have a similar maximum allowed value for all type of dimensions.
The lifting process, berthing, mooring and other processes could be affected when the amplitude of the port is to large. However, for uncommon lengths and widths there are no maximum allowed motions defined for (un)loading of the port. So an assumption is made to compensate when an offshore port has different dimensions than the multi purpose vessel.
A linear extrapolation is used to determine a similar maximum amplitude of the port in the roll and pitch motion. When the length and width dimensions of the offshore port are larger or smaller than 175 x 30 meter. After an iterative process, the linear extrapolation is divided by a value of 1,5. This leads to an equal amplitude in the roll and pitch motion when the dimensions of the port components are horizontally a square. An example for adjusting the allowed roll amplitude for a port with a different with than a multi purpopse vessel is provided in equation 15.

$$Allowed\,roll\,motion = 3.75 - \frac{3.75 - \frac{3.75*30}{new\,width\,of\,port}}{1.5} \tag{15}$$

[22]MPM value is in each vessel design a point of discussion. It is a factor applied to the significant motion amplitudes, generally agreed on 1,86. More information on this can be found in appendix H.1.

In which:
3.75 = The maximum allowed roll motion
30 = Width of the offshore port when represented by a multi purpose vessel

An important result from AQWA is the MPM figure based on a Jonswap wave spectrum. This figure shows for the selected Hs of 4,5 meter the motion response per wave period for each wave direction[23]. Next, this figure can be translated to a workability table for the floating port component. Based on this MPM figure, for each wave period the maximum Hs value can be determined for the floating port component to be operational. This maximum Hs value for a workable condition for the port for each wave period can be calculated by applying equation 16.

$$Maximum\ Hs\ for\ a\ wave\ period = \frac{4.5 * allowed\ motion}{motion\ for\ this\ wave\ period} \tag{16}$$

In which:
4,5 = Hs input value for AQWA
Allowed motion = Motion criteria in a specific direction or movement from table 6.1
Motion for this wave period = Resulted MPM motion of the port in a specific direction or movement for a certain wave period

6.2 Port components

The characteristics, applications and technical behaviour of potential port components that fulfil the five boundary conditions are analysed in this section. A structure that has been constructed before is favorable, but also structures that have never been constructed are taken into account. Based on experimental results these port components could be of interest for this project.
The boundary condition of a suitable structure for a water depth of 30 to 50 meter leads to some restrictions for fixed and floating port components. A fixed structure uses the bearing capacity of the soil to support the loads. An alternative to this is a floating structure, the load is supported by the force of buoyancy.
Both structure types have advantages and disadvantages. For example, a fixed structure depends on the soil conditions, where a floating structure is more susceptible to wave and wind action than a fixed structure. There are more differences, but these are not addressed in this research. The costs are at this stage not taken into account, because the first objective is to investigate a workable port. It is useless when a port component has low costs, but it is not satisfying the workability demands.

As stated in paragraph 4.3.1, the port has to be transportable so it can be applied for multiple offshore wind construction projects. Creating an island by reclamation of land, is therefore not a suitable alternative. Another disadvantage is that the required volume of sand to reclaim an island, increases quadratically with the depth. This is showed by a calculation in appendix F. There are more potential port components for which the average water depth of 40 meter is troublesome. As a consequence they can not be taken into account as a port component.

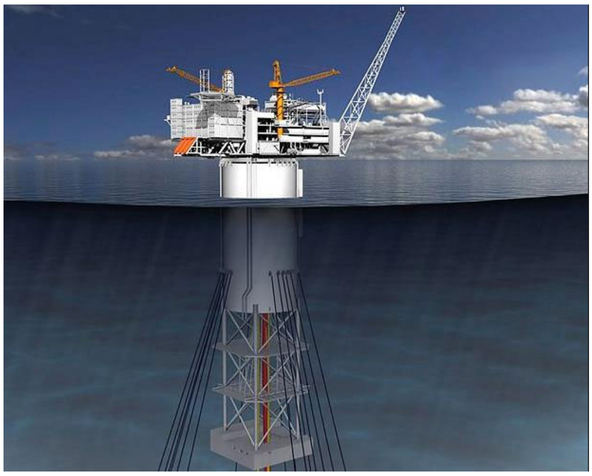
For example a caisson, it can be used for retaining a reclamation fill at sea. It fulfils the functionality for transportation, because when opening and closing the hatches water can flow in or out of the

[23] A Hs of 4,5 meter has a probability of exceedance of 0.01%, based on the wave spectrum of figure 5.9

caisson [39]. Although a caisson has never been reused in a new functionality[24], as long as there is no damage at the caisson, reuse could be possible. It is hard to detect damages, but a positive aspect is that concrete becomes stronger over time. The sand ballast inside the caisson can be limited since it is located temporarily, the amount of sand inside can be removed by sucking the sand out the compartments through a Toyopump. Another possibility is by liquefying the sand.
However, a water depth range around 40 meter is too high for a caisson to be an appropriate fixed port component. Due to the water depth restriction and to ease the movability of the port component, it is preferred to have a floating caisson and not a fixed port component that is supported by the soil. Also preventing the processes of sinking and uplifting of a caisson, saves time and money for the project.

Another example of a port component that has no potential due to water depth restrictions is a spar-buoy. It the foundation for the single operational offshore floating wind farm, Hywind in Scotland. However, this structure requires at least a water depth of 50 meter, as is shown in table 1.1. An example of a caisson and a spar buoy is displayed in figure 6.6.

(a) Construction of caissons [W16]



(b) Spar buoy as an offshore structure [W31]

Figure 6.6: Components that are not taken into account

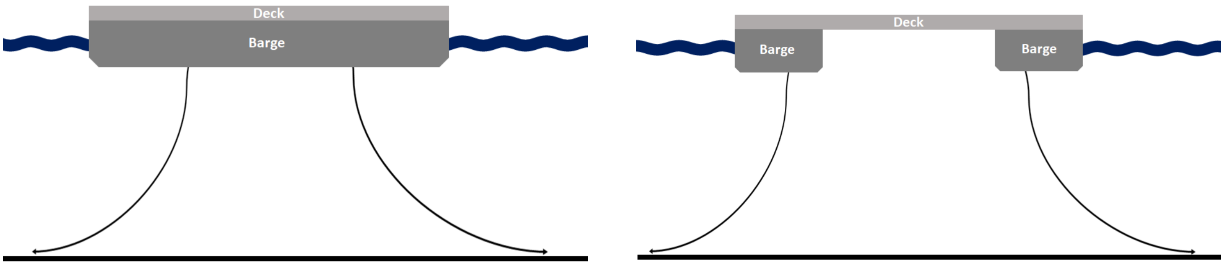
6.2.1 Barge

A barge is a rectangular flat-bottomed hollow shaped box, it is floating due to buoyancy and it is fabricated from metal or concrete. A barge has almost vertical sides and an almost rectangular bottom [63]. Application examples of barges are: floating bridges, floating entertainment facilities, floating terminals and floating houses [202]. A barge constructed from concrete can also be described as a floating caisson.

A different design in lateral and longitudinal direction of the barge affects its behavioural properties. The two most commonly applied hulls are considered [79]. The single barge covers the entire deck area and the catamaran barge type is assumed to support the two 25% ends of the deck. Both barge types are displayed in figure 6.7. A comparison between these two type of barges is made and the major differences are highlighted. The main parameter for the workability of a floating structure is the

[24] Discussed this topic at the University of Delft with a caisson specialist, M. Voorendt

motion response. This parameter and structural differences are explained for these two types of barges.



(a) Single barge

(b) Catamaran barge

Figure 6.7: Most common barge hulls

The differences between the two barge types are shown quantitatively in table 6.2. Very short waves and waves longer than 0.75 the length of the barge have a similar affect on the motion of the barge. The wave forces from these type of wave lengths cancel out a final responding force on the deck. For longitudinal waves on the barge, so from left to right or from right to left in figure 6.7. A wave length that approaches the barge that is less than 0.5 times the length of the barge, but longer than a short wave, can result in the deck of the catamaran barge experiencing more heeling than the single barge. A similar situation could occur for a wave length between 0.5 and 0.75 the length of the barge, because one of the two barges is uplifted. For a transverse wave direction to the barge, the catamaran barge experiences less heeling because the area that endures the wave forces is 50% less.

For a similar load and same deck area, the draught of the catamaran is expected to be twice as large as of the single barge. This is favorable for the submergence of the barge for high waves, this reduces the motion response. It is expected that less surface area on the waterline also reduces the motion response. On the other hand, the static stability of the single barge is expected to be larger.
It should be noted that the design of the catamaran barge should be such, that slamming on the bottom of the deck is prevented. Therefore, the air gap of the catamaran should be at least five meter. It is assumed that the load is distributed uniformly on the barges. Specifically for the catamaran barge, this reduction of peak loads is of importance when the structure experiences a roll, pitch or yaw motion.

Table 6.2: Relative comparison barge types

	Single barge	**Catamaran barge**
Advantage	High GM value	Less surface area on the waterline
Disadvantage	Lower draught	Waves of 0.5-0.75 barge length

The main question arising from table 6.2 is how much the motion response is decreased by a smaller water plane area. The answer to this question in combination with the amount of material required, determines the type of barge that is used in the remaining of this research. The natural oscillation period of the structure is the most important variable to answer this question. A low occurrence of this period in the wave spectrum is favorable. This variable can be calculated when the shape, material and mass of both barge types are determined.

The first step in this determination is the selection of the material. There are several alternatives like: steel, reinforced concrete or other composite material like fiber concrete or a combination of EPS and concrete.
EPS is short for expanded polystyrene, which is a very light synthetic material which provides the barge its buoyancy [115]. Fibre concrete is stronger than EPS, there are actually no technical disadvantages for fibre concrete [174]. However, it has never been applied offshore. Due to these offshore uncertainties for fibre concrete and EPS, a choice is made between steel and concrete.

Steel can have a small wall thickness, which results in a small self weight, which gives high buoyancy. Considering the boundary conditions of a minimum surface area and a minimum load, the buoyancy of a barge is expected to be high. Because the port only has to be transported when a wind farm project is finished, the lower self weight for steel is a negligible advantage, unless the costs are lower. On the other hand, the unfavorable lower draught for a barge of steel is not an issue for motion response. Because the draught can be increased by filling the tanks within the hollow sections with water. A choice between steel and concrete is therefore not based on technical behavioural properties, but on an indication of the costs.

A barge from steel requires about 10 times less material than a barge made from concrete. This is determined by a rough rule of thumb, taking into account the expected failure mechanism of buckling [6] [12]. The price per cubic meter of steel is approximately 25 times as high as for reinforced concrete, the price of prestressed reinforced concrete is € 175/ton and for steel this is € 5.000/ton[25] [122] [33]. Because steel is more than three times as dense than concrete, this results in a cost price that is approximately 75 times as high as concrete for the same weight. However, the amount of steel required is calculated to be approximately 10 times as low. This difference of a factor 7.5 is an estimate by a rule of thumb. But due to the value of this factor being far above 1, also for less favorable conditions the selection of concrete as a material is cheaper and so more favorable.

However, it is only the self-weight which depends on the selection of material. In a subsequent research project, this selection of material can easily be adjusted since it does not influence the technical properties. Another advantage of concrete over steel is the lower need for maintenance, it is almost maintenance free. In the last decade large floating liquified natural gas (LNG), liquified petroleum gas (LPG) and oil production terminals are made from reinforced prestressed concrete. Floating concrete structures have become more attractive as permanent steel structures in the oil and gas industry [63]. An example is displayed in figure 6.8.

When the barge consist of one rigid hollow section, the bending moments are expected to be to high concerning the minimum surface area as stated in the boundary conditions. Vertical inner walls decrease the span width and as a result of these created sections, the bending moments in the deck are lower. The number of sections is based on a trade off between the aim of a minimum wall thickness and a minimum influence on the difficulty of construction. After calculating a few number of sections, the number of sections is set to 36. Stiffeners are placed between the sections to prevent flexible motions. A visualisation is provided in figure 6.9.

[25] Confirmed by the market as the bottom current material price, including the outfitting of the barge.

Figure 6.8: Construction of a concrete LPG floating storage facility, Java sea, Indonesia [W24]

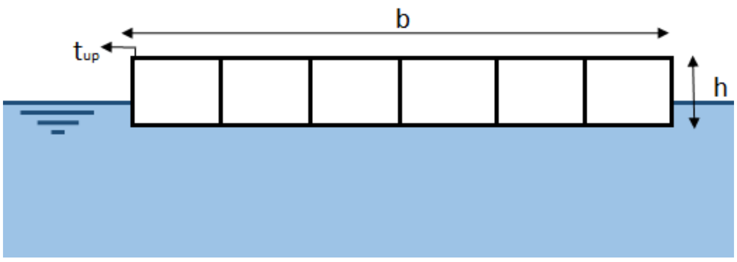


Figure 6.9: Side view of the barge with 36 sections

Instead of creating vertical walls, a solution could be to connect separate smaller hulls to each other. These hulls have to be attached to each other to prevent motions as shown in figure 6.10.

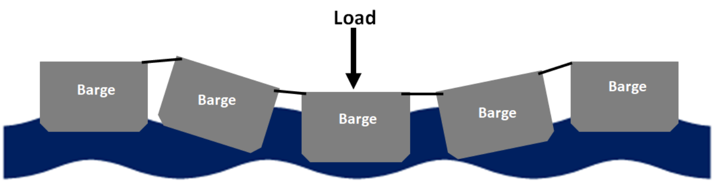


Figure 6.10: Unstable barge system

Tests on floating islands at the MARIN Seminar in march 2018 showed the importance of a flexible connection. The interaction between sections causes high forces and a 100% stiff structure of large dimensions is not feasible. But two important assumptions concerning the stiffness of the barge are made to calculate the static stability and wave susceptibility of the barge.

1. The barge is one rigid structure, by connecting four barges. So each barge consist of nine sections and in total there are 36 sections.

2. The four barges are connected together and make it a single 100% stiff rigid barge. In practice these connections has to be flexible by applying for example: hinges, springs or bolts between the four barges.

A base case is created to compare the single barge and catamaran barge. Within the base case the length and width of the deck is 175 x 100 meter. This length and width ratio is expected to provide a suitable storage are for the turbine components. When a selection is made between the single barge and catamaran barge, the base case is varied to achieve an optimum design regarding the motion response. To determine the natural oscillation period for both type of barges, there are two boundary conditions added to the listed boundary conditions in section 5.4. These two conditions are as follows:

1. A minimum draught of five meter is required, to limit the motion response of the barge. For the maximum wave height that can occur, the barge is still semi-submerged and this prevents slamming.
2. The air gap of the catamaran is at least five meter, to prevent slamming.

Besides the determined material, shape and dimension of a port component, there are four important assumptions made to calculate the static stability and motion response of both barge types.

- As a starting point for the stability calculation, the average wall thickness is assumed to be 0.75 meter. This is based on a previous research with barges as a floating foundation for a city [114].
- The shape of nearly all existing barges is a rectangle or a square. When varying the shape of the barge it still has to be a rectangle or square.
- The inner walls have half the thickness of the vertical outer walls. Their function is to decrease the span width and this thickness is sufficient to handle the vertical loads.

Static stability

The static stability is calculated by the use of six fixed input variables. For each case, these are the length, width, depth, number of sections, vertical load and the densities of concrete and sea water. The fixed input variable of the depth is set to 10 meter, this is due a combination of the boundary condition of the freeboard and the minimum draught for a barge of 5 meter. The wall thickness is adjusted when it does not meet the required thickness. To minimise the amount of material, the wall thickness is decreased to its lowest required value. This is elaborated in appendix H.3 and is summarised by the methodology shown in figure 6.11.

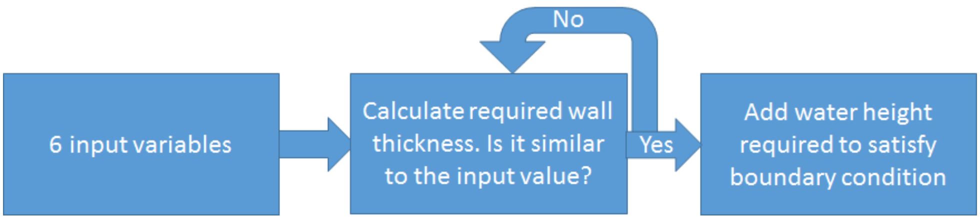


Figure 6.11: Determination of wall thickness

The approach to determine the GM value and the natural oscillation period of the catamaran barge is different as for the single barge, the differences are explained in appendix H.6. Concerning the static stability of the catamaran type, it is striking that the KG value is higher as for the single barge, this can be seen in table 6.3. The KG value is higher because the deck has to be thicker in the middle area of the catamaran barge and there is no supporting bottom in the middle area. The draught of

the catamaran is also higher, this is required to satisfy the boundary condition of the freeboard. More information on the derivation of the catamaran values in table 6.3 and an anlyses on these values can be found in appendix H.4.
In appendix H.5 a calculation is conducted to determine the lightweight of the catamaran barge when constructed from steel. The amount of material required for the catamaran barge made from steel is about 14 times as less as when made from concrete. This difference does not outweigh the larger deviation in material costs, so the catamaran is made from concrete. It can be concluded that instead of the expected 7.5 times cheaper material costs for concrete as assumed by a rough rule of thumb at the beginning of this section. The material costs for concrete are only 5 times as low.

Based on the results of the calculations, the single barge is selected over the catamaran type. The construction costs for concrete are comparable when considering the amount of material required, so this is based on the technical properties of both barge types. The period in the roll motion is similar for both type of barges. This can be seen in table 6.3. The heave motion of the catamaran type is twice the value of the single barge, but both heave eigenperiods are at the outer end of the wave spectrum.
It is expected that the pitch motion is critical because the allowed motion is 1.5°. The oscillation period in the pitch motion is 20% higher for the single barge. The natural oscillation period for pitch is smaller for the catamaran barge since the added mass is lower. So based on the pitch eigenperiod the single barge is more favorable. Though it has to be noted that the differences concerning the natural oscillation period are small and the catamaran type is suitable as well.

Table 6.3: Stability and oscillation period for several barge cases

Unit	Parameter	Catamaran	Case 1	Case 2	Case 3	Case 4	Case 5
m	Length	175	175	225	133	175	175
m	Width	100	100	150	133	100	100
m	Avg. wall thickness	0.65	0.44	0.48	0.36	0.64	0.52
Ton	Load	12.600	12.600	12.600	12.600	12.600	28.600
Ton	Lightweight barge	51.231	48.802	95.244	40.112	66.532	57.413
m	Added water height	-	1.7	2.0	2.3	0.6	0.2
m	Depth	13.0	10.0	10.0	10.0	10.0	10.0
m	Draught	7.1	5.0	5.0	5.0	5.0	5.0
	Sections	12	36	36	36	16	36
m	KG	9.8	3.2	3.0	3.0	3.6	4.3
m	GMt	199	166	375	295	166	165
m	GMl	550	510	843	295	509	509
s	Eigenperiod heave	20.1	13.2	15.9	14.9	13.0	13.0
s	Eigenperiod roll	8.9	8.8	9.9	9.9	8.8	8.8
s	Eigenperiod pitch	8.2	11.0	12.1	9.9	11.0	11.0

Note: GM values are far above 0,5 meter.

As stated before, the buoyancy of the barge is high due to the large surface area, this is confirmed by the GM values in table 6.3 which are far above 0.5 m. The length and width ratios of the barge are varied in table 6.3 to understand the influence of this on the motion response of the barge, which is indicated by the eigenperiod. A eigenperiod out of the wave spectrum leads to less motion response of the barge. Varying the dimensions, amount of section and the load also influences the required wall thickness of the barge. The load of case 5 represents 15 turbines stored instead of 5. The results for six different cases are presented in table 6.3 above, the blue cells indicate the different input variables in relation to case 1.

The optimal dimension for the barge will not be based on GM, because all cases are statically stable. GMt, is an abbreviation for distance between the metacentre and centre of gravity in the transverse direction. GMl, represents the same distance, but in longitudinal direction. The results confirm the generally valid statement, that a wider barge with a low centre of gravity is most stable [185]. The length and width of the first case are based on the required surface area, as determined in section 5.2.3. Results showed that the bending moments initiated by water pressure are higher than the moments by the vertical loads on the port.

Wave susceptibility

The most important result in table 6.3 is the natural oscillation period of the single barge, since the buoyancy capacity and static stability are very high. The depth of the barge is not optimised concerning the eigenperiod, because the costs increase when the draught and depth increase and the effect on the eigenperiod is limited. An increase of the depth and consequently the freeboard by 1 meter, results in an increased eigenperiod of 1%. To analyse the effect of these eigenperiods on the motion response of the barge, a simulation with the motion response program AQWA has to be conducted. This is explained in the next paragraphs. This motion response is time consuming and therefore only conducted once for a barge.

The selection of the preferred dimension for the motion response analysis is based on two variables. The expected motion response and the lightweight of the barge. The lightweight of the barge is equal to total amount of prestressed reinforced concrete steel used. Case 1 and case 3 in table 6.3 are the most favorable regarding these two criteria. The motion response is based on the eigenperiod in relation to the wave spectra and this motion response is a necessity to determine the workability of the barge. As can be seen in table 6.3, case 1 and case 3 have nearly similar results. The workability depends on the maximum allowed motions for continuing operational activities. These maximum motions are determined in paragraph 5.2.3. The result of these two determinative variables is as follows:

- The amount of material for case three is 25% lower, this decreases the costs.
- Applying equation 15 to the length and width of case 1 and case 3. The allowed pitch motion for case 1 is 1.5° and for case 3 this is 1.8°. The allowed roll motion for case 1 is 2° and for case 3 this is 1.8°. Considering the eigenperiods and these allowed motions, the result for workability is similar.

Based on the amount of material required, case 3 is selected and its dimensions are used for the AQWA simulation. A simplistic picture of the barge for case 3 is shown in figure 6.12. The figure is on scale, but the deck and water tanks are not drawn. This eases the understanding of the dimension of the barge. The vertical lines in the middle of the outer walls, represent the connectors between the four barges.

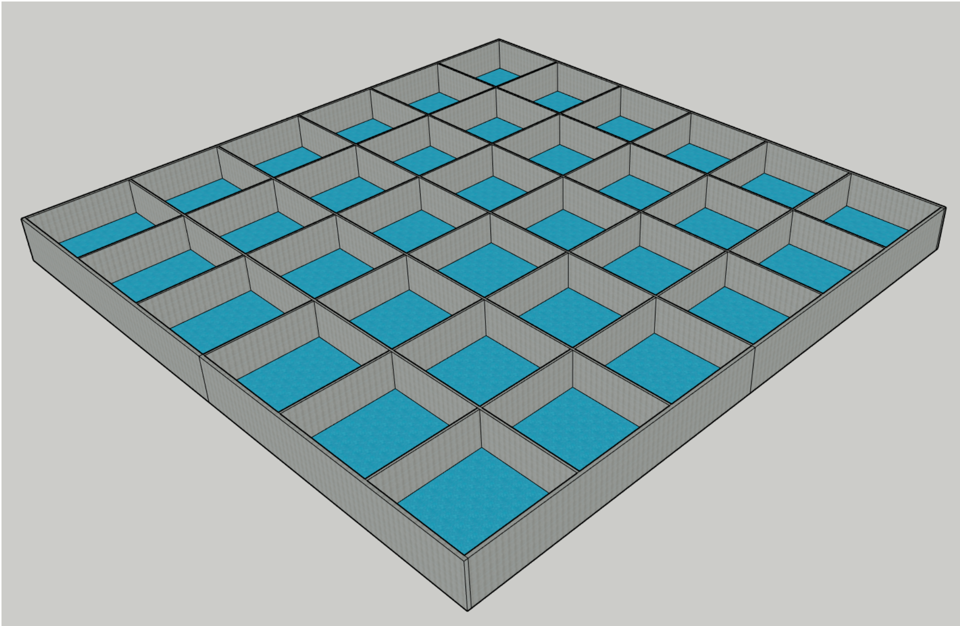


Figure 6.12: 3D view on the barge of case 3

Results

Comparing the three motion response of heave, roll and pitch from the AQWA output and the horizontal and vertical accelerations, with the motion criteria as shown in paragraph 6.1.3. Applying the modification from a multi purpose vessel to the single barge of 133 x 133 meters, the critical motions are as presented in table 6.4.

Table 6.4: Selected barge allowed motions

Heave (m)	Roll(°)	Pitch (°)
0.75	1.8	1.8

The critical motion response of the barge is in the pitch and roll direction. For a Tp of 8 seconds or higher the allowed motion is exceeded. The allowed heave motion is exceeded for a Tp of 9 seconds and higher. The MPM pitch motion response of the barge is shown in figure 6.13. The MPM figure for heave is shown in appendix H.2, the roll motion figure is similar as to the pitch motion figure. This is an obvious result since the barge is a horizontal square. A wave heading of 0°, 90° and 180°on the vessel, is governing for the critical motion. The surge, sway and yaw that were neglected in previous calculations, are as assumed far from critical to the workability.

The GM value, the eigenperiod and the three parameters that lead to the eigenperiod are compared between the AQWA results and the values in table 6.3. The added mass provided by AQWA is selected at the eigenperiod of AQWA. Table 6.5 only shows the values in the pitch direction, although the GM value is used for all directions. The table validates that the values in table 6.3 for the variation of barge dimensions are correct.

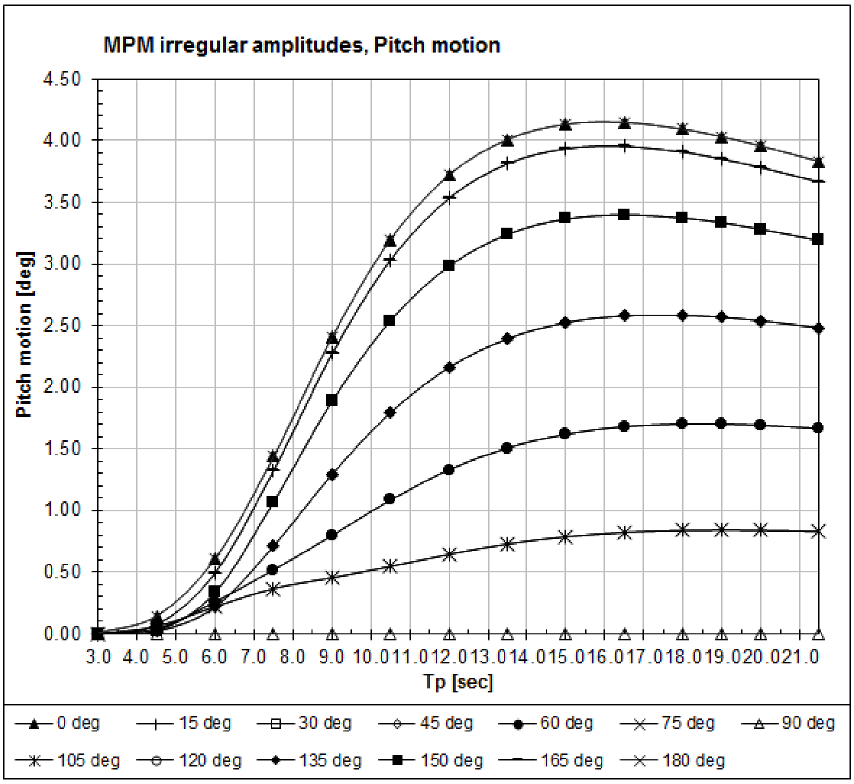


Figure 6.13: Critical response motion for the barge

Table 6.5: Comparison results AQWA and table 6.3

Parameter	AQWA	Calculated
GM (m)	292	295
Eigenperiod (s)	9,7	9,9
Spring term (ton*m^2)	2,6*10^8	2,6*10^8
Mass moment of inertia (ton*m^2)	1,2*10^8	1,3*10^8
Added mass (ton*m^2)	5,0*10^8	5,2*10^8

The increasing motion to the eigenperiod can be seen by the Tp values from 5 to 10 seconds. The motion criteria for roll and pitch are also exceeded higher periods than 8 seconds with a Hs of 4,5 meter. This is because there are more aspects that influence the motion response, easy examples are the wave length and water depth. But these aspects are not taken into account during this research.

Applying equation 16 to figure 6.13, the workability of the barge can be determined. The sea states in which the barge can work are indicated by green cells in figure 6.14. The red cells indicate the sea states for which the motion criteria are exceeded. An important note is made on a specific characteristic of a barge, they are susceptible to green water [94]. The influence of this effect is not integrated in the motion analyses by AQWA.

This is based on the wave spectrum of buoy 15512 in the North Sea as is shown in figure 5.9. When comparing the workability of a barge with all ten wave spectra of the North Sea. It can be concluded that the average workability for all wave spectra is 92%. For the US Atlantic coast, this percentage

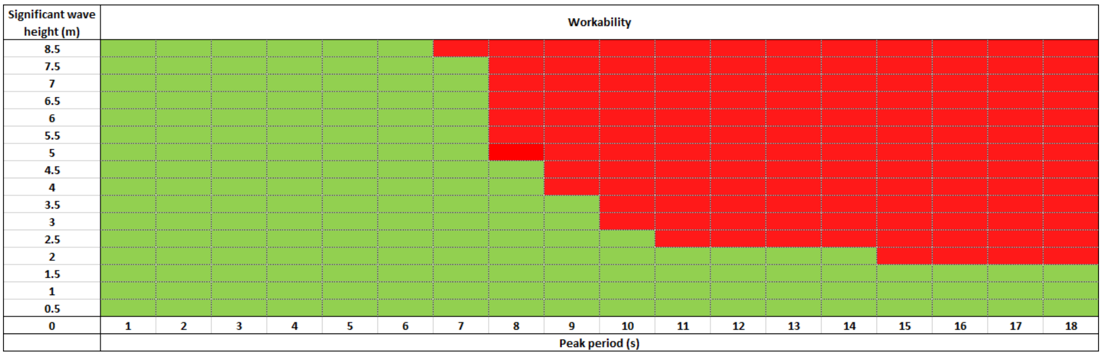


Figure 6.14: Workability of the barge

will be higher, because the wave climate is more moderate. Concerning the single wave spectrum of buoy 15512, corresponding to a high potential area for the offshore port, 98% of the sea states are operational for the barge. It can be concluded that a barge with these dimensions is considered a potential port component.

6.2.2 Semi-submersible

A semi-submersible consist of submerged floaters that provide the buoyancy. It should not be confused with a semi-submersible vessel like the Dockwise, as displayed in figure 6.15b. The concept of a semi-submersible structure is large-based floaters which are fully submerged during operations, supporting four to eight columns which extend through the waterline and support the deck. So there is a large submerged mass combined with a minimum waterplane area. The semi-submersible vessel is therefore subjected to minimum exciting and righting moments [75]. A major advantage of the semi-submersible is the large deck area. In comparison to ships and barges the eigenperiod of a semi-submersible structure is a lot higher.

There are penalties to be paid for these favorable characteristics. It has a smaller buoyancy and it has a lower GM value, the construction costs are higher. The properties of this structure depend on the design, for example a variation in amount of columns, or a variation in volume under water. Assuming a sufficient air gap, a larger draught of the floater decreases the wave susceptibility for most wave periods [156].

The semi-submersible could be self-propelled as is shown in figure 6.15a, it could be towed by a ship, or it could by transported with a semi-submergible vessel as is shown in figure 6.15b. The scope in paragraph 4.3.1 explains why the port has to be transportable, so a self-proppeled semi-submersible is preferred but it is not required. The amount of transport will be limited due to the project duration of the construction of a wind farm. For this research a semi-submersible vessel with two parallel submerged floaters is selected, so there are no floaters in transverse direction. Practical applications of a semi-submersible can mainly be found in the offshore oil and gas industry. It is used as a drilling rig, oil production platform, floatel or as a (radar) ship.

A semi-submersible that is connected to the seabed by vertical tethers is called a tension leg platform (TLP). The buoyancy of the platform keeps the tethers under tension. This stiff connection of the semi-submerged structure with the seabed reduces the vertical motions. However, a TLP is more suitable for a more permanent basis and therefore not taken into account as a semi-submersible design alternative.

(a) Self-propelled semi-submersible [W19]

(b) Rectangular shaped semi-submersible structure transported by the Dockwise (semi-submersible vessel) in Isola del Giglio (Italy) [W22]

Figure 6.15: Two types of semi-submersible structures

Stability

Specifications and characteristic properties of a semi-submersible structure are analysed to make use of its advantages. The specifications are based on three semi-submersibles, the Sleipnir, the OOC Zeelandia and the Thialf. The latter is in operation since 1985 and is the largest constructed semi-submersible structure. The Sleipnir and the OOC Zeelandia are currently in the design phase, but will exceed the dimensions of the Thialf. A visualisation of these three semi-submersible crane vessels is provided in appendix H.7.1. This analyses leads to three additional boundary conditions, to the four general boundary conditions defined in section 5.4.

- Similar as to the catamaran barge, an air gap of at least five meter is required.
- The dimensions of the base case are: a floater height of 10 meter, a floater width of 30 meter, a deck height of 5 meter and a column height of 20 meter.
- The minimum draught of the columns is 15 meter.

The applied approach to determine the static stability and the wave susceptibility is similar as to the barge. The result of the calculations are displayed in table 6.6. The blue cells indicate the varied input parameter in comparison to case 1, which is the base case. Case 2,3 and 4 provide an indication on the effect of adjusting certain parameters. There are five aspects in which the determination of the semi-submersible stability is different than for the barge, these are listed below.

- The moment of inertia of the waterplane area, used to calculate the GMt and GMl is determined different. Steiner's theorem (parallel axis theorom)[26] is applied, this takes into account the distance of the columns and the floaters to the centerline.
- The mass moment of inertia is calculated by adding up the mass moment of inertia from the floaters and columns by using Steiner's theorem[26] and the deck and the load.

[26]Explained in appendix H.6, though for the semi-submersible this also accounts for BMt and BMl.

- The lightweight of the semi-submersible is derived for each case in table 6.6 by multiplying the volume of the semi-submersible by 0,2 ton/m^2. This value holds for large type of vessels[27]. The resulted lightweight of the semi-submersible is a little smaller than of the Thialf semi-submersible. To achieve the required draught, water is added to the floaters as presented in table 6.6. AQWA makes use of the CG value of the semi-submersible, the semi-submersible finite element drawing and the total weight of the semi-submersible with the added water. So the ratio between lightweight and added water is irrelevant for AQWA.
- The added mass of the semi-submersible is determined differently. The equation for a submerged floater is different as for a floating structure as shown in figure 6.5. The derivation of the added mass formula of a semi-submersible structure is explained in appendix H.7.2.
- The parameter KB required to determine GM, is not equal to half the draught. It is derived in a similar way as the parameter KG. The weight of the floaters and the columns that are under water is determined and an element approach is applied. It is assumed that the hull of the floaters, columns and deck has a similar thickness.

The amount of columns of the semi-submersible is six. A semi-submersible can have four to eight columns. When constructing four columns, the buoyancy of the semi-submersible is lower. Table 6.6 shows that the buoyancy of a semi-submersible is not an issue for the determined load condition. However, when constructing four columns, the added water height reduces by 3 meter for case one. Constructing six instead of four columns is relatively cheap and it increases the potential of the semi-submersible to be use in different markets when the offshore wind market declines.

The GM values show that the static stability of all semi-submersible cases is good, since it is above 0,5 meter. For all cases additional water is added to the water tanks to achieve the minimum draught of 15 meter. The tanks are placed on the bottom of the floaters. Case 4 shows better results as case 1 concerning the static stability and natural oscillation periods. So when the semi-submersible is selected as a port component, in the design phase there is a possibility to increase the width of the floater.

The lightweight only increases a little from case 1 to case 4, as can be seen in table 6.6. Case 1 is used for the hydrodynamic simulation because it has the typical dimensions of a semi-submersible and a wider floater does not provide better results for the critical pitch eigenperiod, as is explained in the next paragraph.

Wave susceptibility

For the hydrodynamic simulation the dimensions of case 1 are used as explained in the previous paragraph. A representation of the semi-submersible used in AQWA is provided in figure H.2. The limiting motions are similar as to the barge, for heave this is 0.75 meter, for roll and pitch this is 1.8°. The results show that the pitch motion is critical with a Hs value of 4,5 meter, for Tp values of 8 seconds and higher. The governing wave headings for pitch are 0 and 180 degrees. The critical pitch motion over roll motion can be explained by applying no transverse floaters. The critical motion figures of the roll motion and heave movement can be found in appendix H.8. The pitch motion can be seen in figure 6.16.

[27] Explained by an expert in the field

Table 6.6: Semi submersible hydrostatic and dynamic results

Unit	Parameter	Case 1	Case 2	Case 3	Case 4
m	Length	133	133	150	133
m	Width	133	133	150	133
m	Depth	35	35	35	35
Ton	Load	12.600	28.600	12.600	12.600
Ton	Lightweight vessel	51.000	51.000	58.000	54.000
m	Added water height	9,5	7,7	8,8	9,2
m	Deck height	5	5	5	5
m	Air gap	5	5	5	5
m	Width floater	30	30	30	35
m	Height floater	10	10	10	10
m	Diameter columns	30	30	30	30
m	Draught columns	15	15	15	15
m	KG	16.8	20.8	21.3	20.8
m	GMt	25	20	29	19
m	GMl	42	34	48	35
s	Eigenperiod heave	22.0	22.3	23.1	24.4
s	Eigenperiod roll	16.1	16.8	17.7	16.8
s	Eigenperiod pitch	12.5	12.9	14.4	12.5

The results from AQWA are compared to the values in table 6.6. This is shown in table 6.7 and it indicates that the the applied approach to adjusting certain parameters and analyse their effect is valid. Though, the deviations between AQWA and this table are larger than in comparison to similar results of the barge. The presented results hold for the critical pitch direction.

Table 6.7: Comparison results for semi-submersible

Parameter	AQWA	Calculated
GMt (m)	31	25
GMl (m)	66	42
Eigenperiod (s)	12.2	12.5
Spring term (ton*m^2)	1.9*10^8	1.8*10^8
Mass moment of inertia (ton*m^2)	1.6*10^8	1.9*10^8
Added mass (ton*m^2)	7.0*10^8	5.0*10^8

These differences concerning the eigenperiods can be explained by two aspects. The added mass depends on the frequency, though in Excel a general estimate for all wave frequencies is applied. More governing for this deviation is the usage of a rough estimation method, which is suitable for a barge. In appendix H.7.2 it is attempted to transform this estimate to a semi-submersible structure. But in practice the added mass seems to deviate from the applied approach.

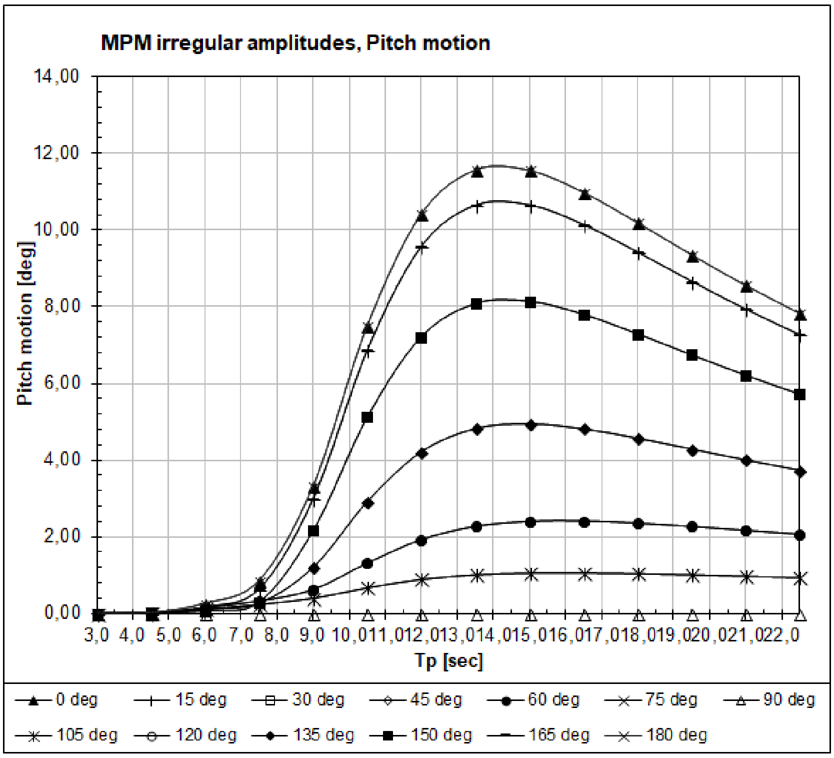


Figure 6.16: Pitch response motion for the semi-submersible

With a similar approach as for the barge, the workability of the semi-submersible vessel is determined. The average workability for all the ten sea states is 85%, considering only the wave spectrum of figure 5.9 the workability is 97%. So the potential of the semi-submersible as a port component, is lower than for the barge in relation to the workability.

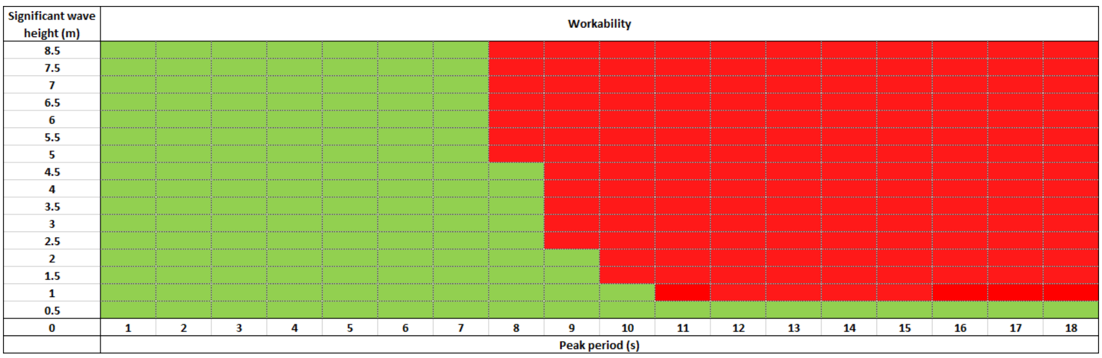
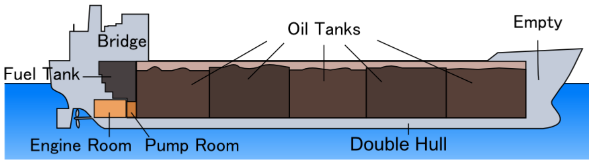


Figure 6.17: Workability for the semi-submersible

6.2.3 Large vessel

Two of the six demands involve a decrease of costs concerning the installation vessel. It seems contradictory to use a large ship as a port component, but there are argumentations to take it into account. The day rate of an installation vessel is in the order of 2 to 4 times as high, in comparison to the largest ships in the world [151] [191]. Also there are vessels in the middle or end period of their lifetime which have a low operational activity due to developments in the market. These type of vessels can be modified which is cheaper as constructing new ones. An very large crude carrier (VLCC) is taken into account as a large ship and so as a port component. It has a larger and also a flatter deck area as for example a container vessel or a bulk carrier. The design and construction of a VLCC shaped vessel will be different, when the goal is to function as an offshore port. It does not require oil tanks and a lower engine power is possible. These aspects ease the construction, though there will be additional requirements to function as an offshore port.

(a) The VLCC Maersk Nautilus at Singapore [W20]



(b) VLCC side view [W34]

Figure 6.18: ULCC in practice and schematically

Crude tankers transport large quantities of unrefined crude oil from the point of extraction to the refineries. They are classified as very large when capable of transporting between 180,000 to 320.000 ton of oil. Dimensions of these vessels are a length between 300 and 350 meter and a width of about 55 meter [133]. Due to the large size of a VLCC, they have some limitations to attend ports and sail some routes.
Considering the length to width ratio of a VLCC and the required surface area for the offshore port. The base case of a VLCC has a length of 350 meter and a width of 50 meter. So the load buoyancy of a VLCC is clearly very high, in relation to the minimum load capacity required for the offshore port. So water tanks will be installed to achieve the aimed draught.

The maximum motion for safe working conditions as determined in paragraph 5.2.3, are based on a multi purpose vessel. However, this port component is a VLCC and therefore has a different motion allowance. For cargo handling of an oil tanker the allowable criteria are determined by the loading arms in the surge and sway direction. Other tanker motions are generally well within the design motion envelopes of the loading arms. As a consequence there are no other criteria determined as for surge and sway. The VLCC used as a port component will among others have a crane on its deck, which is used for handling the cargo. Since an Oil tanker does not use a crane for the cargo handling, the motion criteria of a multi purpose vessel are also applied to the VLCC.

Stability
The depth of a VLCC is about 30 meter and the draught is between 15 and 20 meter [128]. This depth of 30 meter is assumed for the VLCC in this research, this provides an option to integrate the reuse of an operational VLCC as a port component. A 15 meter draught corresponds to a freeboard of approximately 15 meter. This is higher as the installation vessel and the feeder vessel have and unfavorable for the transfer of cargo. Therefore, the draught is set to 20 meter and the freeboard to 10 meter. This satisfies the boundary condition of the freeboard. This requires water tanks to be filled,

since the load on the port does not result in this draught. The lightweight of the vessel is determined with a similar approach as for the semi-submersible.

The total deck area in the base case of the VLCC is similar to the surface area of the selected barge. The results for the static stability analysis are displayed in table 6.8. Again, the blue cells indicate the varied parameters. The length of the VLCC must be substantially longer than the width, so the properties of a VLCC are valid. It can be seen that different length to width ratios of the deck has a negligible influence on the eigenperiod. Case 5 confirms that load buoyancy is no issue for the VLCC. Therefore the dimensions of a typical VLCC are applied, which is represented by case 1 in table 6.8. The GM value shows a static stable situation.

Table 6.8: Hydrostatic and hydrodynamic stability VLCC

Unit	Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
m	Length	350	350	300	400	350
m	Width	50	50	58	44	50
m	Depth	30	25	30	30	30
Ton	Load	12.600	12.600	12.600	12.600	28.600
Ton	Lightweight vessel	105.000	87.500	105.000	105.000	105.000
m	Added water height	12	8	12	12	11
m	Draught	20	15	20	20	20
m	KG	12	9	12	12	11
m	GMt	11	14	15	8	11
m	GMl	599	799	440	783	599
s	Eigenperiod heave	13,7	12,6	14,2	13,4	13,6
s	Eigenperiod roll	14,8	12,3	14,2	15,7	14,6
s	Eigenperiod pitch	17,8	16,9	17,0	18,7	17,8

Wave susceptibility

Although the eigenperiods for heave, roll and pitch are hardly influenced by varying the input parameters, the values in table 6.8 are valid. Because a comparison between the results from AQWA and the results conducted by a hand are approximately similar as can be seen in table 6.9.

Applying equation 15 to modify the allowed motions from a multi purpose vessel to the dimenions of case 1 of the VLCC, leads to a maximum allowed roll motion of 2.75°, a maximum allowed pitch motion of 1°. In figure H.3, the drawing of the VLCC is shown that is imported by AQWA from Ansys. The motion responses result from AQWA shows that the allowed roll and heave condition are exceeded for a Tp value of 7.5 seconds, for pitch this is 9 seconds.

Concerning the workability of the VLCC the roll motion is more limiting and the governing wave heading is 90°. It goes to a peak value of 14°, this is a lot higher as the 6 meter for the maximum heave motion. The MPM motion responses of heave and pitch can be found in appendix H.9. The motion response of the VLCC is presented in figure 6.19.

Table 6.9: Comparison of results between AQWA and calculated by hand

Parameter	AQWA	Calculated
GMt (m)	10	11
GMl (m)	526	599
Eigenperiod (s)	12,6	14,8
Spring term (ton*m^2)	3,4*10^7	3.2*10^7
Mass moment of inertia (ton*m^2)	1.2*10^8	1.4*10^8
Added mass (ton*m^2)	3.1*10^7	4.0*10^7

The workability of all sea states in the ten wave spectra is determined by the same methodology as for the barge. The result is presented in figure 6.20. The averaged workability is 80%, for the single location corresponding to a high potential location this is 93%. The conclusion can be drawn that the workability of the VLCC is low in comparison to the barge and semi-submersible. Because roll is the critical motion, a passive free-surface tanks can be added to reduce the motion response [103].

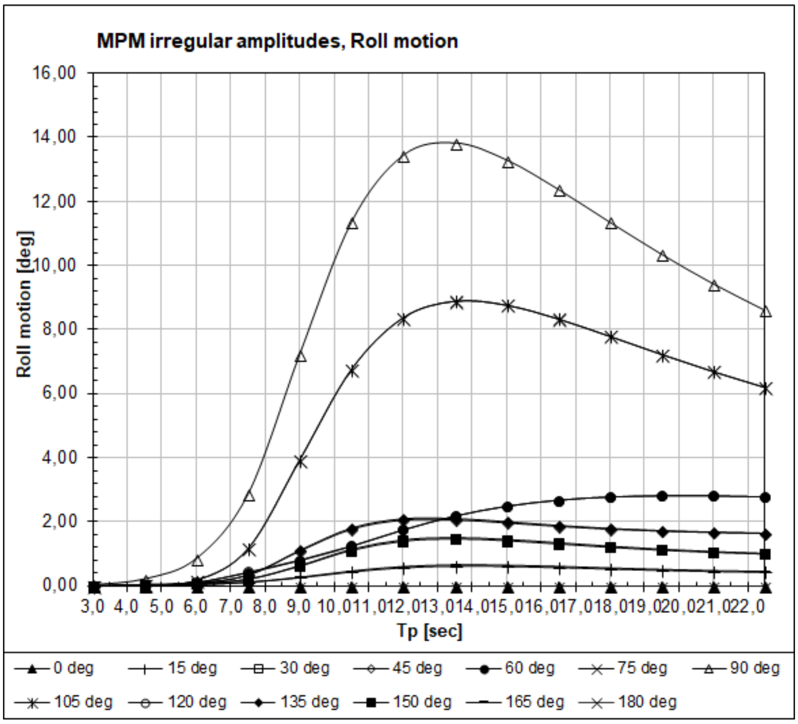


Figure 6.19: MPM roll motion of the VLCC

6.2.4 Versabuoy

This floating structure is an experimental design by Versabar for deep water drilling and production, but it could also be used as a floating port component. The topside is supported by four independent buoys, each buoy is connected to the top deck by an articulating connection. This connection decouples the pitch and roll motions from the buoys to the topside and among the buoys [78]. It also keeps the heave movement to a minimum. A visualisation is provided in figure 6.21.

The required water depth is less than for the traditional spar buoy, because it consist of four legs

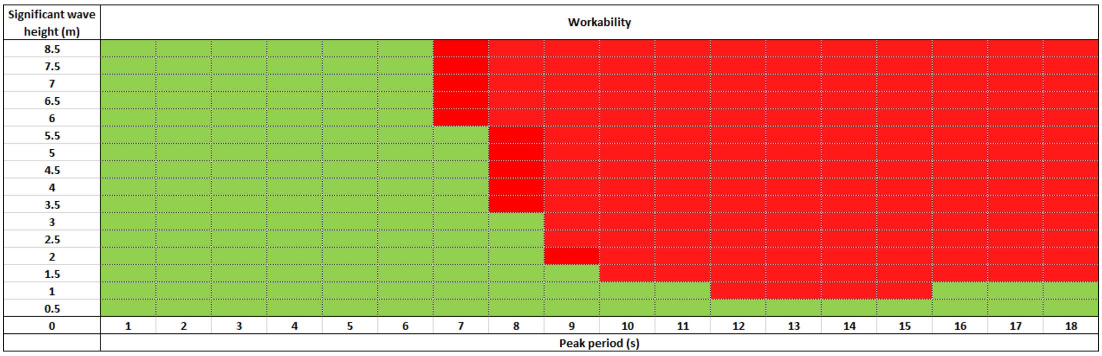


Figure 6.20: Workability of the VLCC

instead of one. Due to these four damping legs, the top deck experiences 10% of the wave motion in comparison to a spar buoy [78]. Therefore it can be considered very stable and is taken into account as a port component. The top deck is placed above the legs by two barges. The mooring of the legs is assumed be complex, since it has to be executed for each leg. The legs are transported by towing, or on a semi-submersible vessel. An important drawback to the design is that when an articulated connection fails and the leg is lost, the entire structure will collapse.

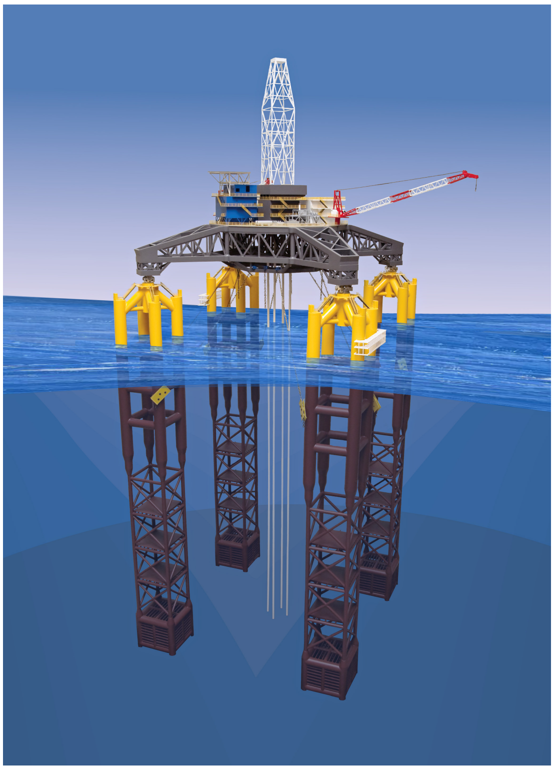
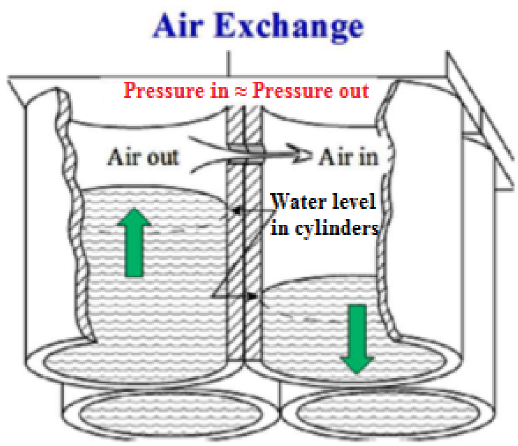


Figure 6.21: Schematic visualisation of the versabuoy [78]

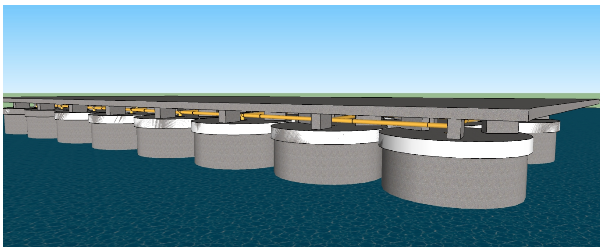
A spar structure in the offshore oil and gas industry has a heave eigenperiod between 20 and 35 seconds, the roll and pitch eigenperiods are between 50 and 70 seconds [50]. These are all out of the considered the wave spectrum. Concerning the 90% wave motion decrease in comparison to the traditional spar buoy, limiting motions for the operation are not expected. The workability of this port component is not calculated by performing a motion response analysis, because the versabuoy is too complex to draw in Rhino.

6.2.5 Pneumatic system

Each component is an open bottomed cylindrical element, which exploits the Archimede's principle to adjust the balancing and position. There is a deck on top of this cylinder of which the altitude, is a response to varying loads on the deck or hydrostatic effects. It achieves its stability and structural loads mitigation, by decoupling the hull from ocean wave pressures. This is done through the use of air buoyancy, which is both compressible and mobile [65].
When the water in each cylinder moves up and down, the air pressure in the trapped airspace changes. These spaces are connected through pneumatic lines and valves, so that these pressure changes result in air moving between cells. This dampens the waves and distributes their force in order to reduce peak load on the structure. With higher deck load capacities, the response of the deck to waves is softer. This mechanism is displayed in figure 6.22a.
The pneumatically stabilised structure (PSS) was originally proposed in 2003 for construction of a floating airport near San Diego, in the Pacific Ocean. However, this design was rejected due to difficulty in transporting goods like fuel, water and electricity from San Diego to the floating airport [169]. The design of the proposed airport with a pneumatic stabilised system is shown in figure 6.22b.



(a) Pneumatic stabilisation [65]



(b) Pneumatic system application [W15]

Figure 6.22: Pneumatic stabilised system

The buoyancy must come from the enclosed air between water and concrete top. For small loads, the cylinders can be a few diameters in depth. Though the cylinders can also be several meters. For the wave climate that occurs at potential areas for the port, a minimum cylinder length is required. Because when the deck is tilted and a few cylinders are exposed with their bottom to the air, the stabilising effect is decreased. This does not only influence the exceedance of motion criteria, but also increases the risk of failure of a PSS.
The total amount of material required for this PSS is determined by calculating the depth of a cylinder and the amount of air required for the buoyancy. The least favorable situation is during an extreme event. Linear wave theory is not applicable for these situations, so it is not valid to calculate the slope α as shown in figure 6.23 and determine from this slope the required depth for each column to be submerged during an extreme wave.

Waves will theoretically break if they become too steep, this occurs when the wave length is less as 7

times the wave height [137]. This is also known as the Miche breaking limit. The most unfavorable situation is as displayed in figure 6.23, half of the wave length is longer than the PSS and the wave crest is at the outer and of the PSS. The length of the structure is 133 meter and with the maximum slope for breaking, this requires a cylinder length of 19 meter.
The highest significant wave height that occurs in the wave spectra is 8,5 meter, this leads to a maximum wave height of 17 meter. The probability of a wave exceeding 19 meter is small, but depending on the duration and amount of storms still present and in the order of 100*((1-Q_{crest})^N), with N the number of waves and Q_{crest} the probability of a wave exceeding the maximum crest height of 17 meter [92].

Because waves are diversified and non-linear a safety factor of 1,5 is generally applied. However, based on the ten wave spectra of potential port locations a factor of 1,2 is applied, because the Hs of 8,5 meter only occurs in one wave spectrum. The outer cylinders require a length of 22,8 meter, interpolating this to the middle cylinder, a maximum depth of 13,1 meter is required. So the average cylinder depth is at least 18,5 meter to prevent tilting of the bottom out of the water by a wave.

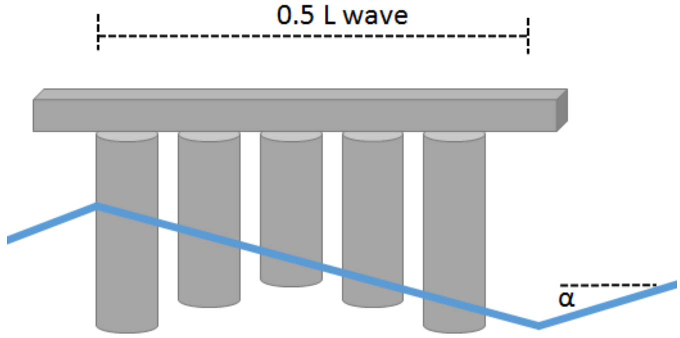


Figure 6.23: Schematic representation of an example of a PSS in a wave

Three assumptions are made to determine the amount of material required for the PSS. These assumptions form the base case, though they are varied to analyse the affect on the required air height within the cylinder.

- It is made from steel and the thickness is 20 mm. The draught will be larger as for the catamaran barge in paragraph 6.2.1 so the water pressure will be higher. Therefore, the steel thickness is increased from 15 mm to 20 mm. This leads to a fixed weight of the deck, which is 2830 ton.
- The diameter of the cylinder is fixed to 10 meter, though this is varied in table 6.10.
- The area on the bottom of the deck covered by cylinders is set to 70%.

The number of cylinders can be calculated based on the percentage covered by cylinders. When this is known, the lightweight of all cylinders can be determined. The load on the port, together with the deck weight and the weight of the cylinders form the total weight of the PSS. The air height required to handle this total weight is calculated by dividing the total weight by a multiplication of the number of cylinders, the dry air density above the sea 1,26 kg/m^3 and the surface area of one cylinder. With the air height and total load, the draught and total amount of buoyancy air can be determined. This applied method is summarised in figure 6.24.

Figure 6.24: Determination of required amount of material and air height

The enclosed air by the deck on the top side and the water on the bottom gives the PSS its buoyancy, the buoyancy from the submerged cylinders is small due to a thin steel plate. When constructed from concrete this buoyancy is higher, but the weight is also higher. The air pressure can be adjusted by air pumps because the dry air density above the sea is only 1,26 kg/m^3. With such a small density a lot of m^3 of air is needed. Due to the open bottom of the cylinder and the sea water that is present in the cylinder an increase of air pressure is very limited. The water pressure at the water line is 1 bar, equivalent to 101.325 Pascal. Every 10 meter of water depth the water pressure increases by 1 bar. When the air pressure exceeds the water pressure, the water depth in the cylinders is decreased. For example, increasing the air pressure by 0.1 bar lowers the water depth in the cylinder by 1 meter. The relation between air pressure increase and the density of air can be showed by Pascals principle and is as follows:

$$\rho = \frac{P}{R * T} \tag{17}$$

In which:
ρ = Density (kg/m^3)
P = Pressure (Pascal)
R = Gas constant (J/(K*kg))
T = Temperature (Kelvin)

Increasing the air pressure from one bar to two bar, leads to a density increase of 1,26 kg/m^3. The air pressure, covered percentage of the deck and diameter of the cylinders are varied to calculate if the PSS can handle the load of 12.600 ton. The results of this calculation are shown in table 6.10.

Table 6.10: Required cylinder length

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Covered (%)	70	70	70	95	95
Air density (ton/m^3)	0,00126	0,00252	0,0063	0,0063	0,0063
Depth cylinder (m)	19	19	19	19	19
Diameter (m)	10	10	10	10	15
Number of cylinders	87	87	87	160	71
Deck (ton)	2830	2830	2830	2830	2830
Cylinder (ton)	1007	1007	1007	1855	1236
Load (ton)	12600	12600	12600	12600	12600
Lightweight (ton)	3837	3837	3837	4685	4067
Air height (m)	1917	959	383	219	211

The required air height to handle the load, deck and cylinders is extremely high. In case 3, 4 and 5 the air pressure is five times higher as the atmospheric pressure. This could demand a thicker cylinder thickness than 20 mm, though this is not calculated. This also lowers the draught of the cylinders by 5 meter, whether this is troublesome is not calculated. The required air density to achieve a suitable air height within the cylinders is about 1 ton/m^3. This is equal to an air pressure of 1000 bar. After benchmarking the air pump industry it is concluded that this is no issue for the cylinders made from steel. However, cylinder length required is unrealistic high. Table 6.10 makes clear that the PSS has no potential as a port component for the construction of an offshore wind farm.

6.2.6 Jack-up barge

The jack-up can be moved to the project site by a self propelling system, towing or transported on top of a transport barge. The legs are set on the sea floor and the deck is jacked up on these legs above the waterline. The jack-up barge behaves like a fixed structure, which does not experience motion by the weather conditions. So a workability table that is based on the wave climate is irrelevant for the jack-up barge. The wind velocity that determines the workability of assembling the turbines is governing for the workability of the jack-up barge.
The bearing capacity of the soil can be used by two types of leg stabilisation. On soft floors an "A" mat support is connected to the bottom of each leg, ensuring that the leg does not punch through the sea floor [204]. In most cases spudcans are used for stability, this are cylindrically shaped steel shoes with pointed ends, similar to a cleat. Spudcans are attached to the bottom of each leg, the pointed ends are driven into the sea floor.

A jack-up design involves numerous choices regarding shape, dimension, amount of legs and other variables. The two most common operational jack ups are the jack up barge as shown in figure 3.5b, with legs made of huge steel tubes and a jack up rig as displayed in figure 6.25, with open-truss legs made of steel sections that are crisscrossed. This type of legs makes them more stable and more lightweight, but also more expensive. The jack-up rig is triangular shaped with three legs, where the jack-up barge is rectangular shaped and has four legs. This could be modified during design, but is an unaccustomed situation and is not preferred. As stated in paragraph 3.3.3 the operational water depth of a jack-up barge is 70 meter, for a jack-up rig this is 150 meter [32] [175].

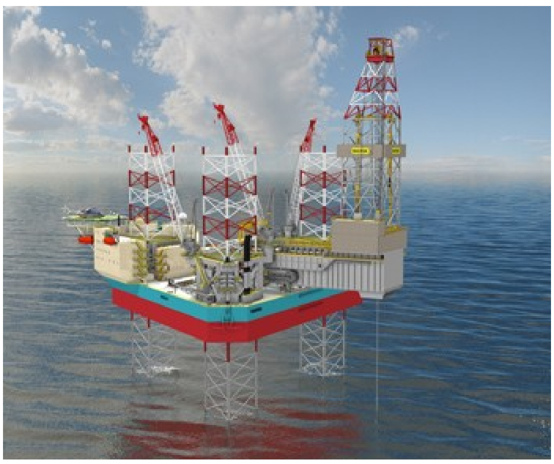


Figure 6.25: Jack-up rig for Norwegian drilling market [W13]

Jack-ups are used for the exploration and drilling in offshore oil and gas fields [204]. They are also used as service platforms and for installation of offshore turbines and the foundations, as can be seen in figure 3.5b. To function as a port component there are three possible construction methods:

- A jack-up is designed and constructed to function as an offshore port component.
- A jack-up that can be used in the offshore field but is not in operation, due to an overcapacity there are jack-ups not in operation. These jack-ups do not satisfy the current market demands for an installation vessel. This is mainly due to lifting capacity, but also sailing speed, deck area or other aspects could be the cause[28]. Also the quick changing offshore wind market, makes it hard for jack ups to adapt to the new demands. The jack-ups with low prospect for operations can be modified to function as an offshore port component.
- A depreciated jack-up that is planned for decommissioning, can be used as an offshore port component after intensive modifications.

The first and last bullet point account for most port components, but the second bullet point is only valid to the jack-ups. Just one jack-up type is taken into account as a port component. The average water depth for construction of an offshore wind farm, is approximately 35 to 40 meters by 2030 for the targeted market of the port concept, as can be seen in figure 2.6. Due to the unnecessary capability of high water depth operability, the construction of a jack-up rig is more difficult. It also has a lower mobility and less deck area, the jack up rig is therefore not taken into account as a potential port component. The rectangular shaped jack up barge with four legs is preferred and a visualisation of this is provided in figure 3.5b.

Jack-ups with a surface area of 17.500 m^2 have never been constructed. To apply the jack-up as a port component, the design has to be different to operational jack-ups. For example, this could lead to nine jack-up systems instead of four. An other opportunity is to apply two jack-up barges, or to combine the jack-up barge with an other port component.

A condition that has to be taken into account to determine the workability of the jack-up barge is the natural oscillation period. For a jack-up these are in the range between 2 to 8 seconds [101]. The eigenperiod of the jack-up barge has to be on the lower side of the wave spectrum to prevent oscillation. A jack-up with curved legs increases the lateral stiffness and this could be a possible solution to reduce the natural oscillation period [116]. Besides motion response, also failure of the jack-up barge can influence the workability.

Scour is a condition that could lead to failure of the jack-up barge, scour is the erosion of sediment around a structure. After pre-loading the steel tubes of the jack-up barge, these are fixed at a certain location throughout the project. To these steel tubes is commonly referred to as spudcans. The pre-loading process is the installation of the spudcans by vertical loading of the soil. During the project the spudcans can lead to vortex development and turbulence of the flow velocity.
During the first stage of design in a marine environment, a scour depth of one to two pile diameters is usually assumed [200]. For a jack-up barge this can lead to a scour depth between six and ten meter

[28] This was stated by interviewed companies and the experts that verified the day rates in chapter 7.

for each spudcan. When no mitigating measures are taken, instability and failure of the jack-up barge can be the result. Three preventive measures for scour are commonly applied for offshore bottom founded structures [207].

A possible mitigating measure is to place a sand or gravel bag adjacent to the spudcan after the pre-loading. The service life of sand bags at platforms in the North Sea is one to two years. This service life is sufficient for the jack-up barge when applied as a port component [207].
Another mitigating measure is to place loose rocks by a fall pipe vessel, this increases the stability of the sea bed around the spudcan. The influence of such a scour protection on the stability of the spudcan is displayed in figure 6.26. A third possibile mitigating measure can be executed prior to the arrival of the jack-up barge. Frond mats are placed on the locations of the spudcans, no additional mitigation measure is than demanded after pre-loading.

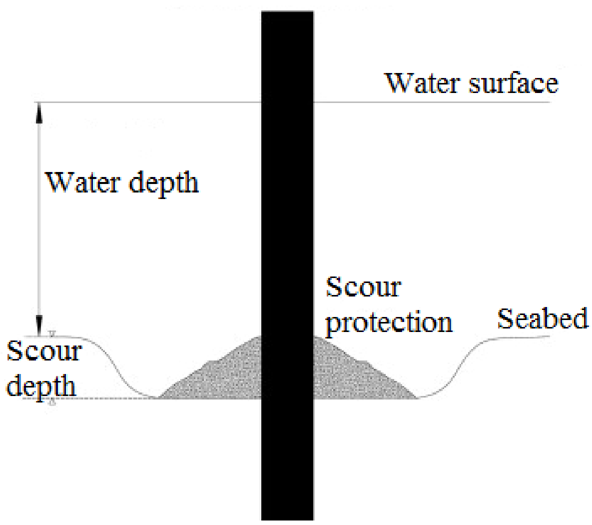


Figure 6.26: Rock protection adjacent to spudcan [208]

6.2.7 Jacket

A steel jacket structure is by far the most common kind of offshore structure that exists, when not considering a wind turbine foundation. The steel welded tubular pipes are pinned to the sea floor through pile guides on the lowest ends of the jacket, who fit in the pre installed pile foundation. An example of this installation is provided in appendix G.1. It can support up to two or three decks, which are separately installed by a heavy lift vessel. Jackets are generally used in shallow and medium water depths [196].

The jacket structure is chosen over other possible fixed structures. Three other structures are considered to function as a port component, but due to the following reasons they are less favorable and not taken into account.

- **Monopile:** A lot of piles are required to carry the load of the deck this increases the installation time. It is also a soil dependent structure which has a very low mobility. There are no offshore structures with a deck that is supported by multiple monopiles.
- **Gravity based:** The main advantage is that they are possible to be reused due to their floating capability. But the construction site requires a deep port and takes a longer period of time as

for the jackets. The natural frequency of the jacket is higher, which leads to an eigenperiod lower than of the gravity based structure and farther away from the wave spectrum. Though, the eigenperiod of the gravity based structure is also on the lower edge of the wave spectrum [101]. A more experienced problem with gravity based structures is the significant heave forces [214]. This geotechnical problem requires an extensive bottom preparation and due to its large weight it can cause soil erosion [31].

- **Guyed tower:** This is a vertical slender structure and used for deeper waters than jackets. It requires a difficult connection to the seabed and a lot of maintenance [31].

The constructed jackets range from very small structures supporting meteorological equipment, medium size applications in the offshore wind to large production platforms in the oil and gas industry. It should be noted that the costs of a jacket increases exponentially with the water depth [32] [196]. Although a jacket is appropriate for higher water depths than the average construction condition by 2030. It is dependent on the water depth. An intermediate jacket dimension is shown in figure 6.27. A visualisation of the guyed tower and gravity based structure is provided in appendix G.1.

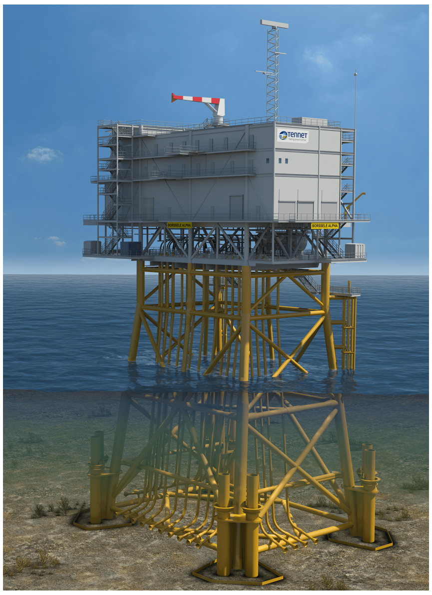


Figure 6.27: Jacket to support substation at Borssele wind farm [W18]

The maximum global loads on a jacket are based on two principles, the maximum base shear and the maximum overturning moment. The environmental wave loads are governing for both principles. Both principles determine the design of the jacket legs [68] [62]. To indicate the required size of the jacket to function as a single offshore port component, the weight of the jacket is calculated. An empirical, but functional relationship between the water depth (m) and the load on the deck (t), leads to the weight of the jacket (t) [106].

$$Weight = 12.8 * waterdepth^{0.19} * Load^{0.48} \tag{18}$$

In paragraph 6.2.1, the load is determined and the water depth used in equation 18 is 40 meters. This combination requires a minimal jacket weight of 2400 ton. This is in the higher range of jackets used as a platform for offshore substations [105]. It can be concluded that one jacket can fulfil the loads on the structure. However, the port also requires a certain surface area. According to TenneT, the substation of the DolWin alpha wind farm is the largest in the world. The substation has a length of 62 meter and a width of 43 meter, the corresponding jacket weights 3400 ton [56]. The design of a jacket that supports a surface are of approximately 133 x 133 meter is assumed to deviate from the one in figure 6.27. The weight of such a jacket requires a heavy lift vessel for installation, the lifting capability of a jack-up is to small.

6.2.8 Port component comparison

The previous paragraphs are summarised in table 6.11. An overview of advantages and disadvantages for each port component is shown, except for the PSS. The aspects listed in this table are relative between all the port components. When a port components has approximately an average value for a certain aspect, it is not displayed in the table. The aspect of mobility is considered low, when a port component can not be moved by its full extent. Or when an installation vessel is required for transport and installation. Some aspects are of more importance than others, though the port concepts are reviewed by all the nine elements listed below. Again, the costs are not taken into account. The primary interest is limited to a technical feasibility.

Manufacturing	Installation	Motion response
Mobility	Experimental	Deck area
Water depth	Soil dependency	Payload

Table 6.11: Advantages and disadvantages of several port components

	Port component	Advantage	Disadvantage
Floating	Barge	Large deck area Easy manufacturing	Low mobility
Floating	Semi-submersible	Mobile Large deck area	Sensible motion response Difficult manufacturing
Floating	VLCC	Mobile High payload	High motion response Deck area
Floating	Versabuoy	Low motion response	Low mobility Experimental technology Difficult installation
Fixed	Jack-up barge	Mobile Low motion response High payload	Water depth restriction Soil dependency Deck area
Fixed	Jacket	Low motion response High payload	Low mobility Water depth restriction

6.3 Port concepts that fulfil the demands

Based on the mobility, motion response and a rough cost indication the potential port concepts are determined. The scope of the research states that the port has to be transportable, so it can be used in multiple offshore wind farm projects. Section 5.2.3 showed that the motion response is the leading condition for a high workability, so therefore the port concept has to fulfil this condition. The third aspect is a rough cost indication, this is based on the cost price of similar structures. Since costs have only been taken into account by considering the amount of material required for the barge. An indication is made to increase the feasibility of the port concept. As stated in section 5.4, port concept can consists of one or two port components. Applying three port components are assumed to be technically and financially unfavorable.

Mobility

The barge, versabuoy and jacket have a low mobility according table 6.11. The barge is considered as one stiff structure, though it does consists of four smaller barges. These can be towed separately to a new offshore location. No lifting crane or expensive semi-submerged vessels are required, so the mobility is assumed sufficient.

A versabuoy does not require a lifting crane either. Though a semi-submersible vessel is required to float-off the deck and the hull. The hull is the yellow part of the construction in figure 6.28. The four legs are already moored in position when two barges arrive. They sail parallel with on top of them the hull and the deck [78]. An example is displayed in figure 6.28, though the versabuoy does not have the white claw, but it does have an additional deck on top. The semi-submerged barges or vessels lower the four connection point of the yellow structure on top of the stabilising legs. The versabuoy structure has to be transported separately from the four legs, though transport and installation costs can be reduced by using locally available semi-submersible vessels.

Figure 6.28: Versabar 10.000 ton lifting capacity [78]

A jacket required to satisfy the boundary condition concerning the minimum surface area, will be the largest constructed jacket in history. As explained in paragraph 6.2.7, the weight of the jacket can be lifted by a single heavy lift vessel. Day rates for heavy lift vessels are higher as for jack-ups. Regarding the objective of this research, applying a heavy lift vessel for the installation of an offshore port is undesired.

The barge requires a lot of sailing trips, though the day rates for corresponding barges are just a few thousand euros [2]. The versabuoy is not eliminated as a potential port component based on the mobility, though the mobility is low. It requires two semi-submerged barges and the mooring system is expected to be complicated after reviewing this concept by a few experts in the market.

Motion Response

The motion response of the barge, semi-submersible vessel and the VLCC are translated to the workability in the North Sea. Comparing these workabilities to a jack-up installation vessel, of which the jacking up an down is limited by a Hs of 2 meter[29]. The workability of the semi-submersible decreases the jack-up installation vessel workability by 2%, the VLCC decreases this workability by 4% of the sea states. The barge does not decrease the workability of the jack-up installation vessel.
The workability of the semi-submersible is 85%, for the VLCC this is 80%. But this 5% difference in the Nort Sea in combination with the 2% decrease of workability for the jack-up installation vessel, leads to a possible reduction of the revenues when selecting the VLCC as a port component. The boundary conditions that are related to this project, make the VLCC a less attractive port component in comparison to the other five. Therefore this port component is excluded as a potential port concept.

Capex

A rough estimation is made on the capital expenditures of the barge, semi-submersible, versabuoy and the jack-up barge. Because it is a rough estimation which can deviate a few factors, none of the four port components is disqualified. But the estimation can lead to an indication of possible port component combinations that are unfavorable regarding the capital expenditures. The cost estimation is based on the costs of the port component including two 1300 ton tub mounted cranes, since these cranes have a substantial influence on the CAPEX.

The construction costs of the operational Versabar 10.000 as shown in figure 6.28 were €100.000.000 [10]. An additional top deck and four stabilising legs are required to make the versabuoy. The white claw does not have to be constructed, but this is outweighed against two cranes that are demanded. The deck, stabilising legs and connector system are assumed to be as expensive as the existing versabar. So the total Capex are roughly estimated at €200.000.000.

Saipem 7000 is world's second largest semi submersible crane vessel after Thialf and is constructed in 1987. The Saipem 7000 has similar dimensions as the semi-submersible that is selected in this research and it already has two cranes of 7000 ton. The construction costs of the Saipem 7000 are estimated in the technical press as being up to $400.000.000 [130]. Due to the lower demanded crane capacity for the offshore port the CAPEX are estimated at $350.000.000

The larger jack-up barges in the market have a capital expenditure around €200.000.000[30] [36] [2]. The boundary condition of the surface area is 17.500m^2, there are no jack-up barges with this dimension. As explained in paragraph 6.2.6 a new design has to be made. This boundary condition is roughly estimated to increase the CAPEX to €300.000.000, including a second crane.
The fourth port component to indicate the CAPEX is the barge. A market analysis is conducted, but the CAPEX of operational large floating concrete structures are classified. A formula is proposed for very large floating concrete structures to estimate the construction costs [118]. It takes into account the volume of the barge and the percentage of the barge filled by prestressed reinforced concrete

[29] Based on the market interview responses

[30] Confirmed by the day rates of a jack-up barge reviewed in the next chapter when applying the offshore vessel rule of thumb: CAPEX = day rate * 1000. This rule of thumb is approximately similar to the result of an academic work with a charter period of one year [36].

material. This volume of concrete is multiplied by €500, for taking into account all direct costs of the barge and results in a direct cost of €18.000.000. Two additions have to be made to these direct costs to transform the barge to a port component. The first addition are the mechanical, electrical and accommodation costs. The construction costs are generally multiplied by a factor 1.3 to include these direct costs [9]. A second addition to the direct costs are the two cranes of 1300 ton to the CAPEX, the additional costs for this are €20.000.000[31].
This approach does not integrate the indirect costs and uplift costs for construction. A simple estimate to determine the total construction costs is multiplying the direct costs by a factor range between 1.3 and 1.4 [9]. For this project a factor of 1.4 is applied. In appendix H.10 the enumeration of the indirect and uplift costs that lead to a 40% increase of the direct costs is presented. The total construction costs are estimated at €45.000.000. The results of the rough cost estimation are summarised in table 6.12.

Table 6.12: Rough cost estimate of the four individual port components

	Barge	Semi-submersible	Versabuoy	Jack-up barge
Construction costs (million euro)	45	350	200	300

Table 6.12 shows the aimed result of the rough cost indication. A combination among the semi-submersible or versabuoy or jack-up barge is undesired. The barge can be combined with the other three port components since the indicated costs is in the order of 5 times lower. The potential port concepts are indicated by a green cell in table 6.13, the red cells are based on the cost estimate and are unfavorable. The result of this section are seven potential port concepts.

Table 6.13: Potential port concepts

	Barge	Semi-submersible	Versabuoy	Jack-up barge
Barge	green	green	green	green
Semi-submersible	grey	green	red	red
Versabuoy	grey	grey	green	red
Jack-up barge	grey	grey	grey	green

6.4 Selected port concepts

The seven port concepts in table 6.13 are interesting to analyse into more detail. Though the combination of a barge and versabuoy seems technically more challenging than other combinations. Due to a lack of time in this research the seven port concepts are narrowed down to fewer port concepts. These concepts are analysed in chapter 8 to determine the CAPEX, OPEX and revenues. A multi criteria analyses, a cost benefit analysis or other analyses could be used to narrowing down to fewer port concepts. This requires more information about the seven port concepts and this is not feasible within this research. Based on the CAPEX and based on the potential workability of the port, two

[31] A construction company provided CAPEX values for three tub mounted cranes. This type of crane can be seen in figures 3.5b and 6.29.

port concepts are most interesting according the researcher.

The first selected concept is the barge, this option is mainly interesting due to the low construction costs and large deck area. The second port concept is the single jack-up barge. It has a low motion response because it is a fixed structure. But an additional argumentation to select the jack-up barge is the interesting challenge to construct a jack-up with a surface area of 17.500 m^2. This is equivalent to a length and width of 133 x 133 meter. There are several interesting options like: using the overcapacity in the market by combining two jack-ups that are low demanded by the market. Another possibility is to design a single jack-up barge, based on the developed knowledge about the jack-up barge technique. A visualisation as in figure 6.29 could be a possible result, the figure is not to scale.

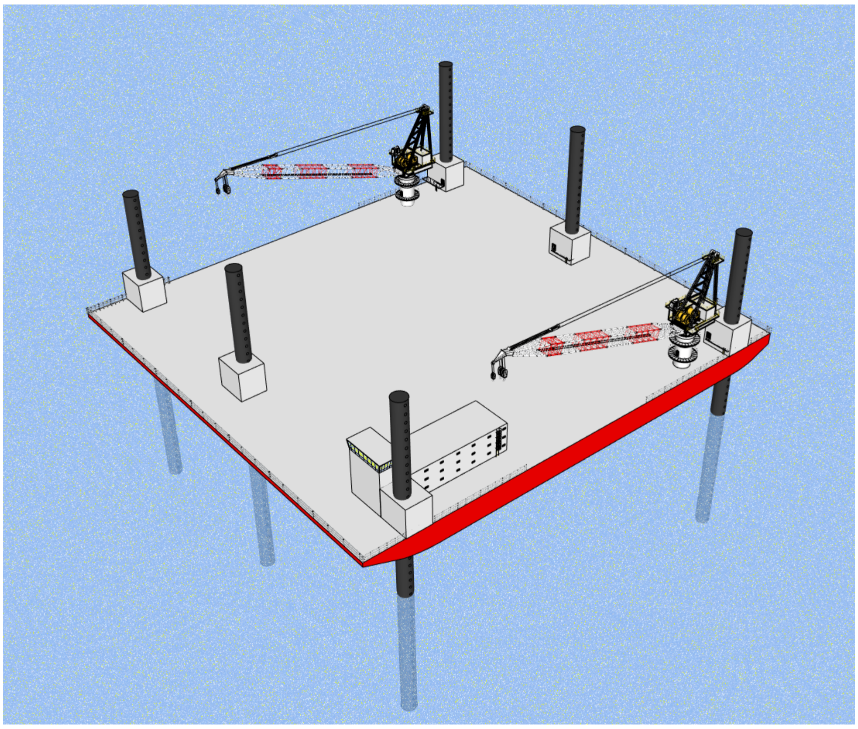


Figure 6.29: Jack-up barge port concept impression

One crane is required for unloading the feeder vessel and a second crane for assembling the turbines. Just one quay wall is required, this is elaborated in the next chapter. The radius of the crane has a large influence on the lifting capacity. The assembling crane is also required to lift a blade to its storage rack, so the storage should be such that the radius is minimised. The affect of the radius on the lifting capacity is explained in appendix G.5. Because blades are stored in a rack, these can not be lifted into the rack by a vehicle.
When the cranes are placed on a single barge, the motion response of the barge decreases. Although modelling the barge without cranes provide a workability of 92%, a lower percentage is unfavorable. For the single barge the two cranes are placed at opposite sides and at the two other edges a contrary weight is placed like the accommodation or storage, so the loads are symmetrical divided. A possible layout can be seen in figure 6.30. Despite that the single barge is a high potential concept as can be seen in the advantages and disadvantages table above, a small jack-up barge is added to this port component as a third port concept. Possible dimensions of the jack-up barge could be a length of 50 meter and a width of 20 meter.

The activities conducted by the crane are the most critical to waves of all potential activities on the port. This limitation of the barge is removed by placing the two cranes on a small jack-up barge, however, this makes it difficult to place the blades in the storage rack. So a possibility is to integrate a third crane for this port concept. There are a lot of designs possible, in figure 6.31 just one alternative is presented with one crane on the jack-up barge and one crane on the barge and an automatic guided vehicle (AGV) which functions as a trailer. A lot of aspects have to be taken into account for these decisions, for example the determination of the quay length.

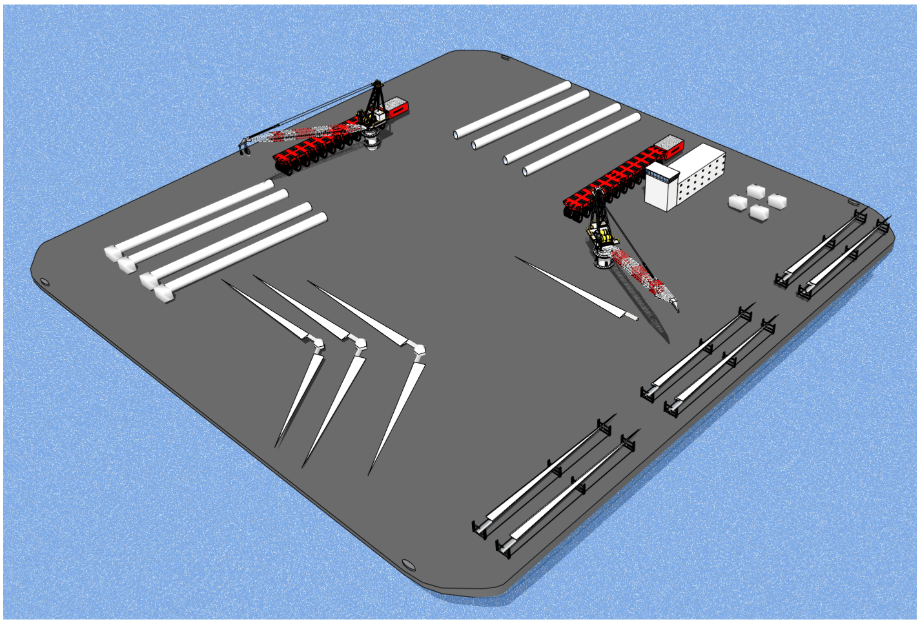


Figure 6.30: Single barge concept impression

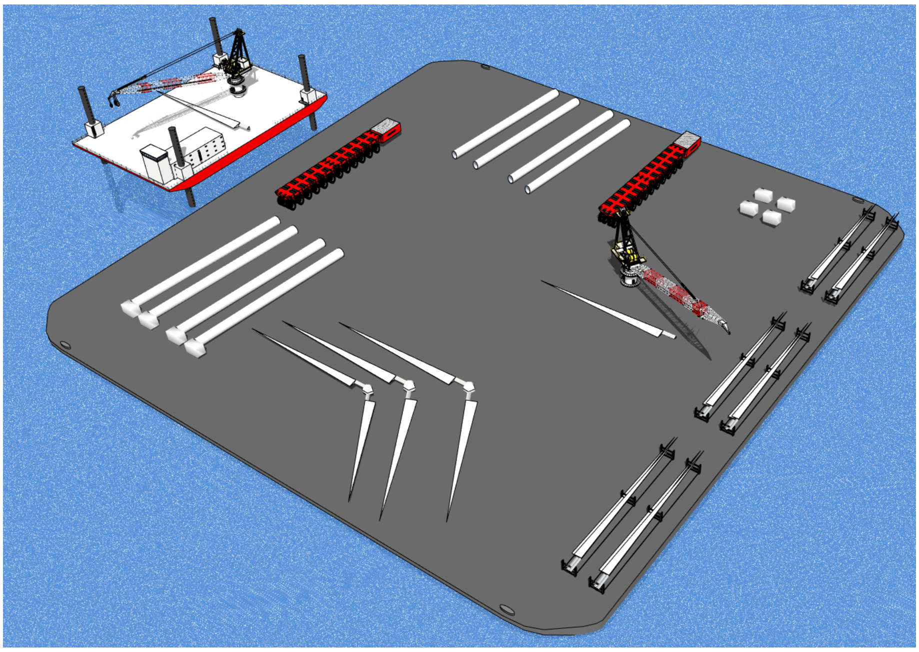


Figure 6.31: Barge and jack-up barge concept impression

6.5 Port concept conclusion

Seven port components that suit the environmental conditions of an offshore wind farm construction by 2030 were analysed in this chapter. Six of them worked out to be a potential port component, the PSS was excluded due to the limited buoyancy. The motion response simulation for a Jonswap spectrum showed that the workability of the barge 92%, for the sem-submersible 85% and for the VLCC this is 80%. Based on mobility and the motion response, there are seven potential port concepts. The researcher is most interested in the financial potential of a single barge, a single jack-up and of the combination between a barge and a small jack-up. This is elaborated in chapter 8.

7. Saving potential

When the costs of a new port concept are lower than the potential savings of the new port concept, the feasibility increases. The port concept could fulfil multiple demands, of which the shorter rental period of the installation vessel has the highest priority. Multiple logistical variations to install turbines are compared with each other, to analyse the potential savings of a new port concept. In section 7.1 the logistical model that is developed to compare the savings is explained. Section 7.2 describes the logistical concepts that are compared and section 7.3 shows the potential of each logistical concept. Sections I.4 and 7.4 elaborate on the assumptions of the logistical model and sections 7.6 and 7.7 indicate the opportunities within the offshore wind market. The chapter is summarised in section 7.8.

7.1 Logistical model

The potential savings on the installation vessel, can be determined by the difference in transport and installation costs between the new port concept and the reference case. The vessel chartering costs contribute the biggest portion to the logistics and installation costs, as stated in section 3.3. An offshore port provides the opportunity to use an installation vessel with a lower day rate[32]. This can decrease the transport and installation costs, but nevertheless, still a certain type of installation vessel is required for the installation. As explained in section 1.2, the day rate mainly depends on the deck area and carrying capacity.

When the installation vessel only sails between the offshore wind farm and the offshore port, the sailing distance is short and the deck area and carrying capacity can be decreased. This is because the requirement of carrying multiple turbines to be cost effective and flexible is weaker in such a scenario. The maximum sailing speed of the vessel also affects the day rate. With a small sailing distance the influence of a high sailing speed is negligible on the installation time, so the maximum sailing speed of the installation vessel can be small.

A new port concept could also decrease the rental period. When the total period of construction is smaller, energy can be generated sooner and electricity profits can be gained. Although, the decline of the wind farm is achieved at an earlier stage the present value of money is worth more than the future value of money.

When the day rate is multiplied by the rental period, the vessel chartering costs can be calculated. A lower day rate and a lower rental period strengthens the potential of a new port concept.

Only OWECOP and ECN Install are available as an installation planning and optimisation tool within in the market, in which the ECN Install tool is the successor of OWECOP [7]. The ECN Install tool is provided for this research by Vuyk and is used in section 7.4. However, activities of interest at the offshore port can not be added to this tool. So a model is developed and there are three main reasons why this model is required:

- **Comparisons:** The offshore transport and installation costs are compared between the several logistical concepts. An additional comparison of the logistical concepts concerns the installation period. The faster a project is finished, the sooner energy can be generated.

[32] The SPS design code could be shifted to a MODU design code, since it becomes primarily an elevation ship. However this effect on the day rate is limited according a senior specialist within the market.

- **Activity analyses:** All activities of interest can be analysed. Activities can be added or eliminated from the logistical model to understand the effect of them on the costs and the installation period. The most important activity in the logistical model is the amount of turbines that are present at the offshore port throughout time. This indicates if the boundary condition corresponding to the minimum surface area is correct.

- **Sensitivity parameters:** In section 8.7 analyses are conducted to show the potential of the port concept in several and deviating market conditions. Parameters like: distance to shore, turbine capacity and day rate are varied to see the effect on the saving potential of a new logistical concept.

7.1.1 Simulation model

The model takes the offshore transport and the installation processes into account. Energy generation profits by a shorter construction period is not included in this chapter, this is elaborated in section 8.4. The logistical model is computed in Microsoft Excel, a spreadsheet program. Each individual logistical concept is optimised, this is based on the total costs versus the carrying capacity and sailing speed. A logistical concept is taken into account when there is a clear logistical difference from the other concepts. Possible deviations within a logistical concept are discussed, but only the one with most potential is taken into account. The logistical concepts are described in paragraph 7.2.

Each offshore wind farm project deviates from previous projects, the site conditions, planned capacity, vessels used and many other aspects are project specific. However, a generalisation of a plausible future offshore wind farm project is modeled based on figure 2.6. The market conditions used from this figure are favorable for the port concept and more elaborated in paragraph 7.1.2.
The installation vessel is a jack-up vessel when it has to sail from the onshore port to the offshore wind farm. When the installation vessel does not have to sail all the way to the onshore port, a jack-up barge is used in the model since this is a cheaper alternative. The difference between these installation vessels can be seen in figure 3.5. By 2030, the jack-up will still install the turbines, since they can cope with the constructional water depths in figure 2.6. There is no demand which requires to adjust the construction of the foundation by a new port concept, so heavy lift vessels are not used in the simulation model.

The simulation model is based on a continues use of the installation vessel, because this is the most expensive share of the transport and installation. This is a boundary condition of the logistic model. The set-up of the simulation model is explained by the logistical concept of one fast feeder vessel jack-up vessel, it supplies the offshore port turbine components. This is equivalent to logistical concept number two in section 7.2. A simplified version of this model is presented by a flowchart in appendix I.1. It shows the determination of the transport and installation costs.

The feeder vessel has no crane, this has a positive affect on the sailing speed and day rate of the vessel. At the offshore port one lifting crane, one assembling crane and two trailers are available for transit to and from the storage area and the assemble process. A jack-up barge loads the assembled turbine components at the offshore port, to execute the installation. From the start moment of loading the jack-up barge, until the feeder vessel is finished with its last unloading, the transport and the installation processes take place a 100% parallel.

In the remaining of this chapter, the abbreviation for a jack-up barge (JUB) is used. The rental period is calculated by multiplying the total cycle time by the amount of cycles. The cycle times are as follows:

Feeder vessel net cycle time: loading + sailing away + unloading + sailing back
Feeder vessel total cycle time: net cycle time + delay by Hs limitation + 10% margin

JUB net cycle time: loading + sailing away+ installation + sailing back
JUB total cycle time: net cycle time + delay by Hs limitation + 10% margin

Within the total cycle time of the feeder vessel, two occurrences are of specific relevance. To these two occurrences is referred as occurrence A and B. The same holds for the total cycle time of the JUB, though to these occurrences is referred to as C and D. These occurrences determine the costs for the feeder vessel;, offshore port and JUB, but also the amount of turbines at the offshore port. The four letters represent the following:

A: Departure of the feeder vessel at onshore port when fully loaded
B: Arrival of the feeder vessel at offshore port
C: Departure of the JUB at offshore port when fully loaded
D: Commissioning of a turbine by the JUB

The maximum amount of turbines that can be stored at the offshore port is set to five according the boundary conditions number two and three for the design of the offshore port as stated in paragraph 5.4. There is an additional boundary condition for the logistic model , the installation vessel has to operate continuously since it has a high day rate. To achieve this boundary condition, the storage of turbines at the offshore port should be at least one during the entire installation process.
The storage could become zero when the cycle time of the installation vessel is lower or equal to the cycle time of the feeder vessel. The percentage of days without a turbine stored at the offshore port is an output parameter for each logistical concept. The two boundary conditions of the logistical model are summarised:

The installation vessel is continuously active and the maximum amount of turbines present at the offshore port is five.

The results of the logistical model depend on the input parameters and on the assumptions made. There are also a few limitations that come along with the model, these three aspects are described in the next paragraph.

7.1.2 Assumptions logistical model

The logistical models are compared relatively to each other, since they use the same input values and are based on similar assumptions. Though the more accurate the input values are, the more practical contribution the most potential logistical concept has. The input values and assumptions made lead to the base case of this research. In section 8.7, these values and assumptions can be adjusted to understand the effect on the results.
The values were initially determined by reviewing literature and the knowledge gained during the in-

terviews. These determined values are verified by multiple experts, in multiple areas of expertise of offshore wind farm projects. The input parameters that have a substantial influence on the results are listed in the paragraph below. These are explained into more detail in appendix I.2, in this appendix also minor influential input parameters are presented.

The capacity of the wind farm is set to 1.2 GW, there are currently wind farms under construction with a similar capacity so this is a conservative value. The wind farm consist of 100 wind turbines, so a single turbine has a capacity of 12 MW. The day rates of the vessels depend on the carrying capacity, lifting capacity and maximum sailing speed. The distance to shore is 175 kilometer and the wave heights the vessels can work in are limited by four activities and this limitation is as follows:

Table 7.1: Workability Hs of vessels

	Sailing	(Un)loading	Jacking up and down
Feeder vessel (m)	2.5	1.5	
Installation vessel (m)	3	2	2
Barge (m)	2	1	

In order to reduce the complexity of the logistical simulation model to be developed, a number of simplifying assumptions is made. Assumptions that are known to have a large influence on the output are listed below, minor assumptions are elaborated in appendix I.3.

- All onshore and offshore costs for transport and installation of the turbines are taken into account by the model. Although the CAPEX of the crane for unloading of the feeder and of the crane for assembling the turbines at the offshore port are not included. Also the CAPEX of the offshore port and the offshore trailers are not included. So when a new logistical model saves 10 million per project and it is used in 20 projects, the savings are 200 million. This is the available amount of money for the offshore port structure and corresponding equipment.
- The feeder vessel has no lifting capacity. Regarding the sailing speed it is more favorable to have an unloading crane at the offshore port and not on the feeder vessel.
- When between arrival and departure at the offshore port the Hs is larger than 1.5 meter, unloading is not feasible for the feeder vessel. The amount of hours in which unloading is not feasible is multiplied by 1,5, as explained in appendix I.3. When the feeder is capable of jacking up and down, the day rate increases. After an iteration it is concluded to save more money when the feeder vessel is not capable of, than having a jacking capability and use it in time saving situations.
- A 10% margin is included within the cycle time for transport and a 10% margin is included for the installation. This is due to three reasons: the weather can be worse than the used weather data, a technical failure can occur and a logistical failure can result in a delay. So it is assumed that the weather data in combination with technical or logistical failures is 90% similar or better than assumed.
- There is one quay, constructing two quays is assumed to be more expensive than the waiting hours of the feeder vessel. When the installation vessel is planned to load the turbine components, the

feeder vessel has to wait. For the installation of 100 turbines, this situation occurs approximately 4 to 8 times. This corresponds to 100 arrivals of the feeder and 100 departures of the installation vessel.

- When there is an offshore port in the logistical model, the degree of assembling is similar as to the onshore assembling in the reference case.
- The transport process starts at the first of February, this date is based on an average weather condition throughout the lifetime of the port. An average of the total costs for various starting dates is achieved by starting on the first of February. This is elaborated in appendix I.4.

7.1.3 Limitations logistical model

The Excel spreadsheets include some limitations, in order for the model not to become too large, resulting in a high complexity and simulation time. Three limitations are applied and these are explained in the listed bullet points below.

- The significant wave height is used as the weather restriction, however for installation of the turbine after the jacking process, the wind speed is the limiting condition. This is not taken into account in the model, though this could be integrated when demanded.
- The sailing speed can be modified before the simulation is ran. During the simulation the sailing speed of the vessels can not be adjusted to optimise the logistical process and react on weather delays or storage space occupied.
- The start of a new cycle of a vessel is matched to the corresponding hour of the entire process duration. This is used to determine the rental period. However, in the model the hours of the cycle time are rounded, which creates a small measurement error in the rental period of the vessels.

7.1.4 Finding the optimum

A logistical concept has to satisfy the two logistical boundary conditions. When this is fulfilled, a minimum value for the total costs of the logistical concept can be determined. This is achieved by varying three parameters. The sailing speed an carrying capacity can be varied for each logistical concept and when there is a second vessel present in the concept, the start date of this second vessel can be varied as well. The total costs of a project consist of two aspects, the costs that are taken into account by the model as explained in paragraph 7.1.2 and the project duration.

Independent of the project duration, the depreciation days for the wind turbines are similar, because the manufacturing, transport and installation have a fine tuned interdependency. So although a project is finished sooner, the turbines will not generate more energy. However, during the days in the year 2030 that the construction of a project is finished sooner, energy can be generated and because the value of money can increase in time profits can be made. This aspect is explained by an example of the logistical concept of the reference case.

Lets assume the project is finished 10 days sooner when the sailing speed of the jack-up vessel is increased by 3 kilometers per hour. Because the first turbine is installed at approximately a similar moment, the average turbine of the wind farm is installed 5 days in advanced by increasing the sailing speed. Considering the trend of the LCOE as shown in section 3.4, offshore wind is forecasted by Windeurope to have a price of 4.5 eurocent/kWh by 2030 [210]. The efficiency of a turbine is included in this LCOE. Taking into account the base case wind farm as explained in the previous paragraphs, the wind farm has a capacity of 1.2 GW. This leads to 6.5 million euro of energy that is generated in these 5 days.

The lifetime of a wind turbine and a wind farm is 20 years [171] [134]. The earlier depreciation of the logistical concept with a faster jack-up vessel, produces the last 5 days of the life time 5 million euro of energy. This is based on a LCOE of 3.5 eurocent/kWh by 2050. The present value of the energy generated in 2030 is 6.5 million euro. The present value of the 5 million euro of generated energy in 2050 is calculated by equation 19 [16].

$$PV = \frac{FV}{(1+R)^t} \tag{19}$$

In which:
FV = Value in year t
PV = Present value
R = Discount rate
t = Number of years ahead

The assumed discount rate for the logistical model is 5,5%, this corresponds to the discount rate prescribed by the Dutch government for most projects [205]. Applying equation 19 provides a present value of 1.7 million in the year 2030. The shorter duration of the fast jack-up vessel provides a potential saving for the offshore wind farm of 4.8 million euro. For each day that the project is finished sooner, the profit increases by 480.000 euro.

However, the 480.000 euro profit per day is based on the assumption of no additional barriers for a shorter project duration. In practice the supply of partly pre-assembled turbines at the onshore port, availability of vessels, higher costs for downtime and other conditions make it inconvenient to assume a 100% energy profit by a shorter project duration. Therefore a factor of 0,5 is applied to these potential energy profits. The sensitivity of this factor is elaborated in paragraph 7.2.1. The three parameters that are varied, can determine the optimum based on the costs of the project that are taken into account by the model and the energy profit per day of 240.000 euro for a shorter project duration.

The optimum value of the logistical concept equivalent to the reference case described in section 3.3, is determined by the lowest total costs. The total costs include an iteration of the costs of the project minus the loss or gain of potential energy profit per day of delay or shortening.
The shorter or longer duration of the other logistical concepts is compared to the project duration of the reference case. The calculation of the total cost of these concepts does not require an iteration.

7.2 Logistical concepts

Four logistical concepts are compared to analyse the potential of an offshore port concept. The concepts are elaborated in the next paragraphs and the final result is presented in figure 7.5. There is a clear logistical distinction between these four concepts. Within a logistical concept many alternatives are considered, but only the most competitive regarding the total costs is taken into account. There

is a fifth logistical concept that could be investigated in the future, but due to time limitations this is not performed within this research. This fifth concept consist of two jack-up vessels that sail back and forth, similar as to the logistical concept number one in figure 7.1.
The wind farm conditions are similar for all logistical concepts, these are described in the previous paragraphs and form the base case. Figure 7.1 is a visualisation of the concepts, in this consecutive order they are described in the next paragraphs.

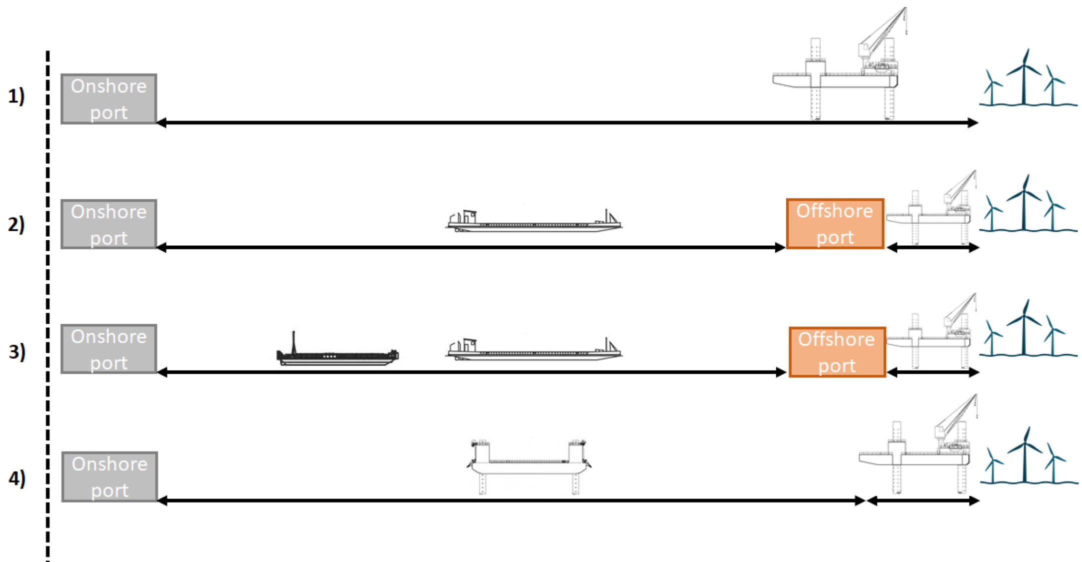


Figure 7.1: The four computed logistical concepts (not to scale)

7.2.1 Jack-up vessel for transport and installation

This concept is equivalent to the description in section 3.3. A JUV sails back and forth to the project site to install the turbines. Although the majority of the time is spent on installation, there is no feeder vessel and the sailing distances are long. Therefore a JUV is applied instead of a JUB, this is similar as to the reference construction case. The turbines are pre-assembled at the onshore port before they are loaded. After the pre-assembling the turbine consist of a tower, a bunny ear and a separate blade.

The carrying capacity and the sailing speed of the JUV is varied to optimise this logistical concept. The optimal amount of turbines is based on the least expensive project. Carrying one turbine leads to the longest project duration, the energy profit of the other carrying capacities is compared to the project duration when carrying one turbine. The total costs are calculated by subtracting this energy profit from the costs of the project. It can be seen in the fourth column of table 7.2, that carrying two turbines is the optimised scenario for the reference case. This is achieved by a sailing speed of 26 km/h.
Although it should be emphasized that the potential of carrying two or three turbines is approximately equal. The day rate is an influential parameter for the total costs and the day rate relies on the carrying capacity. Therefore, the largest amount of turbines does not have the lowest total costs.

The output results are presented in section 7.3 and the sensitivity of adjusting parameters like the limiting Hs, day rate or distance to shore is shown in section 8.7. To gain more insight in the logistical concept and the corresponding results, a graph is created showing the location of the turbines in time.

Table 7.2: Determination of amount of turbines carried

Number of turbines	Installation days	Energy profit (€ Million)	Total costs (€ Million)
1	218	0	39.1
2	170	11.5	30.6
3	152	15.8	31.0
4	144	17.8	34.3

This is displayed in figure 7.2. The blue line indicates the amount of turbines at the onshore port over time. As explained in appendix I.1, the amount of turbines onshore at the start of the model is equal to the total amount of turbines to be installed. In practice, the amount of turbines onshore are supplied to the onshore port throughout the process.

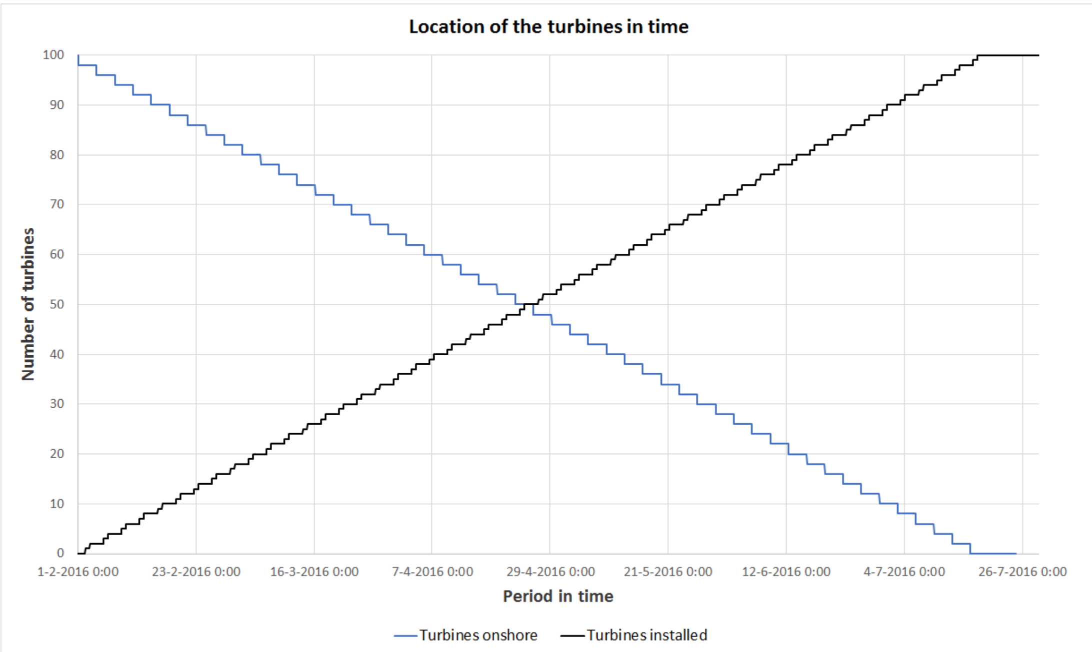


Figure 7.2: Logistic result of turbines for the reference case

Sensitivity energy generation

As explained in paragraph 7.1.4, the energy profit per day for a shorter duration of the project is assumed to be 50%. The influence of this assumption is visible in figure 7.3. The energy profit factor is varied between 0.3 and 0.7 and the result in total costs of the project is only 10%.

Adjusting the sailing speed and carrying capacity has a linear influence on the day rate. To find the lowest total costs also the energy profit is included, this has a linear influence on the total costs as well. However, the influence of the energy profit factor is larger than the influence of the day rate on the total costs. The small influence can be explained by the slow decrease of the project duration by adjusting the sailing speed and carrying capacity. But the variation of these two parameters results in a higher day rate.

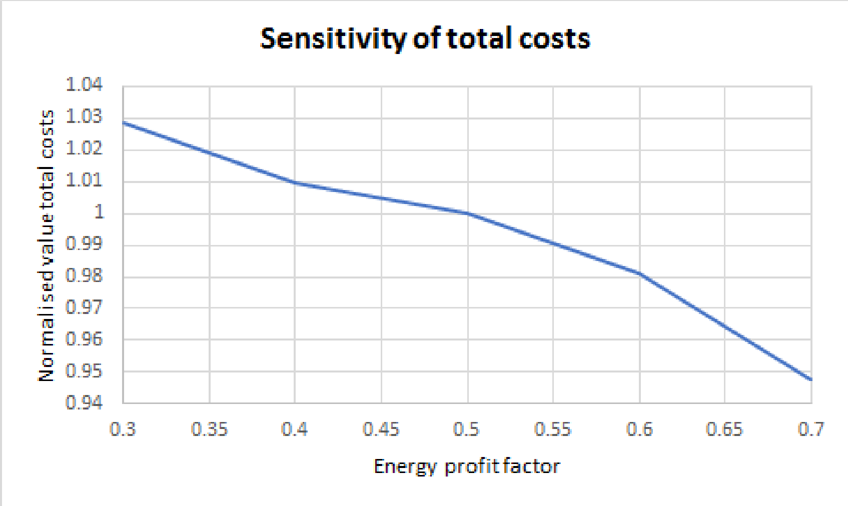


Figure 7.3: Sensitivity of energy profit factor for a shorter project duration

7.2.2 Transport to offshore port by a feeder

The feeder vessel supplies the offshore port with three separate blades, a nacelle with hub and separate sections of a tower. The nacelle and hub are assembled onshore because it saves costs and there is no potential space saving on the feeder vessel when assembling them offshore. A lifting crane places the components on the trailers and the pre-assembling process starts. When this is finished, the partly pre-assembled turbine is stored near the quay wall and loaded by the JUB.

When the JUB installs two turbines in a cycle, the feeder vessel also has to carry two turbines. This increases the day rate, while the reduction of the process duration is only four days. Another advantage of sailing with just one turbine is that the maximum amount of turbines stored does not exceed five so the boundary condition is satisfied. This is impossible when there are two turbines transported, unless the feeder vessel sails very slow which leads to a high rental period.

The remaining two parameters to modify for an optimisation are the sailing speed and start date of the JUB. The maximum storage of five turbines has to be satisfied so a trade off between the total costs and a low occurrence of no turbine present at the offshore port has to be made. The optimised result is a start date of the JUB, after a storage of four turbines at the offshore port. The input and output results of this logistical model can be found in figure 7.5. A visualisation of the logistical result can be found in appendix I.5.

7.2.3 Transport to offshore port by a feeder and a barge

This logistical concept is similar to the previous one, though there is a barge integrated in the supply chain. For the feeder barge and the fast feeder, the optimised amount of turbines transported in each cycle is one. Because carrying two turbines by the barge or applying a faster feeder vessel exceeds the boundary condition of a maximum of five turbines stored offshore.

The sailing speed and start dates of the feeder barge and the installation vessel are varied to achieve the lowest total costs and shortest installation period. As a result the loading of the barge starts when the fast feeder leaves the onshore port. The JUB starts with the installation when the fast feeder leaves the offshore port for the second time. The sailing speeds can be seen in figure 7.5 and the logistical result of this concept is shown in figure 7.4.

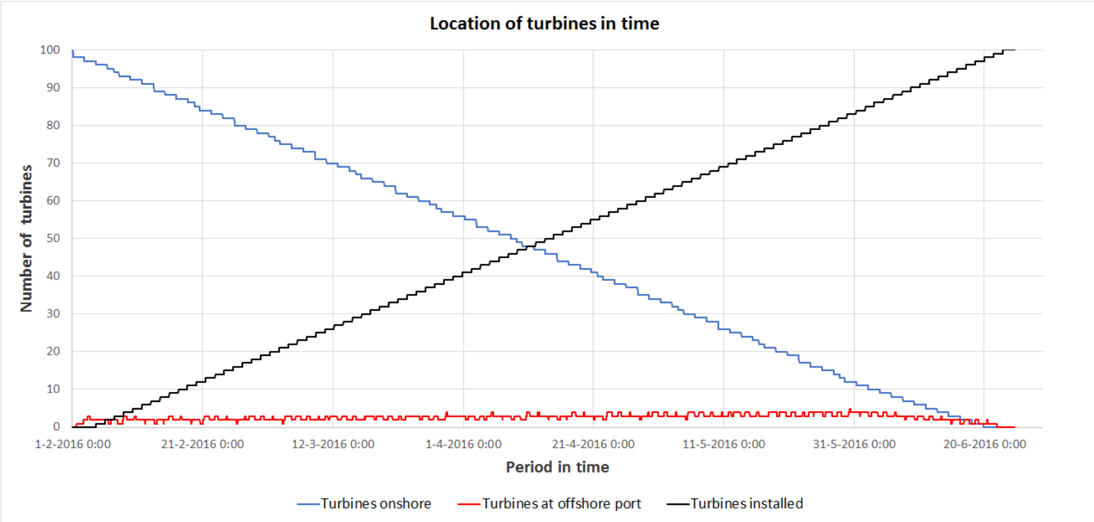


Figure 7.4: Logistical result of the turbines in time for fast feeder and barge concept

7.2.4 Offshore transfer between jack-ups

This logistical concept does not use an offshore port, but the JUB unloads the JUV which sails to the offshore wind farm. Within this logistical strategy, two concepts are analysed. The first concept is as shown in figure 4.1a, a JUV sails to the offshore wind farm and jacks down next to the JUB. The JUB unloads the JUV and directly installs the assembled turbine components. The JUV does not have a lift capacity. This concept requires two JUV, because otherwise the JUB has to wait until the JUV returns after the installation of the turbine. This logistical concept is more expensive as the other concept, because it requires two JUV.

The second concept is a JUV that loads the pre-assembled turbine components at the onshore port and after sailing to the offshore wind farm, it transfers them offshore to the installation JUB. The JUB sails to the wind turbine location for installation and the JUV sails back to the onshore port. This concept only requires one JUV and is therefore selected. The JUV does not have a crane, so a high sailing speed is possible and costs are saved. Within the model the cycle times are equalised by modifying the sailing speed of the JUV, since the cycle time of the JUB is approximately fixed. The cheapest logistical concept is to transfer the turbines close to the offshore port. An optimised input parameter is that both vessels can carry the components of two turbines. In practice this logistical concept will have a different meeting point for each single cycle. The logistical result is visualised in appendix I.5.

7.3 Logistical saving

The most important input and output parameters of the logistical model are presented in figure 7.5. It shows the saving potential of the three new logistical concepts in relation to the reference case, which is presented in the fourth column. The costs for the offshore port structure and corresponding equipment and labour is not included. Therefore, the savings can be considered as availability for investment of the offshore port.
The potential logistical savings are more than 50% within the transport and installation of the turbine. This is based on no costs for the offshore port. The total costs for the transport and installation is lowest for the transport by a fast feeder. An offshore port can reduce the transport and installation time by nearly 20% in comparison to the reference case and the total vessel costs are reduced by

nearly 50% in comparison to the reference case. This chapter clearly shows a potential for the offshore port as a new solution for the installation of offshore turbines. Whether this potential is high enough to be a feasible solution will be determined in the next chapter. The logistical solution of a fast feeder and an installation JUB is the guiding concept for the remaining of this research. The logistical results are in line with the single research that considered the potential of an offshore port [46].

	Parameter	Unit	Concept			
			One JUV for transport and installation	Transport by a fast feeder, installation by a JUB	Transport by a feeder and a barge, installation by a JUB	A JUV for transport and a JUB for installation
Input	Feeder carrying capacity	Ton	3428	1814	1814	3428
	Barge carrying capacity	Ton	-	-	1614	-
	JUB carrying capacity	Ton	-	1614	1614	3228
	Feeder sailing speed	Km/h	26	26	21	12,3
	Barge sailing speed	Km/h	-	-	7	-
	JUB sailing speed	Km/h	-	9	10	11
Output	Installation period per turbine	Days	**1,7**	**1,45**	**1,44**	**1,74**
	Feeder rental	Days	170	144	142	173
	Barge rental	Days	-	-	124	-
	JUB rental	Days	-	139	141	173
	Day rate all vessels	€1000/day	159	177	107	100
	Vessel costs	€Million/project	**28,1**	**14,8**	**15,8**	**32,3**
	Costs	€Million/project	**42,1**	**25,1**	**28,1**	**41,4**
	Energy profit	€Million/project	0	6,00	6,2	-1,0
	Total costs	€Million/project	**42,1**	**19,1**	**21,9**	**42,3**
	Days without turbine for JUB	%	-	1,1	0,0	-
	Max number of turbines at offshore port	-	-	5	5	-
	Savings	**€Million/project**	0	23,0	20,2	-0,2

Figure 7.5: Potential of three new logistical concepts

The lifting capacity of the installation vessel is not included, since this is similar for all the installation vessels and corresponds to the heaviest component to be installed. In the base case provided in figure 7.5 this is the tower, in the next chapter this could be varied depending on the degree of assembling. The total amount of installation days is equal to 100 times the installation period per turbine.
An elaborating note is made concerning the results of the last column in figure 7.5. The offshore transfer seems approximately as favorable as the reference case in column four. This is because the distance to shore is larger than currently operational and the offshore transfer concept is streamlined within the model. While this logistical concept has never been conducted, so possibilities of high delays are present.
The maintenance and risk of failure of the vessel is not included in the logistical model, this is lower for the reference case because it uses only one vessel. Since the difference between column four and column seven is small, the offshore transfer is not preferred as a logistical concept over the reference case.

7.4 Model validation

The ECN Install tool 2.1 is a software that can simulate the installation of an offshore wind farm and is available on the market. However, there are same drawbacks for this tool and that is why a logistical model is developed within this research. The main drawback is the unavailability of an interdependency between steps in the process. For example, the installation vessel and the feeder vessel have no interdependency. However, the ECN Install tool 3.0 does includes this interdependency, but this tool is only available on the market by October 2018. Other disadvantages are the impossibility of adding activities and monitoring the location of the turbines during the installation.

The ECN Install tool 2.1 can still be a valuable contribution to this research. Although it can not simulate the installation that includes an offshore port, it can simulate the installation of the reference case. The logistical model developed in this research can be validated by the ECN Install tool 2.1. Important results to validate are the vessel costs and project duration of the reference case. If the results of the ECN Install tool are similar to the results in figure 7.5, the reliability of the developed logistical model increases. Assumptions made for the logistical model can be adjusted based on the results by the ECN Install tool. For example, multiplying the hours of downtime by 1,5 and multiplying the maximum sailing speed by 0,9 during transport are assumptions that can be adjusted within the logistical model.

The delay breakdown per step is presented in figure 7.6. It can be seen that 75% of the delay is caused by the jacking process and the installation of the turbine. In the developed logistical model this is 80% of the delays for the reference case. The delays per month simulated by the ECN Install tool can be seen in figure I.6 in appendix I.6.
The duration of the project within the ECN Install tool is 135 days and the delay of the project is 23 days. So the total project duration is 158 days, while for the reference case in the developed model this is 170 days. Concluding on the delay and project duration, the assumptions within the logistical model that influence the project duration can be decreased by approximately 5%.

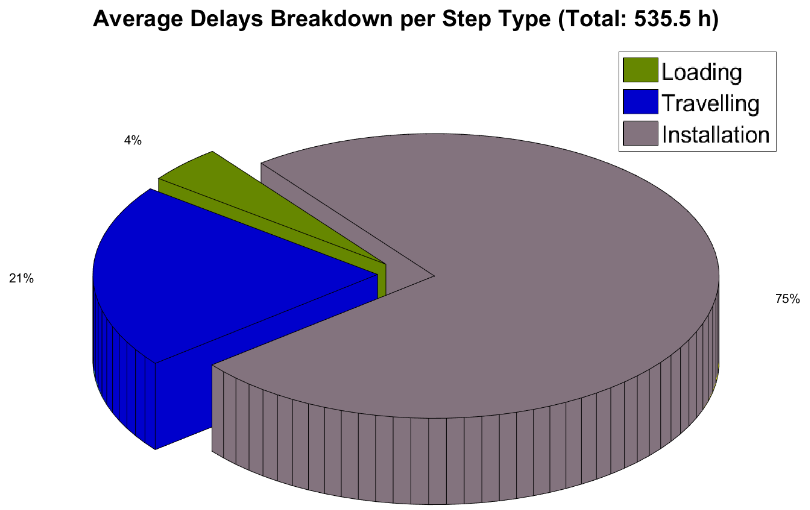


Figure 7.6: Activities that cause a delay

The vessel costs are 28.1 million euro within the logistical model as can be seen in figure 7.5. The results of the ECN Install tool present a total vessel cost of 25.7 million euro. The cost breakdown per resource of the ECN installation simulation can be seen in figure 7.7.
The total costs of the simulated project by the ECN Install tool are not reliable. Because the onshore activities that take place before the loading of the jack-up vessel can not be implemented adequately. Therefore, the distribution of the costs per resource are not convenient and only the vessel costs are a useful result.
For the validation of the logistical model, many more comparisons to the ECN Intall simulation model can be made than only the project duration and the vessel costs. Just one more comparison is analysed within this research, because it is influential on the total costs of the project. The total delay of the simulated project by the ECN Install tool is 23 days, the revenue loss is 13 million euro. So for each

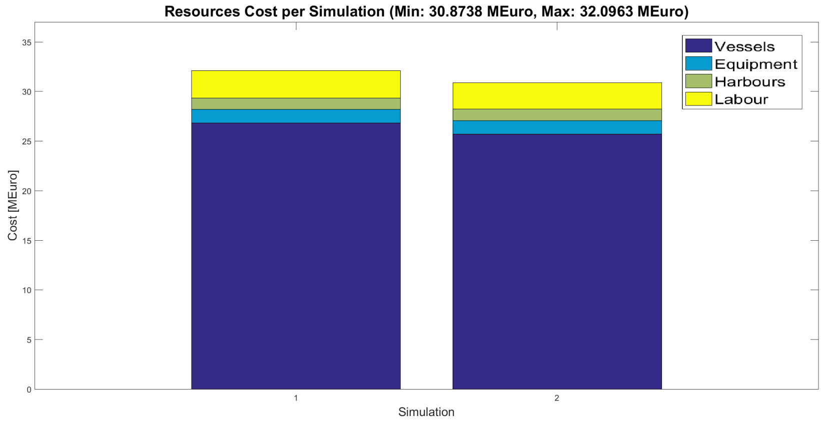


Figure 7.7: Total cost estimate by two simulations

day of delay the revenue loss is 550.000 euro. This is in the same order as the revenue loss for one day of delay for an average turbine. In the logistical concept the revenue loss is 480.000 euro, however 240.000 is applied in the calculations as explained in paragraph 7.1.4.

7.5 Operational days

The port can only gain revenue when it is operational. The potential savings per project are 23 million euro and the project duration is 145 days. To calculate the savings during the lifetime of the port in section 8.4 and the OPEX in section 8.3, the amount of operational days a year has to be known. For each port concept this is calculated in this section, the calculation is based on 365 days a year.

The assumed non operational days for all three port concepts is 50 days. Based on the market conditions of the offshore wind market, the offshore port could have some waiting days per year if the demand is not sufficient. Based on the assumption of 50 non operational days a year and the corresponding waiting days a year, the assumed operational days a year can be calculated. The four conditions that influence the amount of non operational days can be calculated when the operational days are known. Because these conditions influence the amount of non operational days, an iterative process is performed. This process is displayed in figure 7.8.

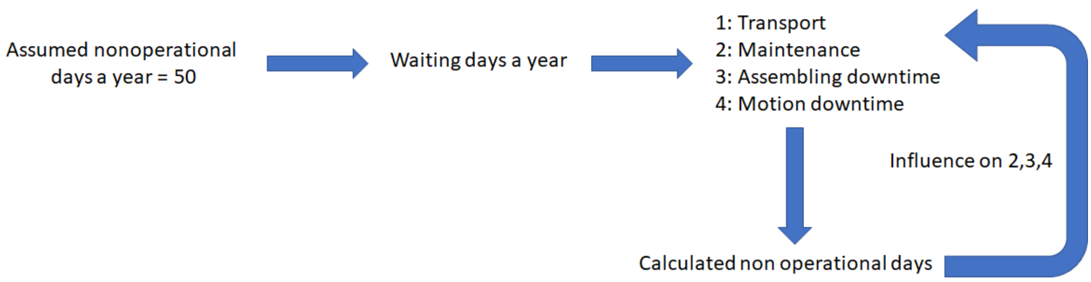


Figure 7.8: Methodology to calculate operational days a year

7.5.1 Lifetime

An average lifetime of a jack-up is 20 years [49]. This lifetime is applied to the port concept of a large jack-up barge and the port concept with a combination of a barge and a small jack-up barge. Based on previous large concrete floating terminals a lifetime of 30 years could be selected, but due to the incidental transport of the barge a more conservative lifetime of 25 years is selected [15].

7.5.2 Moving to the US market

Currently Europe is the continent that has the most developed offshore wind market. However, most researchers forecast a slow decline from the year 2040 on the installed capacity of offshore wind in Europe per year [25] [51]. Following the low offshore wind scenario by WindEurope as shown in figure 2.3, the offshore wind capacity in Europe is 100 GW by the year 2050. By the year 2030 the installed capacity is approximated to be 60 GW, so this is an increase of 40 GW.
Based on the results of the offshore wind market analysis in chapter 2, it is indicated that there is 22 GW offshore wind capacity operational at the US Atlantic coast by the year 2030. Indications on the installed capacity by the year 2050 are rough but for the US this is 85 GW by the year 2050. The share of US installed offshore wind at the US Atlantic coast is 85% by the year 2030 as explained in section 2.4. When this is also considered for the year 2050, the scenario of installed capacity at the US Atlantic coast is 72 GW by the year 2050. So this market increases by 50 GW.
Because the US Atlantic offshore wind market is a younger market than Europe, an annual growth of offshore installed capacity is expected for this market until the year 2050. Therefore, in the years around 2040 the offshore port is transported once to the US Atlantic coast.

7.5.3 Waiting period

Between the year 2030 and 2050, 90 GW of offshore wind is expected to be installed at the European and US Atlantic market. This is equal to 4.5 GW a year for the combined two markets. Assuming a wind farm capacity of 1.2 GW, there are on average 3.75 wind farms installed each year in the combined markets. Assuming that 25% of the projects is installed parallel there are 3 wind farms a year that can be installed by the offshore port.
However, it is assumed that 50% of the offshore wind farm owners is eager to use the offshore port to reduce the LCOE. So on average 1.5 wind farms can be installed each year by using the offshore port.

The amount of wind farms that can be assisted by the offshore port is the operational days a year divided by the duration of an average project, this is equal to 145 for the logistical base case. The operational days a year are assumed to be 365-50, so 315 days a year. So all port concepts can be used for the construction of 2.2 offshore wind farms a year.

It can be concluded that all offshore port concepts have a certain waiting period a year, because only 1.5 wind farms a year are constructed. This waiting period is 98 days, equal to the installation of 0.7 wind farm.

7.5.4 Non operating days

There are 365 days per year that the offshore port can be operational. However, there are waiting days that decrease the amount of operational days a year. Also the assumed amount of non operational days a year decrease the operational days. While working on the construction of an offshore wind farm there are three conditions that can cause downtime. Also the transport to a new project and the transport to the US market causes non operating days for the offshore port. The four conditions that determine the non operational days per year are elaborated below.

Transport

When moving from one project to the next project, transport of the port is required. The jack-up barges are self-propelling and have a maximum speed of 12 km/h, while each of the four barges require two tugs which have a sailing speed of 10 km/h. The barge carries a crane and is therefore limited by a sailing speed of 5 km/h and requires favorable weather conditions. The sailing distance is 300 kilometers, from the centroid of the North Sea, nearly every area in the North Sea can be reached with this radius.

On arrival of the port at a new project location, installation of the port has to take place. The barge has to be anchored by 8 mooring lines, under the assistance of two tugs. An expert in this field showed that one anchor line can not withstand the required loads. Therefore, at least eight mooring lines are required, so even in unfavorable wind directions there are two mooring lines that handle the load. Including the deployment of the anchor and the test load phase after anchorage the duration of anchoring is two days.
A reverse process of two days takes place at the finished project site. An additional two days is required to connect the separate four barges and form a stiff barge.
The jack-ups have to jack-up and at the new location jack-down, the total duration of these two processes is 9 hours. This is similar as applied to the logistical model. The duration for transport and installation for the large jack-up barge concept is 2 days, for the single barge 9 days and for the combination of a barge and small jack-up barge this is also 9 days.

An average project duration to install the turbines of an offshore wind farm is 145 days, so it takes 218 days a year to install 1.5 wind farm. Because finishing a wind farm project for 50% does not make sense, it is assumed that the cycle of a port consist of finishing two wind farm projects in a row.
Multiplying the lifetime of the port concepts by 1.5 and divided it by 2, results in the amount of cycles during the lifetime. One cycle consist of the offshore port sailing from the buoys at an onshore port to the first wind farm project and after the last wind farm project is sails back to the onshore port.
The duration of a cycle can be calculated by three times the transport and installation duration, although for the barge this is 2,5 times the transport and installation duration because at the onshore port the four barge sections can stay separated.
The time required for the single transport to the US Atlantic market is spread out over all cycles.

The four barge sections are transported by a semi-submersible vessel due to the weather conditions at the Atlantic Ocean. The jack-up barges in the port concepts are self-propelling and this is used to sail to the US Atlantic coast. The distance from the North Sea to Rhode Island is approximately 8.000 kilometer. Multiplying the maximum sailing speed by a factor of 0.75 the crossing of the ocean takes 37 days for the jack-ups. The four semi-submersible vessels are assumed to have the same sailing speed and corresponding travel time. The total amount of transport for each port concept can be seen in table 7.3.

Maintenance

Five days a year are reserved for maintenance on the jack-up barge during an operational period, this also holds for the combined port concept [6]. The single barge concept has 3 days a year reserved for maintenance. This is based on concrete LPG and LNG floating storage facilities like the Ardjuna Sakti that had no significant maintenance during their life time of 30 years [15]. For all three port concepts there is one day a year reserved for the survey and dry-docking.

Table 7.3: Transport days a year for each port concept

	Large jack-up barge	Barge	Barge & small jack-up barge
Cycles in lifetime	15	19	15
Duration US transport (days)	37	37	37
Transport during lifetime (days)	217	892	712
Transport a year (days)	11	36	36

Assembling downtime

In paragraph 5.2.3 it is explained that for assembling of turbines the maximum wind velocity is 14.7 m/s. Similar environmental data as in the previous chapter is used, with a buoy location approximately 100 km to the shore. There are 652 hours in the year 2014 that the minimum wind velocity of 14.7 m/s is present. This is multiplied by 1.5 to achieve environmental conditions similar to the base case of the port concept as explained in the previous chapter. This leads to 40 non operational days a year due to the wind velocity.

However, there are 98 days a year that the offshore port is waiting at the onshore port. The weather conditions do not influence the operational days when the offshore port is not in operation. So instead of 40 days of assembling downtime there are ((365-98)/365)*40 days of assembling downtime. This is equal to 29 days.

Motion downtime

The maximum allowed weather condition for unloading and loading is taken into account by the logistical model. However, the single barge has additional days of downtime that are not related to the wave heights included by the logistical model or the maximum wind velocity for assembling. The workability for the barge is determined in paragraph 6.2.1, this is equivalent to 92% of the year. This downtime by motion response is 30 days a year for the single barge concept. It is assumed that half of the non operational days due to a limiting motion response, occur at the same period in time as the limiting wind velocity. So the single barge concept has a downtime of 15 days a year due to motion response.

Applying the same reasoning as for the assembling downtime concerning the weather conditions that have no influence during the waiting period. The single barge has 11 days of downtime a year due to motion response.

7.5.5 Iteration operational days

As shown in figure 7.8, an iteration can be performed to determine the operational days. By subtracting non operational days from 365, the waiting period can be determined because only 1.5 wind farm a year is installed. The total amount of operational days can be calculated by subtracting the non operational days and the waiting days from 365.

The distribution between the amount of waiting days and the amount of non operational days influences the amount of downtime and maintenance.

The amount of maintenance per year is decreased by one day when there is a waiting period of at least 3 days a year. This is because the survey and dry-docking can take place during these waiting days. Downtime can only occur when the port is active in an offshore wind farm project. The weather conditions have no influence on the workability when the offshore port is located at the onshore port during a waiting period.
For each offshore port concept, two iterations are performed to validate the amount of operational days per year. An overview of the results and the constant value for the non operational days a year after two iterations is shown in table 7.4.

Table 7.4: Operational days a year for the three port concepts

	Large jack-up barge	**Barge**	**Barge & small jack-up barge**
Assumed non operational days a year	50	50	50
Waiting period a year (days)	98	98	98
Operational days a year	218	218	218
Transport a year (days)	11	36	36
Maintenance a year (days)	6	4	6
Assembling downtime (days)	29	29	29
Motion downtime (days)	0	11	0
Waiting days a year	101	68	77
Operational days	**218**	**218**	**218**
Non operational days after second iteration	44	84	72
Waiting period a year (days)	103	63	75
Operational days after second iteration	**218**	**218**	**218**

Based on the results of table 7.4 he following conclusion can be drawn:

The waiting days at the onshore port are different for all three concepts, also the amount of days that the port is non operational while working on the construction of an offshore wind farm deviates between the three port concepts. However, the amount of operational days that the port concepts is working on the construction of an offshore wind farm is similar for all three port concepts.

7.6 Demand analyses

All six demands can be fulfilled by the offshore port, since all four required activities take place at the offshore port. The demand with highest priority to be satisfied is analysed in the previous sections. The other five demands are not analysed for the potential of the offshore port concept, because their potential saving have a lower potential due to the priority of implementing. The remaining five demands are analysed in this section. An overview of the required and desired activities per demand is displayed in figure 5.2. The followed methodology regarding the demands and activities is showed by figure 7.9.

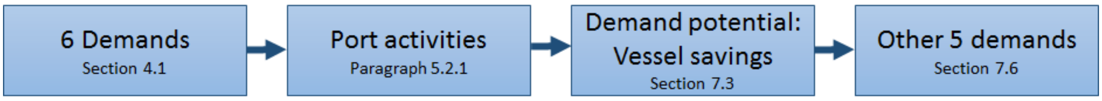


Figure 7.9: Overview demand savings

7.6.1 Deep water port near wind farm

The required activities for this demand are implemented in the port. The desired activity for this demand is to assemble the spar-buoy foundation, this is not taken into account by the port. The market potential of this type of floating foundation increases when an offshore deep water port is available. Assembling the monopile foundation at the offshore port could be a potential activity as well. However, this is not a demand by the market because of the coating that takes place after assembling. Due to a lack of time within this research only the required and desired activities that correspond to the market demands are analysed.

Using the logistical model developed in the previous chapter the assembling of the spar-buoy foundation is implemented. Premised that a larger surface area than 133 x 133 meter is required for the offshore port when implementing this activity, the corresponding CAPEX and OPEX rise. The saving aspect of a shorter duration of the project and a sooner generation of energy is included neither. This saving condition is only valid for the installation of a turbine. Only the logistical savings concerning this activity are analysed, because integrating a full workability and financial analysis for this activity consumes a lot of time.
The reference case is similar to the executed construction of the floating wind farm in Scotland, Hywind. The turbine is completely assembled at the offshore port. The spar-buoy is towed to the site and turned vertically by adding ballast. A heavy-lift vessel sails from the onshore port to the site and installs the turbine. In this analysis there are 25 spar-buoys installed. This is based on Hywind, which only has six wind turbines installed and a potential increase for this number. The reference case in the logistical model is replaced by this new reference case including the assembling of the spar-buoy foundation. There are three modifications conducted to implement the new reference case in the old reference case model, these are the following:

- The sailing speed of the heavy-lift vessel is 14 km/h instead of 26 km/h for the JUV which only carries a partly assembled turbine. The heavy lift vessel carries a full assembled turbine.
- The installation duration is halved. Since the JUV has to jack up, jack down and conduct three lifts. The heavy-lift vessel only has to execute one large lift. However, the limiting wave height for sailing decreased from 3 meter to 1.5 meter and for installation this decreased from 2 to 0.5 meter.
- There are two tugs who tow the spar-buoy to the offshore site. First the buoy is filled with sea water by a barge and when there is 8000 ton added, 5000 ton is replaced by a solid ballast supplied by a rock installation vessel.

Using similar assumptions and input parameters for the logistical model as for the previous reference case, the project has a total duration of 83 days. So during these 83 days a heavy lift vessel, two tugs, a rock installation vessel and a barge are required. These vessels have a crew of 60, of which 20 are active, this consists of 10, 4, 4 and 2 people. Applying different working shifts has a limited influence on the costs. Onshore there are continuously 25 people involved in the transport and assemble process, just as in the reference case of the previous chapter. The day rates of the vessels are based on academic works and the gained expertise throughout this research [37] [107]. The heavy-lift vessel is most dominant for the vessel costs, with a day rate of €250.000 a day. There is only one crane required at the onshore port, the heavy lift vessel has a lifting capacity that is sufficient for installing the turbine by a single lift.

The potential of assembling the foundation offshore is determined by comparing the total costs of the reference case with the total costs for transport and installation with an offshore port concept. The logistics of the latter are discussed.
A fast feeder vessel provides the offshore port with the components of the spar foundation, transition piece and the turbine. Applying a spar-buoy as foundation automatically means that a jack-up vessel is not suitable due to depth restrictions. The spar foundation is slowly filled with sea water and then filed by a rock installation vessel. This is assumed for simplicity, in practice a purpose designed equipment can fill the spar with a solid ballast. The spar foundation is turned vertically and then the turbine is placed on top. This entire structure is towed to the project site and moored, again 25 spar-buoys are installed. In comparison to the selected logistical system for the offshore port in section 7.3 a few modifications are made, these are:

- The feeder vessels also carries the components of the spar-buoy foundation, as a consequence the loading and unloading of the feeder takes 2 hours longer and its carrying capacity is increased. Its sailing speed is reduced to 12 km/h, because the processes at the offshore port and the installation take longer. The tugs who transport the spar buoy to the offshore site have a sailing speed of 5 km/h.

- The assembling of the spar-buoy requires an additional crane, this process has the same duration as the assembling of the turbine. However the assembling of the turbine is extended by 2 hours because the turbine has to be fully assembled instead of just assembling a bunny ear, and the tower.

- Filling the spar-buoy with sea water and a solid ballast is assumed to take 10 hours.

- The crew on the vessels consist of 5 for the feeder and 4 for the tugs and the rock installation vessel.

- The limiting Hs for sailing of the tug with a spar-buoy is 1 meter, the limiting Hs for the installation of this spar-buoy is 0,5 meter. The mooring time of the spar-buoy foundation is assumed equal to the installation of a turbine in the reference case of section 7.2.1. This is assumed because no jacking up and jacking down is needed and the installation of the turbine can be executed by a single lift.

Assembling the turbines and the spar-buoy foundation at the offshore port leads to a total transport and installation period of 70 days. This is 13 shorter than the reference case. These results are based on the installation of 25 spar-buoys at 175 kilometer from the shore. Costs for adding the activity of assembling the spar-buoys at the offshore port are not approximated, but the result shows a potential of integrating this activity at the offshore port.

7.6.2 Usage of one installation vessel

This demand mainly holds for the US offshore wind market. The offshore port concept fulfills this demand, but legislation, shipyard development and the importance of sustainability to the government in the U.S. determine the potential of the offshore port for this demand. This is explained in chapter 4.

7.6.3 A shelter with loading facilities

The required and desired activities for this demand are implemented at the offshore port. The potential savings of this demand is the lowest of all six demands. Cable installation vessels, fallpipe vessels or other vessels can use the offshore port as a shelter when the weather conditions are rough. This could save a trip of sailing forth and back to the onshore port. The amount of trips could be reduces even more when a feeder vessel supplies the offshore port by drinking water, food or other needs. Assuming that one trip per project is saved the saving is €50 per day of the project. This is based on a project duration of 145 days, crew expenses for ten people and fuel costs. So the potential saving of this demand is small.

7.6.4 Smaller support vessel

The single required and two desired activities of this demand are implemented at the offshore port. So the support vessel that is used throughout the installation phase of the offshore wind farm can be reduced in size. The crew does not have to sleep on this vessel any longer, though the support vessel is still a contribution to the installation phase. It deposits the required equipment at the transition piece before the turbine is installed. It can also assist other vessels by sailing nearby them for the required equipment or crew supply for an installation aspect.

In paragraph 5.2.3 it is described that the dimensions of a berth shall be at least 198 centimetres by 80 centimetres. Assuming a bunk bed on two decks, for each crew member an additional 1.6m^2 of vessel area is approximately required on the installation support vessel. Taking into account the increase of the CAPEX per m^2 as explained in section 8.2 and assuming a total crew of 20[33], the saving on the CAPEX are €20.000.

7.6.5 Ease the transport of the tower

The required activities of this demand are implemented at the offshore port, the desired activity of more berthing area is not. In the offshore port there is one quay wall that satisfies for each single vessel type that berths. A longer quay wall provides an opportunity of direct shipping from low-cost labour countries to the offshore port. The onshore port can be skipped when from fabrication the tower could be directly sailed to the offshore port.

Perhaps it could also be feasible for other turbine components to be directly transferred from fabrication to the offshore port. Equipment, labour and port rental at the onshore port are decreased. Transport costs regarding the feeder system are lowered and the project duration decreases. However, there is also a downside of easing the transport of the tower.

Large vessels who sail long distances have a higher day rate as the JUV feeders used in the base case of the logistical model. Mooring forces of these large vessels are higher. This aspect is not analysed within this research, but an increase of these forces can be expected. These two examples increase

[33] The market explained that the support vessels commonly work according two shifts a day. There are other installation phases that apply three shifts a day. This has no influence on the crew expenses determined in this research since these are calculated per working crew member per hour.

the costs regarding the direct transport of the tower.
In the base case of the logistical model, the feeder vessel only has to wait four times on the installation JUB, which takes in total nine hours. Assuming the length of the quay wall is sufficient for one large vessel, and extension of the quay wall is not needed for multiple vessels to berth, this extension leads to additional costs. It can be concluded that there is a potential to transport the tower directly to the offshore port.

7.7 Saving opportunities

There are more saving opportunities which can cause a decrease of the LCOE than the six demands by the offshore wind industry. A vessel opportunity is explained and also opportunties for the offshore port are emphasized by the life-cycle and possible markets that can join the offshore port.

7.7.1 Vessels

The logistical concepts in the previous sections are based on the expected market by 2030. However, the feeder and installation vessels used in the model are types currently used in the market and appropriate for the logistical concepts. There are opportunities like a roll on roll off vessel, that are in the first stages of entering the market. A roll on roll off vessel is shown in figure 7.10 and has the potential of reducing the loading and unloading time. It has a large bow door that can be opened and can transport multiple 8 MW Siemens nacelles per trip. So far, this is only used for the transport of a nacelle, but when they can also transport blades and components of the tower it can be used as a feeder vessel. At least, when the workability is higher as unloading the feeder with a crane from the offshore port.

Figure 7.10: Siemens customised turbine transport vessel in Esbjerg [W30]

The logistical concepts do not take into account the assembling or storage of the foundation. In paragraph 7.6 the potential of assembling and storing of a monopile is analysed. This is expected to be the dominant type of foundation in the market by 2030 as explained in section 3.4. However when a jacket or gravity base structure will become more dominant, it is a possibility that purpose built installation vessels are constructed. This could be an opportunity for the offshore port since these purpose built installation vessels have the main function to install the foundation and not to transport it.

7.7.2 Life-cycle

There are some aspects of the life cycle of the port which are hard to quantify, but can qualitatively be elaborated. The lifetime of the port concepts is set to 20 or 25 years. Extending the decline of the port increases the lifetime and increases the NPV and consequently increases the financial feasibility.

Examples of life-cycle opportunities for the port are qualitatively described by the bullet points below.

- A high residual value at the end of the life time of the port increases the financial feasibility. A barge made from concrete strengthens over time, as long as there are no cracks the residual value is high by reusing it for other markets. Components of the jack-up barge could be used for the construction of new jack-up barges.

- Reusing the port in other markets when the demand for the port is lower as predicted decreases the risk of a financial unfavorable scenario. The jack-ups could be used for offshore installations and the barge could be used as a transshipment terminal or LPG offshore storage facility. Constructing a semi-submersible with six columns instead of four and increasing the concrete cover of the barge to 75 milimeter are examples of integrating the life-cycle during the design to increase the reusing opportunities.

- The risks during design and construction should be attempted to be minimised. This could be done implementing en execute a lot of components in the port that are designed and constructed before. This reduces the delay, saves expenses and increases the profit.

- Designing a modular system has when feasible, many advantages for the flexibility of the port. If a offshore wind farm project requires more or less storage area the port can be adjusted. This increases the market potential and consequently the financial feasibility. This explicitly is an opportunity for the two port concepts that contain a barge.

7.7.3 Joined markets

The CAPEX of the port can be shared by multiple markets by combining offshore markets at the offshore port. This demands an adjustment of the boundary conditions, though the offshore port potential can increase. Several markets that could be combined with the offshore wind market at the offshore port are listed below.

- **Wave energy:** A combined wave power converter and offshore port can reduce the LCOE in comparison to the separate energy device. An integration of the port and the wave energy converter improves the utilization of the ocean space and decreases the associated costs regarding installation and maintenance. There are possibilities to share substructures and infrastructure [111]. Possible combinations are presented in figure 7.11

- **Marine aquaculture:** One of the most promising multi-use concepts of European basins, is the combination of offshore wind and aquaculture [182]. Especially the aquaculture of seeweed and mussels were evaluated as a concept that should be explored for further research. The aquaculture keeps is position by the use of anchorage. On the non berthing sides of the port aquaculture facilities can be developed. An impression of an offshore aquaculture system is provided in figure 7.12a.

- **Solar energy:**Floating solar panels can be connected to the offshore port, this reduces the investment costs of the solar energy device. A main advantage is the energy peak that is later in the day than for solar energy [113] [93]. An example of floating solar energy and wind energy is provided in figure 7.12b

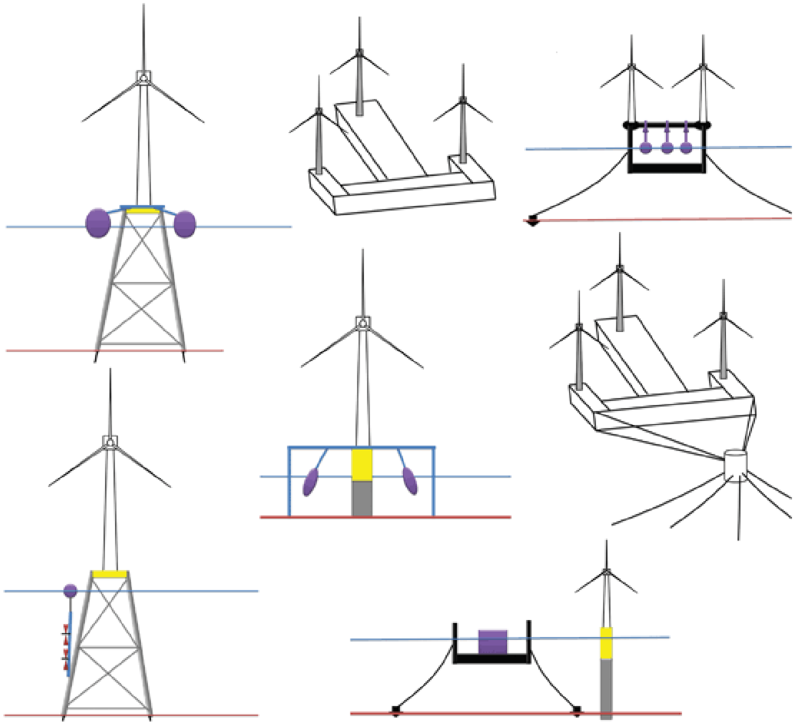


Figure 7.11: Combined wave and wind energy converter [111]

(a) Artist impression of the aquaculture [80]

(b) Solar energy combined with wind energy [129]

Figure 7.12: Examples of joined markets

7.8 Logistical conclusion

There are three potential logistical concepts that deviate from the reference case. All four concepts are optimised regarding the total costs by modifying the parameters: sailing speed, carrying capacity and start date. The total costs are based on the costs of the project and the energy profit by a shorter project duration. The project duration of the three potential logistical concepts is limited by the two boundary conditions and the required time for installation of a turbine.
The boundary conditions are contrary in their goal. A maximum number of five turbines and a continues sailing of the installation vessel are achieved by a trade off. The installation vessel is continuously active in each of the four models, but the storage of turbines at the offshore port is not always at least one to guarantee the continuous activity of the installation vessel. Though the percentage of no turbine stored is kept to a minimum.

The results are presented in figure 7.5 and the logistical concept of a fast feeder vessel is selected. A potential port layout is presented in figure 7.13, with a similar layout as to the images in the previous chapter that show an impression of the port. Of course alternatives are possible to this layout. Overtaking of the trailers can take place between the unloading crane and the assembling area. For example, the blades are stored by the assembling crane and the pre-assembled turbines are stored by the assembling crane or the unloading crane. But the storage of towers and nacelle is conducted by the trailers.

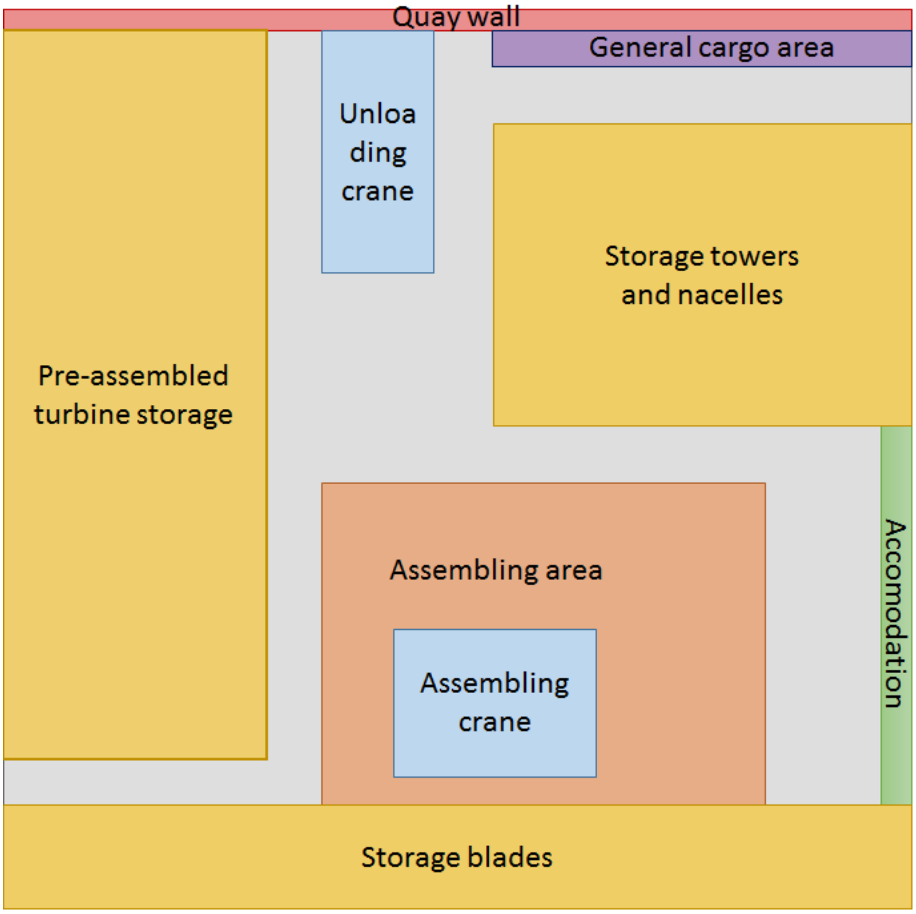


Figure 7.13: Potential port layout for a port concept consisting of one port component

8. Business case

The base case of the logistical model is applied it uses a fast feeder vessel to transport the turbine components to the offshore port. Section 8.2 shows the investment costs for the offshore port, section 8.3 determines the operational costs of an offshore port and in section 8.4 the revenues for the three offshore port concepts are calculated. The financial performance is evaluated in section 8.5 and in section 8.6 the design with most potential is selected based on the financial indicators. Section 8.7 consists of a sensitivity analyses to evaluate the influence of important parameters and the conclusion of this chapter can be found in 8.8.

8.1 Introduction financial analysis

The financial performance of three offshore port concepts are compared by a quantitative cash flow analysis. The logistical concept applied to all three concepts is a fast feeder that supplies the turbine components to the offshore port and a jack-up barge that loads the partly pre-assembled turbine and sails a small distance to the wind farm to execute the installation.

A cash flow analysis determines the overall profitability of the investment, this is achieved by taking into account the determined revenues and expenditures in each period throughout the duration of the project and calculate the corresponding financial performance indicators. An example of a cash flow for a port project is shown in figure 8.1. By applying a discount rate to the expected cash flows, the principle that one money-unit today is worth more than one money-unit tomorrow is included in the financial analysis. In this stage of the design a simplified financial model can be used, called a real pre-tax pre-finance financial evaluation [123].
The prefix real, indicates that inflation is not taken into account, the prefix pre-tax indicates that tax payments is not included and the pre-finance indicates that the finance structure is not included in the model. So the result of this real pre-tax pre-finance analysis is the overall profitability of the project.

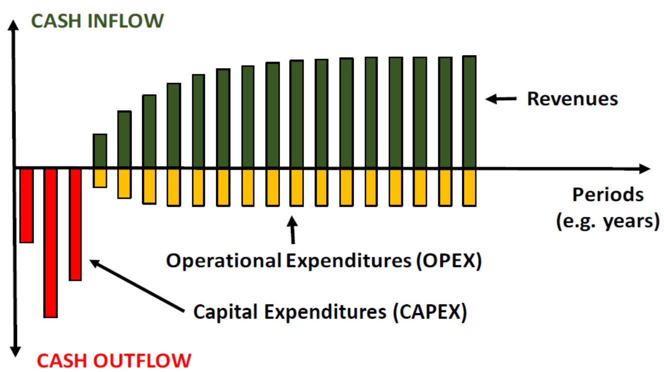


Figure 8.1: Example of an investment cash flow for a new port [123]

A lot of judgments have to be taken during a design process, a question like: what is the trade-off between steel weight and motion response when lengthening a design? Has to be answered. A designer therefore needs a rather complete model of the life-cycle costs of a ship. The CAPEX comprise the investment costs for construction of the offshore port that are non-recurring, whereas the OPEX are recurring costs to operate the offshore port.

At the end of the lifetime the residual sales value of a vessel is 5% of the CAPEX, this is also applied to the offshore port concepts [6]. In the financial analysis and the determination of the amount of operational days it is assumed that the amount of days per year is 365.

8.2 CAPEX

An average division of the CAPEX of 25 jack-ups constructed in the United States between 2000 and 2012 can be found in figure 8.2. This pie chart is used for determining the CAPEX of the port concepts including a jack-up. Equipment represents a large share to the pie chart. This group consist among others of: steering system, mooring system, lifesaving, fire fighting and accommodation. [6] [14]. The share for propulsion is higher for the vessel, but the outfitting costs are lower. Outfitting includes among others the labour costs and the equipment costs for construction.

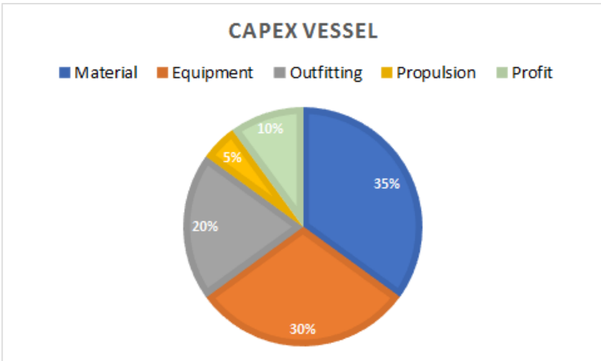


Figure 8.2: Division of CAPEX jack-up over major cost groups [108]

Some of the cost groups from figure 8.2 are known to determine the CAPEX of the offshore port concepts, while others are not. For example, man hours for the hull are a function of the length, width depth and CB value [6]. However, other influential parameters like the amount of material, equipment and electrical installation have to be estimated. Due to these uncertainties it is decided to determine the CAPEX of the jack-up barges required for two potential port concepts by a market analysis.

The CAPEX of jack-up barges with a similar shape and dimension as applied in this research, which can be seen in figure 3.5b, 6.29 and 6.31 are mostly classified. However, there are researches that mention the CAPEX value for jack-up barges with approximately similar dimensions [107] [36]. For of a length of 150 meter, a width of 40 meter and a lifting capacity of 900 ton the CAPEX of ten jack-up barges are gathered. The average CAPEX for these jack-up barges is $140.000.000, equivalent to €120.000.000[34].
The maximum sailing speed of the ten jack-up barges is 18 km/h. However, the propulsion power of the jack-up barges in the port concept can be very low. It is only required to be self-propelling when moving from one project site to the other project site. Taking into account the pie chart of figure 8.2, the CAPEX of €120.000.000 is decreased to €118.000.000.

[34]Based on the dollar-euro ratio in may 2018.

In section 6.3 the CAPEX of a jack-up barge is determined by a market analysis. The CAPEX value of large jack-up barges are multiplied by 1.5 to derive the CAPEX. In this section the CAPEX of a jack-up barge and a single barge are determined by more detail, first the CAPEX of the jack-up barge is determined. Two steps have to be taken to do this, as a start the costs of a 1300 ton tub mounted crane and the costs of two trailers are added.

As explained in section 6.3 the CAPEX of a 1300 ton hub mounted crane is €10.000.000. can be seen in figures 3.5b and 6.29. Using an automatic guided vehicle as a trailer on the offshore port can reduce the manpower [124]. However, after an extrapolation of the carrying capacity of multiple AGV's in the market, the CAPEX is calculated to be €10.000.000 [168] [86]. Due to this high CAPEX it is expected to be more profitable to use a truck as shown in figure 8.3. After benchmarking the industry, a truck as displayed in figure 8.3 has an estimated CAPEX of €400.000.
The blades can not be stored by this truck due to the presence of the blade rack and the assembled turbines are also not possible to transport by this truck, the cranes are used for these two operations. A one person crew for each of the two trucks is included at the OPEX. A purpose built trailer could provide potential savings in the future, this could for example be a an AGV that can lift a nacelle.

Figure 8.3: Tower component transport at San Diego USA, image by Wikimedia

The second step to determine the CAPEX of the jack-up barge is to extrapolate and interpolate the CAPEX, to become suitable for the two port concept. Applying a linear theory to all the gathered CAPEX of jack-up barges, which have a small deviation in dimension. Provides the increase per ton lifting capacity and increase per square meter deck area. Other useful parameters which could be used for extra or interpolation are not provided for the ten jack-up barges [107] [36]. Jack-up barges with similar dimensions but a different crane capacity determine the increase per ton lift capacity. A similar approach with a constant lift capacity is applied to determine the increase in CAPEX per square meter deck area. This leads to the following cost increase:

- An increase of the deck area by 1 m^2 increases the CAPEX by: €4.000
- An increase of the lift capacity by 1 ton increases the CAPEX by: €7.000

The additional CAPEX to upgrade the 900 ton crane to a 1300 ton crane is €2.800.000. The CAPEX of the large jack-up barge consist of one 1300 ton crane, an additional 400 ton to the existing crane, two LAGV and the CAPEX increase due to the required surface area. The latter accounts for €47.000.000, so the CAPEX of the large jack-up barge equals:

€118.000.000 + €47.000.000 + €800.000+€10.000.000+€2.800.000 = €178.600.000

The construction costs for the barge is determined in section 6.3 by applying a formula developed and used by the offshore market. Because the CAPEX of large LPG, LNG or other concrete floating terminals are classified and the rule of thumb concerning the day rate transformation to CAPEX is not applicable to these structures. The result generated in section 6.3 is the CAPEX and equals €45.000.000. This includes the material and outfitting costs of the concrete structure.
A mooring system for the barge still has to be added, the costs of a mooring system are linear to the weight of the structure and the water depth. The mooring costs are about 5% of the capital cost [144] [187]. So as a CAPEX for the single barge, €47.200.000 is taken into account.

For the port concept of a barge with a small jack-up barge a similar methodology is applied. The costs of the barge are €37.200.000 and the CAPEX of the small jack-up barge is derived by an interpolation of the CAPEX values of the ten jack-up barges. It is assumed that the dimension of this small jack-up barge is 60x20 meter and it has one crane of 1300 ton. The CAPEX of this small jack-up barge is €101.600.000. The port concept that combines two port component has a CAPEX of €138.800.000. The CAPEX for all three port concepts is summarised in table 8.1.

Table 8.1: CAPEX of the three port concepts

	Large jack-up barge	Barge	Barge & small jack-up barge
CAPEX (million euro)	179	47	139

The pre-tax pre-finance financial analysis does not take the depreciation of the CAPEX over the lifetime into account. Applying this analysis leads to a full depreciation of the CAPEX before the year 2030, it is assumed that this full depreciation takes place in the year 2029.

8.3 OPEX

The operational expenditures of the port consist of the costs for transport and installation, the operational expenditures and the costs for the waiting period. The OPEX for all three port concepts are determined separately. First the transport costs per project are determined,

8.3.1 Transport

The port has to be movable so it can function for multiple offshore wind farms as is explained throughout this research. The transport costs can be split up into two groups. The transport and installation costs for starting a new project and the transport costs for moving from the European to the US Atlantic market.

In paragraph 7.5.4 the travel time for transport and installation to a new project is determined. For the large jack-up barge this is two days and for the other two port concepts this is nine days. The day rate of a tug is €9.000 including fuel costs [107]. Eight tugs are used and each tug is assumed to have a crew of three. Based on the used tug, fuel and crew costs, the total costs for transport and installation of each port concept can be determined.
The total crew of 24 people is continuously active on a tug. The large jack-up barge has a crew of 10 people, this is similar to the amount of crew that works at the offshore port. The small jack-up

barge has a crew of 5 people. The fuel costs for a large jack-up barge are €13.000 per day and the crew expenses are based on a salary of €65.000 a year, these values are similar to the applied logistical model in the previous chapter. The transport and installation costs for the start of a new project are presented in table 8.2.

Table 8.2: Transport and installation costs for a new offshore wind farm project

€1.000/project	Large jack-up barge	Barge	Barge & small jack-up barge
Crew	12	130	142
Fuel	26		22
Tugs		324	324
Total	38	454	488

As explained in paragraph7.5.3 there are two offshore wind farm constructions consecutively executed by the offshore port before it returns to the onshore port. The corresponding costs for this cycle are three times the total amounts presented in table 8.2. However, for the barges the total costs in table 8.2 are multiplied by 2,5 because at the onshore port the four barge sections can stay separate.
The theoretical amount of projects is 1.5 per year, this is multiplied by the lifetime and divided by two to determine the amount of cycles in the lifetime of the offshore port. The corresponding costs during the lifetime for starting a new project can be calculated and then divided over the lifetime.. This leads to the transport costs per year for starting a new project.

The transport costs for crossing the Atlantic Ocean consist of crew expenses, rental costs, fuel costs and mitigation measures to secure the equipment of the offshore port. The latter is assumed to cost €500.000. The crew expenses and vessel costs are similar to the transport of one offshore wind farm project to the next wind farm project. The transport costs for the large jack-up barge port concept is €1.200.000.
A semi-submersible vessel is rented to transport the four barge sections to the US Atlantic coast. Ther day rate of a semi-submersible including the fuel costs is €75.000 and it is assumed that the four semi-submersible vessels have a crew of fifteen, of which five are continuously active. It is assumed that the semi-submersible vessels can sail back to Europe with an order from another client [107].
The rental costs of a semi submersible vessel to transport the single barge are €11.500.000, adding the crew expenses to this leads to a total cost for transport of €11.950.000. The combined port concept has a transport cost of €12.650.000. The OPEX per year for crossing the Atlantic once depend on the lifetime of the port concept.

8.3.2 Operational costs offshore port

The costs required to have the port operational are determined in this paragraph. Whether the port is not in operation due to the weather conditions or maintenance is irrelevant for the cost components that determine the running costs. All the components have ongoing costs for non operational days during the construction project of an offshore wind farm. The main components are the crew expenses, maintenance costs, management, dry docking and insurance costs [6]. The five main cost components are elaborated by the bullet points below.

- Crew expense depend strongly on the nationality of the crew, but the costs per mixed crew per member is €65.000 per year [6]. This includes wages, traveling, holidays and victuals. For the single barge and single jack-up barge concept there are continuously 10 people working. The concept that combines a small jack-up barge and a barge has a crew of 15 people. These amount of crew member include two crew members for the driving of the truck. These crew numbers have to be multiplied by 3 due to the working shifts, as explained in appendix I.3
- The management costs consist of an office rental and five members with a yearly salary of €100.000. Together this accounts for €600.000 per year.
- A special survey and drydocking has to be executed after 5, 10 and 15 years. A similar reasoning as to the maintenance is applied to determine the costs. The corresponding costs are 1.4, 1.6 and 1.8 % of the capital costs [6]. These numbers hold for the jack-up barge. For the barge a conservative assumption of 50% of these percentages is made.
- It is assumed that the port can be insured. An insurance is taken for risks on damage and loss on hull and machinery and for protection for damage to third from third parties. A rough estimate is 1% of the new building value of the port [6].

8.3.3 Waiting costs

The amount of waiting days a year are determined in paragraph 7.5.5. For the large jack-up barge this are 103 days a year, for the single barge 63 and for the single barge in combination with a small jack-up barge this are 75 days a year. There are ongoing operational expenditures for each day that the offshore port is waiting for the next project. These OPEX components are: port rent, management and insurance. The present buoy dues in the Port of Rotterdam are €2.85 per meter of vessel length for each day[35]. The management and insurance costs are already taken into account at the operational costs and are valid for 365 days a year.

8.3.4 Operational expenditures

The OPEX results are presented in table 8.3. It should be noted that the not all cost components are there all year round, depending on the amount of transport, non operational days during an active period and the amount of waiting days per year the cost component is calculated. Two other important aspects used to calculate the values in table 8.3 is that the offshore port works on 1.5 offshore wind farm a year and the lifetime is used to depreciate costs that are planned during certain stages of the lifetime. In table 8.3 the OPEX per year are shown.

[35]https://www.portofrotterdam.com/en/shipping/port-dues/buoy-dolphin-and-quay-dues Retrieved on 13-06-2018

Table 8.3: OPEX of the three port concepts

Cost components (million €/year)	Large jack-up barge	Barge	Barge& small jack-up barge
Transport for new projects	0.09	0.86	0.92
Transport to US market	0.06	0.48	0.63
Port rent	0.04	0.02	0.03
Crew expenses	1.40	1.61	2.32
Maintenance	0.90	0.14	0.70
Management	0.60	0.60	0.60
Survey & Dry-docking	0.45	0.05	0.34
Insurance	1.79	0.47	1.39
OPEX	**5,33**	**4.23**	**6.93**

8.4 Revenues

The expenditures of the offshore port are determined in the previous two sections, when the expected revenues are determined as well the quantitative cash flow can be examined. The revenues of the port concept are the savings in comparison to the reference case. The logistical model with a fast feeder vessel selected in the previous chapter, is the base case to calculate the revenues of the port concepts. The quantitative savings calculated in section 7.3 are taken into account, the qualitatively savings determined in section 7.6 are not taken into account as savings. The logistical model of the base case shows a potential saving of 23.0 million euro, as can be seen in figure 7.5.

The total savings are based on two saving groups. The first is a lower project cost of 17 million euro, which is mainly achieved by lower vessel costs. The second group is the energy profit by a shorter project duration and consequently a sooner generation of energy which saves 6 million euro.
However, the savings of the port depend on the ownership of the port. The offshore port can be profitable for the electricity distributor and the turbine construction company. It is assumed that the turbine construction company owns the port, because these type of companies already have an existing fleet which is used in the offshore wind market. As a consequence the energy profit will not be a 100%, the electricity distributor only allows the turbine company to use the offshore port when it is favorable for themselves. A profit of 25% is expected for the owner of the port from all electricity that is generated sooner than generated by the reference case.
Therefore, the potential saving is not equal to 23.0 million euro but 18.5 million euro per project. Theoretically 1.5 offshore wind farms are assisted per year by the offshore port. Multiplying the revenues of one project by 1.5 determines the revenues per year. The revenue per year for all three port concepts is €27.750.000. It is assumed that the revenues are not credited at the end of a project, but constantly throughout the cycle, which includes the waiting days. As a result the revenues are similar for each year in the lifetime of the offshore port.

Throughout this research four influential assumptions are made for the potential savings. These four assumptions are repeated by the bullet points below. The degree of influence of these four assumptions on the profitability of the project is explained in section 8.7.

- 50% of the profit by a sooner energy generation is not a profit due to other barriers that arise due to a shorter project duration.
- 50% of the potential wind farms is eager to use the offshore port during the construction phase.
- The potential offshore wind farms are constructed for 25% parallel. Meaning, if four wind farms are constructed in one year, three wind farms are constructed consecutively and the fourth wind farm is constructed in the meanwhile.
- 25% of the energy profit due to a shorter project duration is allocated to the owner of the port.

8.5 Financial performance

The financial performance of the three port concepts will be assessed in this section. A cash flow of the three port concepts is determined and the financial performance indicators that are used are the NPV and the IRR. The NPV and IRR are the two main appraisal methods for investors [16]. The NPV is a measurement of profit, it is calculated by subtracting the present cash outflows, including the CAPEX, from the present values of cash inflows over a period of time [16]. The rate of return that is calculated for a NPV equal to 0 is the IRR.

Before the financial performance can be assessed, several general parameters have to be defined. By applying a discount rate, the time value of money can be expressed. The weighted average cost of capital (WACC) is commonly used to determine the discount rate. It is defined as the rate at which the present value of the discounted free cash flow is similar to the present value of equity cash flows plus the present value of the debt cash flows [123]. The simplified WACC with a constant debt to equity ration can be calculated by equation 20.

$$WACC = \frac{E}{D+E} * R_e + \frac{E}{D+E} * R_d * (1-T) \tag{20}$$

In which:
WACC = weighted average cost of capital
D = value of debt
E = value of equity
R_e = required (nominal) return to equity
R_d = required (nominal) return to debt
T = marginal corporate tax rate

The port concepts are assumed to be 60% debt funded and 40% by equity. The WACC is calculated by a targeted return to equity of 13% and the company pays 10% interest over their loans. The marginal rate is 25%. The result is a nominal discount rate of 10,5%. The real pre-tax pre-finance financial analysis is applied, so inflation should be excluded from the discount rate. The last twenty years the average inflation in Europe is 2%[36]. The relation between the nominal and real discount rate is shown in equation 21. With an inflation of 2% and a nominal discount rate of 9,7% the provided real discount rate is 7,5%.

[36]https://tradingeconomics.com/euro-area/inflation-cpi Retrieved on 13-06-2018

$$R = (1 + r) * (1 + i) - 1 \tag{21}$$

In which:
R = nominal discount rate
r = real discount rate
i = rate of inflation

The applied discount rate in the logistical model to calculate the energy profit is 5,5%. When a discount rate of 7,5% would be applied the energy profit would be larger and a shorter duration of the project is more favorable. As a consequence the reference case should carry three turbines instead of two to achieve the lowest total costs. However, the logistical results are not optimised by a recalculation due to time limitations of this research.

8.5.1 Cash flow

A cash flow analysis is used to evaluate the financial performance of the project. The expected cash flow consist of the CAPEX, OPEX and revenues in each year through the lifetime of the offshore port. As an example the cash flow of the large jack-up barge port concept is presented in figure 8.4. The horizontal axis shows the cash flow results by the end of a single year. The lifetime of the offshore port starts at the first of January 2030, in section 8.2 it is explained that the CAPEX is depreciated just before the offshore port becomes operational.

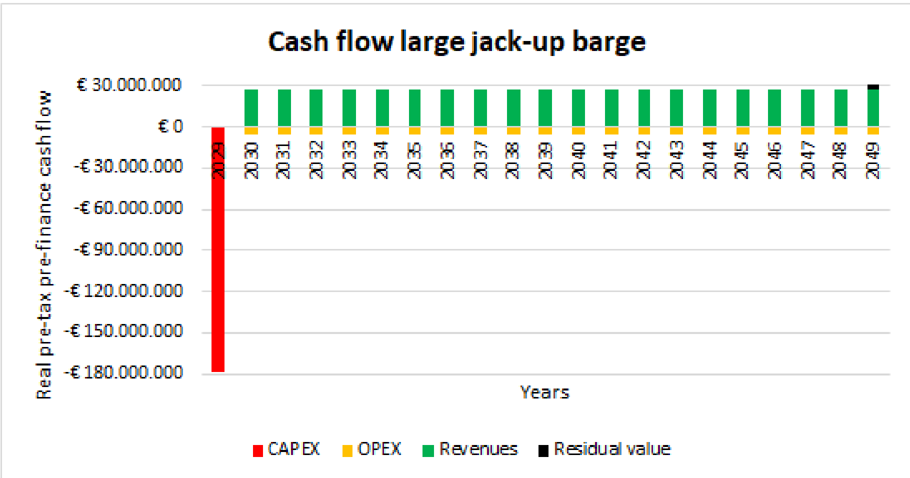


Figure 8.4: Forecasted cash flow large jack-up barge concept

For a project to be feasible the revenues need to be larger than the expenditures, but they can not simple be add-up without compensation for the time value of money. As explained in the previous paragraph a real discount rate of 7,5% is applied to the offshore port concepts. The discount rate is kept constant over time, so the present value of the cash flow at the beginning of the project can be calculated by equation 19 as shown in paragraph 7.1.4. The discounted cash flow of the large jack-up barge concept is shown in figure 8.5. The discounted cash flow of the other two port concepts can be found in appendix J.1.

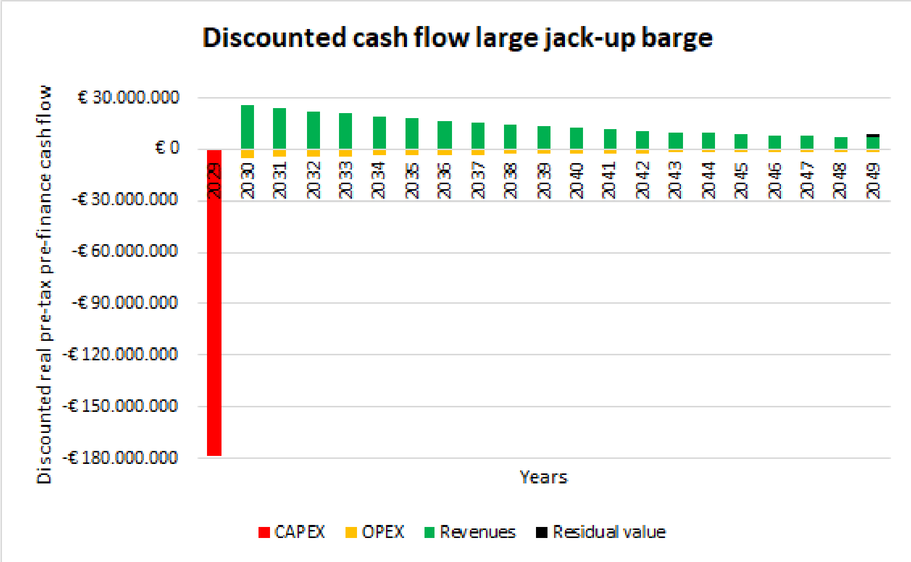


Figure 8.5: Forecasted discounted cash flow large jack-up barge concept

8.5.2 Performance indicators

The offshore port concepts are feasible when they have a positive NPV. So the sum of the present values of incoming and outgoing cash flows over their lifetime is larger than 0. An investor aims for a high expected NPV so the project is more viable. A NPV of 0 which requires a large investment could be seen as a risk by the investor. The NPV for all three port concepts are calculated and shown in table 8.4, these are based on a real discount rate of 7,5%.

The IRR is the discount rate at which the NPV of the project is zero. A feasible project should have an IRR that is larger than the applied discount rate of the project. The calculated IRR of the three offshore port projects is presented in table 8.4.

Besides the two main appraisal methods, some investors could also be interested in the payback time of the project. This is the period that it takes before the cumulative revenues are larger than the cumulative expenditures. The real discount rate of 7,5% is applied to calculated the payback times shown in table 8.4.

Table 8.4: NPV of the three potential port concepts

	Large jack-up barge	Barge	Barge & small jack-up barge
NPV (Million euro)	52.0	215.5	75.0
IRR (%)	11.1	50.0	13.9
Payback time (Years)	12.9	2.3	9.7

The NPV displayed in table 8.4 represent the NPV for the full lifetime of the port concepts. Due to the applied discount rate the NPV does not increase linear during the life time of the offshore port. The cumulative NPV for all three port concepts is shown in figure 8.6. The influence of the value of money over time is clearly visible, therefore the slope of the NPV curves declines over time.

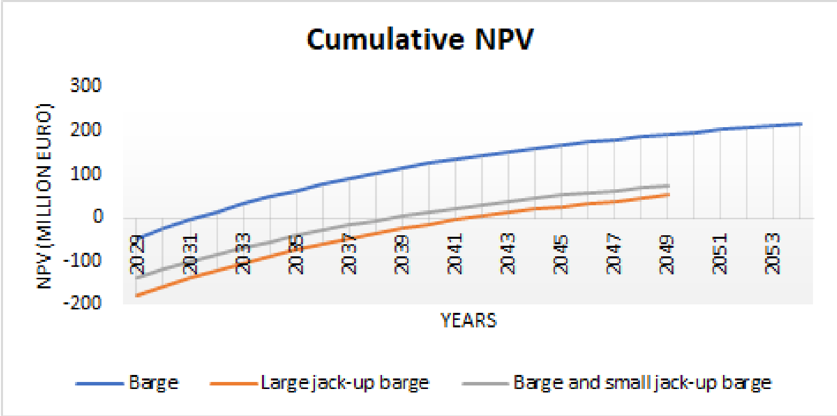


Figure 8.6: Cumulative NPV for all three port concepts over throughout their lifetime

8.6 Potential offshore port concept

Based on the NPV and IRR results in the previous section, the single barge is selected as a port concept. However, it is clearly demonstrated that all three port concepts have a financial potential. From the financial results it can be concluded that also other port concepts that have a technical potential, are financially feasible. The net present values in table 8.4 show that there is a large margin for the CAPEX and OPEX to increase and still be a financial feasible port concept.

The life-cycle aspects and remaining five demands are not taken into account for selecting the port concept with the highest potential, because they are only described qualitatively. Because the single barge has the best financial results it is selected as the port concept for the next section. Although it should be emphasized that all three port concepts have a high potential.

8.7 Sensitivity analysis

Input parameters that determine the financial potential of the single barge are varied. The sensitivity of these parameters on the financial potential, illustrates the market potential of the offshore port for certain market conditions. From the sensitivity analysis it can also be derived which parameters have a large influence on the potential of the offshore port.

Many parameters can be varied, though only ten parameters are selected within this research. The ownership, energy profit, parallel construction and market reach are the four main financial assumptions made throughout this research. The selection of the other six parameters is based on the expected influence on the financial potential. The sensitivity is normalised to the NPV for the base case of the single barge. The base case represents the savings of the logistical concept of a fast feeder vessel in comparison to the reference case. The following ten parameters are varied:

Distance to shore	Surface area	Assembling	Day rate vessels	Turbine capacity
Weather	Ownership	Energy generation	Market reach	Parellel construction

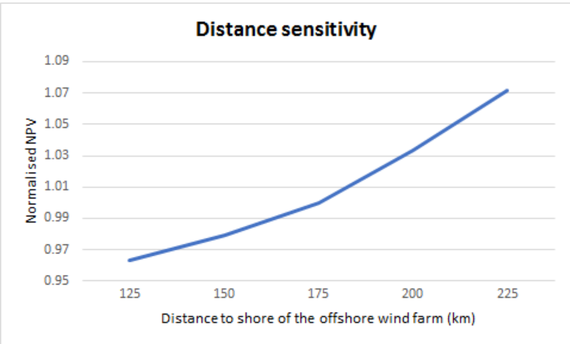
Distance to shore

The average construction of an offshore wind farm in Europe and the US Atlantic coast is at 75 kilometer from the shore by the year 2030, this is determined in chapter 2. The base case of the logistical savings has a distance to shore of 175 kilometer. This parameter influences the savings and the OPEX, which affect the NPV of the port. The result of varying the distance to shore is presented in figure 8.7a.

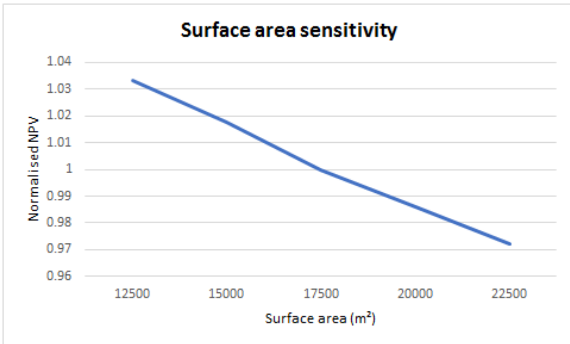
For each varied distance, the sailing speed and start moment of the vessels are optimised. A 50 kilometer smaller distance to shore has a negligible affect on the NPV, also the influence of a longer distance to shore is small.

Surface area

Varying the surface area of the port is only possible when the design is modular. This possibility is not analysed within this research, though it is addressed as a life-cycle opportunity. The influence of different surface areas when it is fixed for the lifetime of the port is small and linear as can be seen in figure 8.7b.



(a) Offshore port distance to shore



(b) Available surface area on the port

Figure 8.7: Sensitivity of distance and surface area on NPV

Assembling

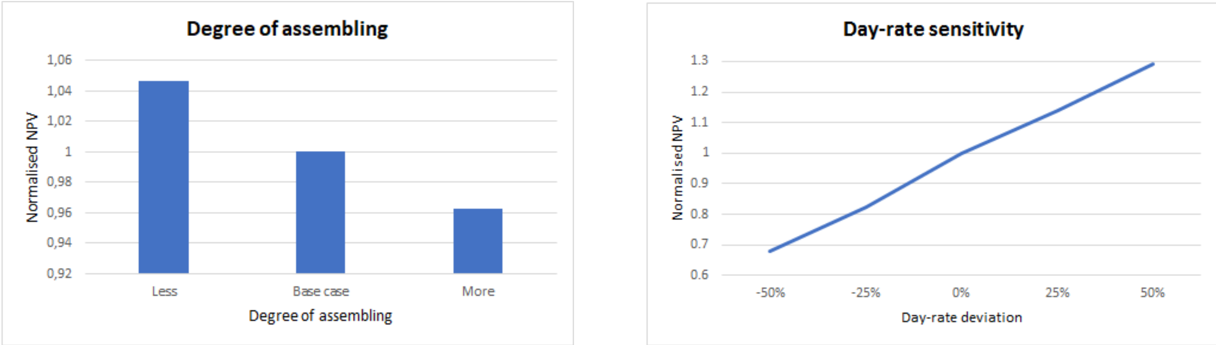
The assembling of the base case consist of a bunny ear, a tower and a separate blade. So in total three lifts are required to install the turbine. Increasing the degree of assembling leads to two required lift, one lift for the tower and blade and one lift for the bunny ear. Additional time during the assembling and a reduction of time during (un)loading and installation is taken into account. A decrease of the degree of assembling requires four lifts, there are two separate blades instead of one. The results are presented in figure 8.8a.

Day rate vessels

The fourth sensitivity analysis is about the day rates of the vessels and is conducted as well for the reference case and for fast feeder concept. A similar deviation to all the used vessels in the logistical model is assumed. The graph in figure 8.8b shows a linear influence of the day rate deviation. The sensitivity of this parameter is higher as for the distance to shore and the surface area.

Turbine capacity

A higher frequency of trips for the reference case is expected to be influential on the savings. More trips to the offshore wind farm have to be made when the wind farm size increases and the turbine capacity is increasing relatively less. Or when turbines are decreasing in capacity and the wind farm size is constant.
The base case of the logistical model assumes a turbine capacity of 12 MW and a wind farm size of 1.2 GW. The results of a sensitivity on the amount of trips is shown in figure 8.9a. It shows that a larger number of trips has approximately a quadratical influence on the NPV. When the amount of



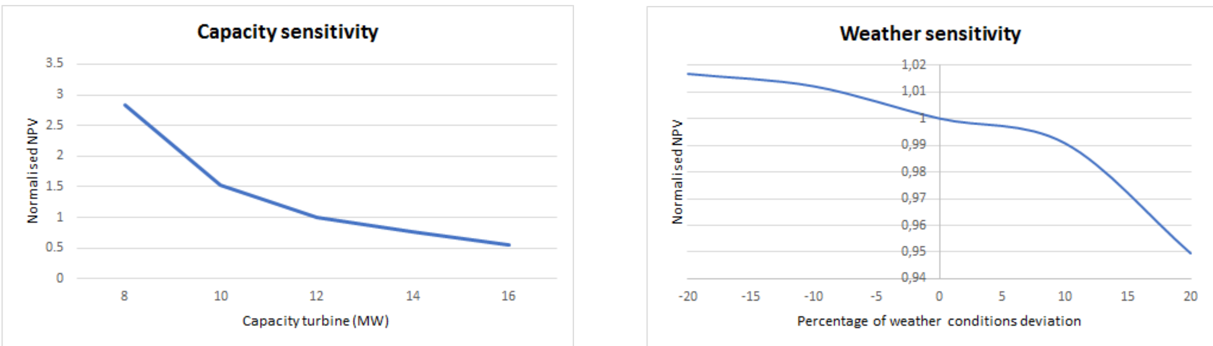
(a) Degree of assembling on the NPV of the port (b) Day rate in comparison to current market

Figure 8.8: Sensitivity of capacity and day rate on NPV

trips decreases the influence on the NPV is relatively less, but in comparison to other sensitivities it still has a large influence.

Weather

The global temperature rise can be slowed down when the share of energy generation by RES is high. Climate change also effects the weather conditions at sea. The applied weather data concerning the significant wave height, wind velocity and current velocity is varied, to evaluate the sensitivity of the weather on the NPV of the single barge.
As a consequence the three parameters that can be varied within the logistical model are modified to find the optimum value for the reference case and the new logistical concept. Also the assembling downtime due to the wind velocity that influences the NPV is changed, because the wind velocity deviates. The sensitivity is displayed in figure 8.9b and it is clear that more rough conditions decrease the potential of the offshore port. However, the NPV only decreases by 5% while the weather conditions increase by 20%. This is because the reference case also suffers from these rougher weather conditions.



(a) Turbine capacity for a 1.2 GW wind farm (b) Deviations of weather conditions

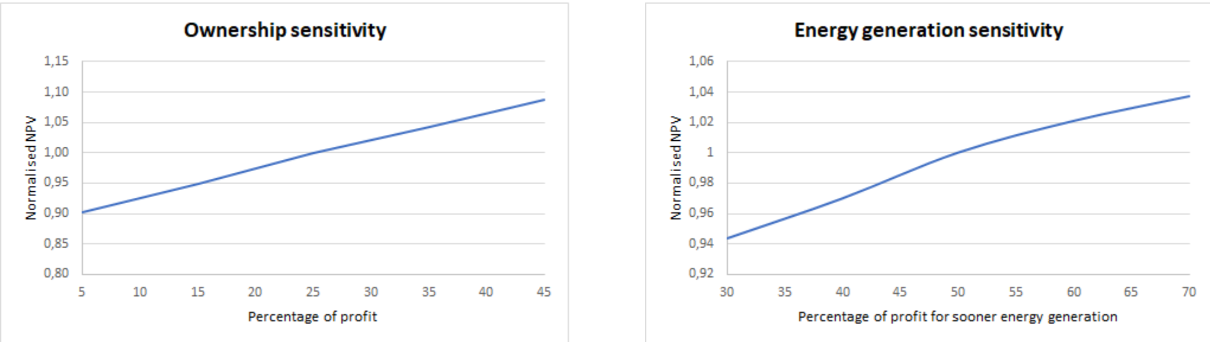
Figure 8.9: Sensitivity of turbine capacity and weather condtions on NPV

Ownership

The result of ownership is based on the assumed 25% profit for the owner when energy can be generated sooner than the reference case. A linear relation exist between this ownership factor and the NPV of the port. However, the degree of influence on the NPV is not known yet. This result is presented in figure 8.10a and shows a substantial influence on the NPV, but a lower effect than the day rate of vessels or the turbine capacity.

Energy generation

For each day that the construction of an offshore wind farm is finished sooner, the energy profit is €480.000. However, an assumed percentage of 50% is applied to these profits due to other barriers that arise. This factor of 50% is varied, the results to the NPV are shown in figure 8.10b.
It can be seen that the influence is small. This is due to the installation procedure of the turbine and the boundary conditions that limit faster finishing of a project. For 60% and higher, the jack-up vessel in the reference case carries three turbines instead of two. This is the reason for the declining slope from left to right figure 8.10b.



(a) Energy profit for the owner of the port

(b) Varying barrier percentage energy generation

Figure 8.10: Sensitivity of ownership and energy generation on NPV

Market reach

From the wind farms that are constructed during the lifetime of the port concept, 50% is assumed to call the offshore port for the construction of an offshore wind farm. The sensitivity of this percentage is analysed. However, a percentage that is larger than 62% is not of interest for the barge concept. The amount of waiting days a year then becomes 0 and no more projects can be executed.
For a 60% market reach the operational days a year are 265 and for a 30% market reach the operational days are 131. The amount of operational days is derived by subtracting the non operational days and the waiting days from 365. The result of the sensitivity can be seen in figure 8.11, there is a linear result with a substantial influence on the NPV.

Parallel construction

By determining the operational days a year it is assumed that 25% of the market is constructed parallel. So when three projects are constructed consecutively in one year, there is an additional project installed in the meanwhile. By deviating the assumed percentage the amount of operational days increases or reduces. So it has the same effect as the market reach on the NPV. However, the percentage of parallel construction has approximately 50% fewer influence on the NPV than the market reach. Therefore, no sensitivity graph of this parameter is produced.

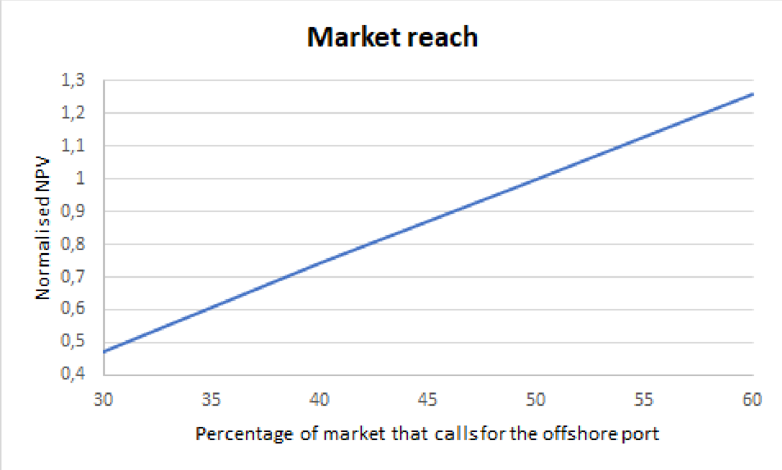


Figure 8.11: Percentage of the market that wants to be assisted by the offshore port

8.8 Business conclusion

An offshore port concept that reduces the vessel costs and the duration of transport and installation has a high potential for the future offshore wind market. The development of the turbine capacity and wind farm size is the most important market indicator for the potential of the offshore port concept. But also the market percentage that wants to use the port and the day rate of the vessels are influential parameters for the potential of the offshore port concept. However, in unfavorable and unexpected future conditions concerning the turbine capacity the NPV is still positive.

The NPV and IRR of the port concept show an investment opportunity within the offshore wind market. The single barge concept has the highest financial potential due to its relative low CAPEX value. The CAPEX of the jack-up barges are estimated by a market analysis of similar structures. It can be concluded that the gap between the current market and the offshore wind market, for a financial feasible offshore port concept is not existing under current favorable market conditions.
However, when adding up a lot of unfavorable conditions that are assumed to be more positive, the NPV value becomes lower than 0 for the large jack-up barge concept and the port concept consisting of a barge and small jack-up barge. For the small barge a NPV of below 0 is not expected based on the technical assumptions made throughout this research. Although the NPV shows a high potential, this port concept has most technical challenges and these should be answered during further research.

9. Conclusion

This is the finalising chapter of this study. Section 9.1 describes the final conclusions that are drawn from this study. A discussion on the uncertainties of this research is described in section 9.2. This is followed by the recommendations for further research.

9.1 Conclusion

The goal of this study is to explore the market potential of an offshore port concept, to reduce the LCOE for an offshore wind farm. This study focuses on the market conditions of the offshore wind market by 2030 and the workability of an offshore port concept in combination with the financial savings. By looking at multiple variables, an integral conclusion can be drawn on the potential of the offshore port concept.

The main conclusion that is drawn from this study is: When the offshore wind market follows the tendency of developments of the last years, there is a market potential for an offshore port concept to reduce the construction costs. According to this study, the total savings are highest for an offshore port concept that is supplied by a fast vessel. Despite technical uncertainties and based on the boundary condition of a maximum of five turbines at the offshore port, the offshore port concept with most potential is the single barge.

The potential of an offshore port concept is sensitive to the ratio of turbine capacity and the wind farm capacity, also the day rate of the vessels and the market share that is eager to make use of the offshore port are substantial sensitivities for the potential. Further research should focus on the interest of potential port owners and the motion response analysis should be performed into more detail.

Additional conclusions that can be drawn from this study and support this main conclusion are presented below, grouped by the three main topics of this study.

Offshore wind market

In order to determine the forecasted offshore wind market developments, academic works are reviewed and market players throughout the entire construction phase are interviewed.

- There is just one paper that discusses the potential savings of an offshore port for the construction of an offshore wind farm. The results of this work show a potential time saving of 500% when not taking into account technical or financial feasibility. The clear potential of this academic research is not in line with the results explored within this research which does take the technical and financial feasibility into account. The time savings are nearly 25% and the financial savings provide a 120% return on investment.

- Due to the high amount of cancellations of planned wind farms, academic works show a large deviation on the potential capacity of the offshore wind market. Based on the three most reliable market indications of future offshore wind capacity, an estimation is made on the average conditions for construction of an offshore wind farm by the year 2030. This estimation is displayed in figure 9.1. The bubble size of the European market indicates an installed capacity of 60 GW.

- A result from the interviews shows six market demands throughout the construction phase of offshore wind. The demand to decrease the rental period of the vessels has the highest effect on the profitability of the port. Based on the market analysis there is a low potential for floating wind turbine foundations, but if a deep water port is available, the construction of spar-buoy foundations could substantially influence the profitability of the offshore port.

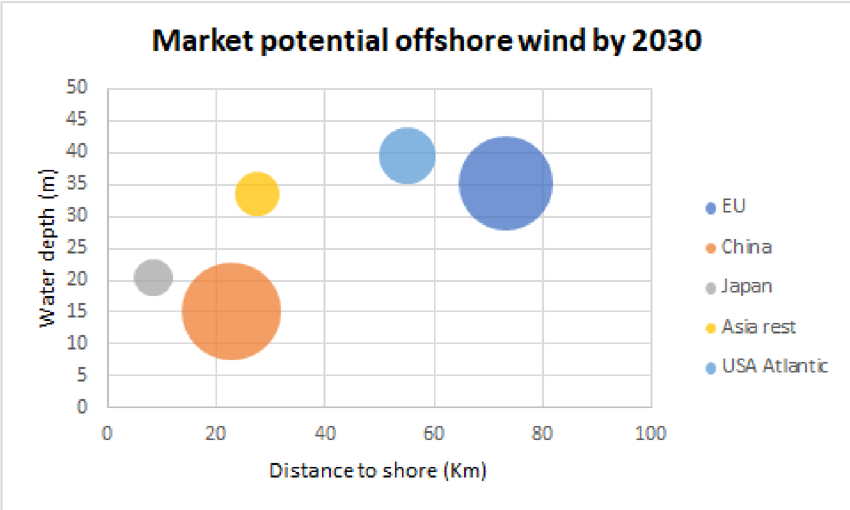


Figure 9.1: Average market conditions for construction by the year 2030

Port concepts

A lot of judgments are made during this research, as a result there are seven potential port concepts. A port concept consist of one or two support structures, which are referred to as port components. The workability of seven port components is calculated and based on the workability and transportability three port concepts are selected. The three selected port concepts are: a large jack-up barge, a single barge and a single barge in combination with a small jack-up barge. The following conclusions can be generally drawn on the offshore port concept.

- The six demands can be fulfilled by four activities at the offshore port. These are: assembling of the turbine, (un)loading of the turbine components, the use of storage area and the sleeping and transfer of the crew. These four activities have a maximum condition for the workability. Wind velocity and storage area are leading this workability for fixed port components and for a floating port component the motion response is the leading workability condition.

- The barge, semi-submersible, VLCC, versabuoy, jack-up barge, pneumatic stabilised structure and the jacket are taken into account as port components. The pneumatic stabilised structure has to little buoyancy to be a suitable port component. The motion response of the VLCC is to high for a satisfying workability and the jacket has a low mobility. The four remaining potential port components, form the seven potential port concepts.

Potential savings

The revenues and expenditures are determined for three offshore port concepts. Based on the discounted cash flows throughout the lifetime of the offshore port the financial performance are evaluated by the NPV, IRR and payback time. The revenues mainly consist of vessel savings and in a smaller extent by the electricity profit of a sooner generation of energy. Five conclusions are drawn concerning the potential savings of an offshore port concept.

- The developed logistical model shows that the logistical concept of a fast feeder vessel leads to the highest saving potential of the offshore port. It decreases the project duration by 20% and the vessel costs by 50%.
- The boundary condition of a maximum of five turbines at the offshore port and the required duration for installation of the turbine limit the increase of savings by this new logistical concept.
- Based on a lifetime of 20 years for the large jack-up barge and combined port concept and a lifetime of 25 years for the single barge, the NPV, IRR and payback time are determined as shown in table 9.1. Although the costs and savings are an estimate and the NPV and IRR could decrease, it shows a clear potential for the offshore port concept to reduce the construction costs for the offshore wind market.
- The total expenditures for an offshore wind farm during the lifetime vary between one and two billion euro. Although the savings of the offshore port concept could be €23.000.000 per project, this is still a small share of the total value of an offshore wind farm project.
- The turbine capacity in combination with the wind farm size have a large influence on the values presented in table 9.1. Also the day rate of the vessels and the market share that wants to make use of the offshore port have a substantial influence on the three financial indicators.

Table 9.1: Financial potential offshore port

	Large jack-up barge	**Barge**	**Barge & small jack-up barge**
NPV (Million euro)	52.0	215.5	75.0
IRR (%)	11.1	50.0	13.9
Payback time (Years)	12.9	2.3	9.7

9.2 Discussion

Numerous assumptions are made during this study that lead to uncertainties of the offshore port potential. To increase the reliability and accuracy of this study it is recommended to take note of these assumptions. Numbers one, two and three that are listed below, emphasize the technical point of discussions and numbers four to seven emphasize financial points of discussion.

1. The floating port components of a barge, semi-submersible and VLCC are analysed on their static stability and motion response. Other floating port components like the versabuoy and PSS are not evaluated into depth due to a lack on information of these port components. This provides a distorted indication on the workability of these port components.
2. No analyses on the mooring forces and berthing forces is conducted. Also the green water effect of the barge and its assumption of a 100% stiffness is not elaborated in this study. This leads to behavioural uncertainties in the feasibility of the floating port components. Although it is financially the most profitable port concept, a barge within the port concept also leads to more uncertainties and challenges in comparison to the large jack-up barge concept.
3. Among others, two cranes are taken into account to calculate the vertical loads on the port. Although the two trucks are not included, the motion response or statical stability of the three

port concepts is hardly influenced by an addition of this relative small vertical load. An additional crane would make the logistical process on the offshore port easier, also with this extra load the influence on the motion response and statical stability is small.

4. The logistical model includes a 10% margin on the entire project duration and delays due to weather conditions. However, when the offshore port concept is during its used for multiple offshore wind farm projects, there is a higher probability of unforeseen delays as for a single project. The logistical model assumes a repetition of the base case project with for each repetition, similar conditions. Though, when used for multiple offshore wind farm projects, there can be expected that at least one project experiences a high delay.

5. The reference case of the logistical model represent a jack-up vessel that carries two turbines. However, when applying the calculated real discount rate of 7,5% instead of the assumed 5,5% the lowest costs are achieved by carrying three turbines. Based on the sensitivity results of the electricity profit percentage, a decrease of 5% on the NPV can be expected.

6. A sensitivity analysis is conducted for ten parameters. Other parameters can have an influential affect on the NPV and IRR of the offshore project as well. Examples of parameters that could be integrated in the sensitivity analysis, are a different amount of consecutive projects executed before returning to the onshore port for a waiting period, the lifetime of the offshore port concepts and more frequent transport of the port between the US and European markets.

7. The logistical concept of two jack-up vessels that sail between the onshore port and the wind farm and also execute the installation is not taken into account. It is not expected that if a contractor has two jack-up vessels it is eager to use both of them for one offshore wind farm project. If two contractors are involved with their installation vessel the responsibility of delay is a difficult topic within the contract.
   However, the savings are expected to be €240.000 a day when the project finishes a day sooner and the costs per day for an installation vessel are lower. So this logistical concept could be financially more profitable than the reference case, therefore it should be evaluated.

9.3 Recommendation

Further research in this study area can help to take away the uncertainties, that required the researcher to make assumptions during this study. With the obtained knowledge during this research, the following recommendations are suggested concerning the offshore wind market, port concepts and the financial feasibility.

Offshore wind market

Developments of the offshore wind market should be forecasted into more detail by a larger group of market players. Due to the sensitivity on the potential of the offshore port, the focus of this larger market review should be mainly on the following three aspects:

- The turbine capacity development and the offshore wind farm size development.
- The day rates of the vessels in the offshore wind market.
- The amount of potential offshore wind farm owners that is interested in applying the offshore port concept during the construction of an offshore wind farm.

The US Atlantic coast is combined with Europe as the potential areas for the offshore port. The developments within the US offshore wind market rely on the legislation regarding the Jones Act. It should be investigated into more detail if the offshore port concept can bypass this act, this increases the potential of the offshore port concept. Also the legislation regarding an offshore port that is located on international waters and the allowance for a fixed location of the port during the project, should be researched more extensively.

Port concepts

Seven potential port concepts are presented during this research, six of them contain a floating port component. The technical feasibility of these port concepts are influenced by the mooring system of the port and the mooring forces of berthing vessels. This aspect is not analysed within this study and is the most relevant technical topic to be investigated into further detail.
Motion response are derived for the barge, semi-submersible and VLCC to determine the workability of these port components. This hydrodynamic assessment is conducted with a uniformly distributed load and a the effect of green water not being implemented in the assessment. The influence of these aspects on the workability of the offshore port should be taken into account in a further research.
A possibility to decrease the downtime of the offshore port, is to let the (un)loading of turbines be less affected by the wind velocity. A sliding system, a roll on roll off system or a conveyor belt could be implemented at the offshore port. Reducing the influence of the wind velocity of the downtime by assembling is expected to be more challenging, just like the reduction of motion response due to the presence of a limiting Hs.

Potential savings

There are three main recommendations to increase the certainty on the financial potential of the offshore port concepts.

- The vessel savings are based on a logistical model developed by hand, that makes use of EXCEL. The reference case is validated by the ECN Install tool 2.1. When the ECN install tool 3.0 is available with the interdependency between installation steps, the logistical savings should be validated.
- The potential savings of three new logistical concepts are compared to the reference case. More logistical concept should be compared to find the lowest total costs for the construction of an offshore wind farm.
- From the six demands derived from the market players, only the decrease of the vessel rental period and the spar-buoy foundation assembling at a deep water port are calculated quantitatively. Of which the potential of the spar-buoy assembling at a deep water port is only indicated by the time savings. The other four demands are expected to have a lower affect on the profit. It is recommended to analyse these four qualitatively described demands into more detail.
- The contractual agreements of the construction of an offshore wind farm are not taken into account during this research. When the construction company is rewarded for finishing the project sooner, the interest of the company regarding an offshore port concept increases. The details of a general offshore wind construction contract could provide valuable insights for the selection of the logistical concept.

Bibliography

[1] 4COffshore. (2017). Offshore wind farms. Retrieved 07-11-2017, from http://www.4coffshore.com/windfarms/.

[2] Ahn, D., Shin, S.-c., Kim, S.-y., Kharoufi, H., & Kim, H.-c. (2017). Comparative evaluation of different offshore wind turbine installation vessels for korean west–south wind farm. *International Journal of Naval Architecture and Ocean Engineering*, *9*(1), 45–54.

[3] Ait-Alla, A., Quandt, M., & Lutjen, M. (2013). Aggregate installation planning of offshore wind farms. In *Proceedings of the 7th international conference on communications and information technology (CIT 13). Cambridge (US)*, (pp. 130–35).

[4] Ali, A. (2005). *The Floating Transshipment Container terminal*. Master's thesis, University of Delft, Delft, Netherlands.

[5] Arapgianni, A., Genachte, A., et al. (2013). Deep water: the next step for offshore wind energy. *European Wind Energy Association, 2013*.

[6] Arends, G. (2017). Handleiding ontwerpen draagconstructies. TU Delft, Faculty of Building Schiences.

[7] Asgarpour, M. (2016). Assembly, transportation, installation and commissioning of offshore wind farms. In *Offshore Wind Farms*, (pp. 527–541). Elsevier.

[8] Ayuso, M., Kjaer, C., Anticoli, M., Rodolfo, R., et al. (2016). World energy resources, wind 2016. *World energy council*.

[9] Baars, v. S., Bezuyen, K., Colenbrander, W., Kuijper, H., Molenaar, W., Spaargaren, C., & Vrijling, J. (2009). Course: Hydraulic structures 1, lecture notes ct3330–general. *TU Delft*.

[10] Bachanan, S. (2012). Push is on the declutter golf of idle iron. Retrieved 6-05-2018, from https://www.marinelink.com/news/declutter-push-gulf347104.

[11] Barltrop, N. D. (1998). *Floating Structures: a guide for design and analysis*, vol. 1. Oilfield Pubns Inc.

[12] Barltrop, N. D. (1998). *Floating Structures: a guide for design and analysis*, vol. 2. Oilfield Pubns Inc.

[13] Beels, C., Henriques, J., De Rouck, J., Pontes, M., De Backer, G., & Verhaeghe, H. (2007). Wave energy resource in the north sea. In *EWTEC 2007-7th European Wave and Tidal Energy Conference*.

[14] Benford, H. (1969). The practical application of economics to merchant ship design. Tech. rep., University of Michigan, Michigan, USA.

[15] Berner, D., & Gerwick, B. C. (2001). Large floating concrete lng/lpg offshore platforms. In *UJNR/MFP 24th Joint Meeting*.

[16] Berry, A., & Jarvis, R. (2005). *Accounting in a business context*. Cengage Learning EMEA.

[17] Bhambu, M. K. (2016). Future of wind energy in india. Government College of Commerce and Business Administration, Chandigarh.

[18] Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915.

[19] Bishop, R. H. (2002). *The Mechatronics Handbook, -2 Volume Set*. CRC press.

[20] Blanco, M. I. (2009). The economics of wind energy. *Renewable and sustainable energy reviews*, *13*(6), 1372–1382.

[21] BOE. (2015). Renewable energy promotion policies in taiwan. Ministry of economic affairs Taiwan.

[22] Boers, G., Brongers, Y., & van Heijningen, R. (2016). Motion sickness at sea. *Maritime Symposium Rotterdam*.

[23] Breton, S.-P., & Moe, G. (2009). Status, plans and technologies for offshore wind turbines in europe and north america. *Renewable Energy*, *34*(3), 646–654.

[24] Brinkmann, S. (2014). Interview. In *Encyclopedia of Critical Psychology*, (pp. 1008–1010). Springer.

[25] Bussel, G. (2016). Wind werkt.....ook in 2050. Retrieved 15-05-2018, from `https://www.kivi.nl/uploads/media/56050192e9fb6/20130613_Van_Bussel_Wind_2050.pdf`.

[26] C2ES. (2017). State climate policy. Retrieved 09-11-2017, from `https://www.c2es.org/content/state-climate-policy/`.

[27] Capros, P., De Vita, A., Tasios, N., Apostolaki, M., Paroussos, K., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., et al. (2013). Eu reference scenario 2013-energy, transport and ghg emissions trends to 2050. European Commission Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport.

[28] Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., et al. (2016). Eu reference scenario 2016-energy, transport and ghg emissions trends to 2050. European Commission Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport.

[29] Carroll, J., McDonald, A., & McMillan, D. (2015). Reliability comparison of wind turbines with dfig and pmg drive trains. *IEEE Transactions on Energy Conversion*, *30*(2), 663–670.

[30] Carroll, J., McDonald, A., & McMillan, D. (2016). Failure rate, repair time and unscheduled o&m cost analysis of offshore wind turbines. *Wind Energy*, *19*(6), 1107–1119.

[31] Chandrasekaran, S. (2016). *Dynamic analysis and design of offshore structures*. Springer.

[32] Chandrasekaran, S., & Jain, A. K. (2017). *Ocean Structures: Construction, Materials, and Operations*. Crc Press.

[33] Chozas, J. F., Kofoed, J. P., & Jensen, N. E. H. (2014). User guide–coe calculation tool for wave energy converters: ver. 1.6-april 2014.

[34] Commission, U. S. F. E. R. (2003). *Ocean Express Pipeline Project: Environmental Impact Statement*.
URL https://books.google.nl/books?id=WfA0AQAAMAAJ

[35] Cornell University Law School, U. S. A. (2017). Legal information institute, title 46 appendix shipping: Chapter 24 - merchant marine act, 1920. Retrieved 09-11-2017, from https://www.law.cornell.edu/uscode/html/uscode46a/usc_sup_05_46_10_24.html.

[36] Dalgic, Y., Lazakis, I., & Turan, O. (2013). Vessel charter rate estimation for offshore wind o&m activities. *Developments in maritime transportation and exploitation of sea resources.*.

[37] Dalgic, Y., Lazakis, I., Turan, O., & Judah, S. (2015). Investigation of optimum jack-up vessel chartering strategy for offshore wind farm o&m activities. *Ocean Engineering*, *95*, 106–115.

[38] Damassa, T., Ge, M., & Fransen, T. (2014). The u.s. greenhouse gas reduction targets. *World Resources Institute*. Retrieved 07-11-2017, from https://www.wri.org/sites/default/files/WRI14_Fact_Sheet_US_GHG_singles.pdf.

[39] Danad, M. (2015). The reuse of caissons in the port of rotterdam.

[40] Darvishi-Alamouti, S., Bahaari, M.-R., & Moradi, M. (2017). Natural frequency of offshore wind turbines on rigid and flexible monopiles in cohesionless soils with linear stiffness distribution. *Applied Ocean Research*, *68*, 91–102.

[41] de Vos, R. (2016). Flow, competitive through cooperation. Retrieved 15-07-2017, from http://www.flow-offshore.nl/images/flow-openbaar/FLOW_Book-11_EN.pdf.

[42] DECC. (2013). Electricity generation costs. *Report commissioned by UK department for business, energy & industrial strategy*.

[43] Department Of Energy, U. S. (2015). A new era for wind power in the united states. *Wind Vision*.

[44] Dewan, A. (2014). *Logistic & Service Optimization for O&M of Offshore Wind Farms*. Master's thesis, University of Delft, Delft, Netherlands.

[45] Dewan, A., & Asgarpour, M. (2016). Refernce o&m concept for near and far offshore wind farms. *Operation & maintenance Joint Industry Program*.

[46] Dewan, A., Asgarpour, M., Savenije, R., & Nederland, S. E. C. (2015). *Commercial Proof of Innovative Offshore Wind Installation Concepts Using ECN Install Tool*. ECN.: E-series. ECN.
URL https://books.google.nl/books?id=1tCrswEACAAJ

[47] Dillman, D. A., & Christian, L. M. (2005). Survey mode as a source of instability in responses across surveys. *Field methods*, *17*(1), 30–52.

[48] Dinwoodie, I., Endrerud, O.-E. V., Hofmann, M., Martin, R., & Sperstad, I. B. (2015). Reference cases for verification of operation and maintenance simulation models for offshore wind farms. *Wind Engineering*, *39*(1), 1–14.

[49] Dinwoodie, I., McMillan, D., Revie, M., Lazakis, I., & Dalgic, Y. (2013). Development of a combined operational and strategic decision support model for offshore wind. *Energy Procedia*, *35*, 157–166.

[50] DNV-GL. (2016). Floating offshore structures. Retrieved 10-03-2018, from https://www.dnvgl.us/Downloads/TW16-Floating%20Offshore%20Structures_Hydro_handout_tcm14-80891.pdf.

[51] DNV-GL (2017). Energy transition outlook 2017. Retrieved 15-05-2018, from https://www.dnvgl.com/technology-innovation/sri/climate-action/research-projects/energy-transition-outlook.html.

[52] DONG. (2017). Dong energy awarded three german offshore wind projects. Retrieved 28-11-2017, from http://www.dongenergy.com/en/media/newsroom/company-announcements-details?omxid=1557851.

[53] Dorliner, H., & Dixon, M. (2012). Maritime cabotage laws and wind power installations in the gulf of maine. University of Maine.

[54] Dowd, P. J. (1974). Sleep deprivation effects on the vestibular habituation process. *Journal of Applied Psychology*, *59*(6), 748.

[55] Durstewitz, M., Berkhout, V., Hirsch, J., Pfaffel, K., S. Rohrig, et al. (2017). New turbine installation by average distance from coast and water depth. Retrieved 16-07-2017, from http://windmonitor.iwes.fraunhofer.de/windmonitor_en/4_Offshore/2_technik/2_Kuestenentfernung_und_Wassertiefe/.

[56] Ehrhardt-Unglaub, T. (2013). Grid connection to the mainland. Energy symposium 2013. URL https://www.waddensea-forum.org/images/archive/meetings/Energy/symp_2013/Tennet_presentation_2013_06_03.pdf

[57] Electrek (2017). Updated: Cheapest electricity on the planet is mexican wind power. Retrieved 30-11-2017, from https://electrek.co/2017/11/16/cheapest-electricity-on-the-planet-mexican-solar-power/.

[58] Elzinga, T., Iribarren, J., & Jensen, O. (1993). Movements of moored ships in harbours. In *Coastal Engineering 1992*, (pp. 3216–3229).

[59] Energy, D. O., & Climate Change, U. K. (2009). Uk offshore energy strategic environmental assessment. *Offshore energy SEA*.

[60] EuopeanCommission. (2016). Energy strategy. Retrieved 20-10-2017, from https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union.

[61] Faiz, T. (2014). *Minimization of transportation, installation and maintenance operations costs for offshore wind turbines*. Master's thesis, Louisiana State University, Louisiana, U.S.

[62] Faseela, A., & Jayalekshmi, R. (2015). In-place strength evaluation of jacket platforms and optimization of bracing configurations. *International journal of research in Advent Technology*.

[63] Fernandez, R. P., & Pardo, M. L. (2013). Offshore concrete structures. *Ocean Engineering*, *58*, 304–316.

[64] Ferroukhi, R., & Wuester, H. (2017). Rethinking energy 2017. *International Renewable Energy Agency (IRENA)*.

[65] Floateurope (2017). pneumatically stabilised platform. Retrieved 21-2-2018, from http://floateurope.eu/technology/pneumatically-stabilized-platforms-psp/.

[66] Fousert, M., Vrijling, J., Molenaar, W., & van Kessel, J. (2009). Floating breakwater, theoretical study of a dynamic wave attenuating system. In *Coastal Structures 2007: (In 2 Volumes)*, (pp. 339–350). World Scientific.

[67] Franco, L., De Gerloni, M., & Van der Meer, J. (1995). Wave overtopping on vertical and composite breakwaters. In *Coastal Engineering 1994*, (pp. 1030–1045).

[68] Frangopol, D., & Sorensen, J. (2005). *Advances in Reliability and Optimization of Structural Systems: Proceedings 12th IFIP Working Conference on Reliability and Optimization of Structural Systems, Aalborg, Denmark, 22-25 May, 2005*. Balkema-proceedings and monographs in engineering, water, and earth sciences. Taylor & Francis.
URL https://books.google.nl/books?id=SIFjKr9IAYMC

[69] Freeman, k., Hundleby, g., Nordstrom, C., et al. (2016). Floating foundations: a game changer for offshore wind power. *International Renewable Energy Agency (IRENA)*.

[70] Fried, L., Qiao, L., Sawyer, S., et al. (2016). Global wind energy report, annual market update 2015. *Global wind energy council*.

[71] Fried, L., Qiao, L., Sawyer, s., et al. (2017). Global wind report, annual market update 2016. *Global wind energy council*.

[72] Garret, C., Giles, J., Kumar, P., et al. (2016). Supply chain, port infrastructure and logistics study. *Fowind.*.

[73] Gaythwaite, J. W. (2014). Mooring of ships to piers and wharves. American Society of Civil Engineers.

[74] Geos, F. (2001). *Wind and wave frequency distributions for sites around the British Isles*. Great Britain, Health and Safety Executive.

[75] Gerwick Jr, B. C. (2007). *Construction of marine and offshore structures*. CRC press.

[76] Gielen, D., Saygin, D., Wagner, N., et al. (2017). Renewable energy prospects for india. *International renewable energy agency*.

[77] Green, R., & Vasilakos, N. (2011). The economics of offshore wind. *Energy Policy*, *39*(2), 496–502.

[78] Greeves, J. (2017). Versbuoy - white paper. Retrieved 20-2-2018, from http://www.vbuoy.com/About_Versabuoy/whitepaper.html.

[79] Groenenberg, X. (2016). *Floating Cruise Terminal in Exposed Sea at Curaçao: Feasibility Study on the Dynamic Behaviour and Resulting Downtime*. Master's thesis, University of Delft, Delft, Netherlands.

[80] H., S. (2016). *How to make the fish farming industry more climate friendly*. Master's thesis, University of Stavanger, Stavanger, Norway.

[81] Hansen, J. H., & Holmen, I. M. (2011). Sleep disturbances among offshore fleet workers. a questionnaire-based survey. *International maritime health*, *62*(2), 123–130.

[82] Hasager, C. B., Mouche, A., Badger, M., Bingöl, F., Karagali, I., Driesenaar, T., Stoffelen, A., Peña, A., & Longépé, N. (2015). Offshore wind climatology based on synergetic use of envisat asar, ascat and quikscat. *Remote Sensing of Environment*, *156*, 247–263.

[83] Haver, S., & Winterstein, S. R. (2009). Environmental contour lines: A method for estimating long term extremes by a short term analysis. *Transactions of the Society of Naval Architects and Marine Engineers*, *116*, 116–127.

[84] Haver, S. K. (2011). Prediction of characteristic response for design purposes. *Lecture notes for MR*, *8207*.

[85] He, D.-X. (2016). Coping with climate change and china's wind energy sustainable development. *Advances in Climate Change Research*, *7*(1), 3–9.

[86] Henesey, L., Davidsson, P., & Persson, J. A. (2008). Evaluation of automated guided vehicle systems for container terminals using multi agent based simulation. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, (pp. 85–96). Springer.

[87] Heptonstall, P., Gross, R., Greenacre, P., & Cockerill, T. (2012). The cost of offshore wind: Understanding the past and projecting the future. *Energy Policy*, *41*, 815–821.

[88] Hermans, K., & Peeringa, J. (2016). Future xl monopile foundation design for a 10 mw wind turbine in deep water.

[89] Hernández, C. V., Telsnig, T., & Pradas, A. V. (2017). Jrc wind energy status report 2016 edition.

[90] Ho, A., Mbistrova, A., Corbetta, G., et al. (2016). The european offshore wind industry - key trends and statistics 2015. *European wind energy association*.

[91] Ho, A., Mbistrova, A., et al. (2017). The european offshore wind industry - key trends and statistics 2016. *Windeurope*.

[92] Holthuijsen, L. H. (2010). *Waves in oceanic and coastal waters*. Cambridge university press.

[93] Hoste, G., Dvorak, M., & Jacobson, M. Z. (2009). Matching hourly and peak demand by combining different renewable energy sources. *VPUE Final Report, Stanford University, Palo Alto, California*.

[94] Huang, E. T., Chen, H.-C., et al. (2001). Stability investigation of a pontoon barge in wave basin. In *The Eleventh International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

[95] Hundleby, G., Freeman, K., et al. (2017). Unleashing europe's offshore wind potential, june 2017. *Windeurope*.

[96] IEA. (2016). *World energy outlook 2016: Special focus on renewable energy*. Organization for economic cooperation and development oecd.

[97] Ikeda, Y., Komatsu, K., Himeno, Y., & Tanaka, N. (1977). On roll damping force of ship-effect of hull surface pressure created by bilge keels. *Journal of Kansai Society of Naval Architects*, *165*, 31–40.

[98] Ilas, A., Ralon, P., Rodriques, a., et al. (2018). Renewable power generation costs in 2017. *IRENA.*.

[99] IMCA., et al. (2010). Guidance on the transfer of personnel to and from offshore vessels. Publication.

[100] Irawan, C. A., Jones, D., & Ouelhadj, D. (2015). Bi-objective optimisation model for installation scheduling in offshore wind farms. *Computers & Operations Research*.

[101] Jia, J. (2017). Offshore structures versus land-based structures. In *Modern Earthquake Engineering*, (pp. 73–106). Springer.

[102] Journée, J. (1976). *Prediction of speed and behaviour of a ship in a sea-way*. Delft University of Technology.

[103] Journée, J., & Massie, W. (2001). *OFFSHORE HYDROMECHANICS*. Delft University of Technology.

[104] JWPA. (2017). Wind power in japan. Revision2017 Experts Meeting Renewable Energy Institute, march 7, 2017.

[105] Kaiser, M. J., & Snyder, B. (2010). Offshore wind energy installation and decommissioning cost estimation in the us outer continental shelf. *US Bureau of Ocean Energy Management, Enforcement and Regulation*.

[106] Kaiser, M. J., & Snyder, B. (2012). *Offshore wind energy cost modeling: installation and decommissioning*, vol. 85. Springer Science & Business Media.

[107] Kaiser, M. J., & Snyder, B. F. (2012). Modeling offshore wind installation vessel day-rates in the united states. *Maritime Economics & Logistics*, *14*(2), 220–248.

[108] Kaiser, M. J., Snyder, B. F., et al. (2012). Labor, material needs estimated for us construction of jack ups. *Oil & Gas Journal*, *110*(8), 50–50.

[109] Kaldellis, J., & Kapsali, M. (2013). Shifting towards offshore wind energy—recent activity and future development. *Energy policy*, *53*, 136–148.

[110] Kaldellis, J. K., & Zafirakis, D. (2011). The wind energy (r)evolution: A short review of a long history. vol. 36, (pp. 1887–1901). Elsevier.

[111] Karimirad, M. (2014). Combined wave-and wind-power devices. In *Offshore Energy Structures*, (pp. 105–128). Springer.

[112] Karppinen, T., Helasharju, H., & Aitta, T. (1988). Seakeeping performance prediction program skp. *Nordforsk*.

[113] Katz, J., & Denholm, P. (2015). Using wind and solar to reliably meet electricity demand, greening the grid; nrel (national renewable energy laboratory). Tech. rep., NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)).

[114] Ko, K. (2015). *Realising a floating city*. Master's thesis, University of Delft, Delft, Netherlands.

[115] Koekoek, M. (2010). Connecting modular floating structures.

[116] Koole, T. (2015). *Modern Jack-Ups and their Dynamic Behaviour: Investigating the trends and limits of moving into deeper waters*. Master's thesis, TU Delft, Delft, Netherlands.

[117] Krape, E. (2017). research team determines that constructing offshore wind turbines in port is the most cost effective method. University of Delaware, "Retrieved 20-11-2017, from https://phys.org/news/2017-10-team-offshore-turbines-port-effective.html.

[118] Kurt, I., Boulougouris, E., & Turan, O. (2015). Cost based analysis of the offshore port system. In *ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*, (pp. V001T01A044–V001T01A044). American Society of Mechanical Engineers.

[119] Larive (2014). Market study: Wind energy in brazil. *Ministry of Economic Affairs in the Netherlands*.

[120] Leijendeckers, P., Fortuin, J., van Herwijnen, F., & Schwippert, G. (2003). *Polytechnisch zakboek*. Reed business information.

[121] Lensink, L., S.M. Beurskens (2017). Kosten wind op zee 2017. Retrieved 21-01-2018, from https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-N--17-022.

[122] Li, W., Wei, P., & Zhou, X. (2014). A cost-benefit analysis of power generation from commercial reinforced concrete solar chimney power plant. *Energy Conversion and Management*, *79*, 104–113.

[123] Ligteringen, H. (2017). *Ports and Terminals*. Delft Academic Press.

[124] Ligteringen, H., & Velsink, H. (1999). Ports and terminals. *VSSD: Lecture Notes CTwa*, (pp. 4330–5306).

[125] Lis, N., DeLeon, J., Ektvedt, I., et al. (2017). Canada's adoption of renewable power sources. *National Energy Board*.

[126] Lourens, E. (2015). Support structure design. Lecture sheets OE5662 Offshore Wind Farm Design, University of Delaware.

[127] Lyman, R. (2015). Climate change targets for canada examining the implications. *Friends of Science*.

[128] Machado, C. L., & Santos, M. A. (2002). Structural optimization on topside supports for ship-shaped hulls. In *ASME 2002 21st International Conference on Offshore Mechanics and Arctic Engineering*, (pp. 417–423). American Society of Mechanical Engineers.

[129] Maldivesbest. (2013). Solar island for renewable energy in maldives capital. Retrieved 21-0-5-2018, from http://www.maldivesbest.com/news/solar-island-maldives/.

[130] Mambra, S. (2017). The saipem 7000: one of the biggest cranes in the world. Retrieved 7-05-2018, from https://www.marineinsight.com/types-of-ships/the-saipem-7000-one-of-the-biggest-cranes-in-the-world/.

[131] Maples, B., Saur, G., Hand, M., van de Pieterman, R., & Obdam, T. (2013). Installation, operation, and maintenance strategies to reduce the cost of offshore wind energy. Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States).

[132] Maracoos. (2018). Results from the mid atlantic high frequency radar network. Retrieved 05-03-2018, from http://slideplayer.com/slide/7503077/.

[133] Maritimeconnector. (2017). Vlcc and ulcc. Retrieved 24-01-2018, from http://maritime-connector.com/wiki/vlcc/.

[134] Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., & Blanco, J. (2009). Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy*, *34*(3), 667–673.

[135] Matsangas, P., Shattuck, N. L., & McCauley, M. E. (2015). Sleep duration in rough sea conditions. *Aerospace medicine and human performance*, *86*(10), 901–906.

[136] Matsuo, Y., Yanagisawa, A., & Yamashita, Y. (2013). A global energy outlook to 2035 with strategic considerations for asia and middle east energy supply and demand interdependencies. *Energy Strategy Reviews*, *2*(1), 79–91.

[137] Molenaar, W., & Voorendt, M. (2016). Manual hydraulic structures. *Collegedictaat CIE3330*.

[138] Moulas, D., Shafiee, M., & Mehmanparast, A. (2017). Damage analysis of ship collisions with offshore wind turbine foundations. *Ocean Engineering*, *143*, 149–162.

[139] Mudronja, L., Vidan, P., & Parunov, J. (2015). Review of seakeeping criteria for container ship sustainable speed calculation in rough weather. In *MARTECH 2014 Maritime Technology and Engineering*.

[140] Musial, W., Beiter, P., Schwabe, P., et al. (2016). 2016 offshore wind technologies market report. *U. S. Department Of Energy*.

[141] Musial, W., Butterfield, S., Ram, B., et al. (2006). Energy from offshore wind. In *Offshore technology conference*. Offshore Technology Conference.

[142] Musial, W., & Ram, B. (2010). Large-scale offshore wind power in the united states: Assessment of opportunities and barriers. Tech. rep., National Renewable Energy Laboratory (NREL), Golden, CO.

[143] Myers, J. A. (1962). Handbook of equations for mass and area properties of various geometrical shapes. Tech. rep., NAVAL ORDNANCE TEST STATION CHINA LAKE CA.

[144] Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. A. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy*, *66*, 714–728.

[145] Nadar, J. (2016). Large wind turbine blade design challenges and r&d needs. *Siemens wind power*.

[146] NDBC. (2018). National oceanic and atmospheric administration's. Retrieved 05-03-2018, from http://www.ndbc.noaa.gov.

[147] Nghiem, A., Pineda, I., et al. (2017). Wind energy in europe: Scenarios for 2030, september 2017. *WindEurope*.

[148] Normile, D. (2017). South korea's nuclear u-turn draws praise and darts.

[149] Oelker, J. (2016). Offshore wind. *GWEC - Global wind 2016 report*.

[150] Office, U. S. N. Y. O. C. S., & of Land Management, U. S. B. (1978). *Final environmental impact statement: proposed 1979 OCS oil and gas lease sale*. No. v. 1 in Final Environmental Impact Statement: Proposed 1979 OCS Oil and Gas Lease Sale. New York OCS.
URL https://books.google.nl/books?id=oEDxAAAAMAAJ

[151] O&GJournal. (2016). Oil tanker freight-rate volatility increases. Retrieved 22-01-2018, from http://www.ogj.com/articles/print/volume-114/issue-7/transportation/oil-tanker-freight-rate-volatility-increases.html.

[152] Pachakis, D., Libardo, A., & Menegazzo, P. (2017). The venice offshore-onshore terminal concept. *Case Studies on Transport Policy*.

[153] Paik, J. K., & Thayamballi, A. K. (2007). *Ship-shaped offshore installations: design, building, and operation*. Cambridge University Press.

[154] Paramor, O., Allen, K., Aanesen, M., et al. (2009). *MEFEPO North Sea Atlas*. University of Liverpool, ISBN 0906370604.

[155] Park, J. (2016). Report on wind power industry 2015, south korea. *Rijksdienst voor ondernemend Nederland*.

[156] Pedersen, E. A. (2012). *Motion analysis of semi-submersible*. Master's thesis, Institutt for marin teknikk, Trondheim, Norway.

[157] Peeringa, J., Brood, R., Ceyhan, O., Engels, W., & de Winkel, G. (2011). Upwind 20mw wind turbine pre-design, blade design and control. ECN.

[158] Pierrot, M. (2017). Offshore wind farms database. Retrieved 24-10-2017, from http://thewindpower.net/store_continent_en.php?id_zone=1006.

[159] Pranavi, K. (2016). *Power electronics technology in wind turbine system*. Master's thesis, GMR Institute of Technology, Razam, India.

[160] Prässler, T., & Schaechtele, J. (2012). Comparison of the financial attractiveness among prospective offshore wind parks in selected european countries. *Energy Policy*, *45*, 86–101.

[161] Pullen, T., Allsop, N., Bruce, T., Kortenhaus, A., Schüttrumpf, H., & Van der Meer, J. (2007). Eurotop, european overtopping manual-wave overtopping of sea defences and related structures: Assessment manual. *also published as Special Volume of Die Küste*.

[162] Quante, M., & Colijn, F. (2016). *North Sea region climate change assessment*. Springer.

[163] RAB. (2010). Value breakdown for the offshore wind sector. *Report commissioned by UK Renewables Advisory Board*.

[164] Rademakers, L., Braam, H., & Verbruggen, T. (2003). R&d needs for o&m of wind turbines. *ECN Wind Energy, Tech. Rep. ECN-RX–03-045*.

[165] Rodrigues, S. M. F. (2016). *A multi-objective optimization framework for the design of offshore wind farms*. Ph.D. thesis, University of Delft, Delft, Netherlands. Retrieved 10-07-2015, from https://pure.tudelft.nl/portal/files/4477274/Silvio_Rodrigues_PhD_Thesis.pdf.

[166] Rodrigues, S. M. F. (2016). *A multi-objective optimization framework for the design of offshore wind farms*. Ph.D. thesis, University of Delft, Delft, Netherlands. Retrieved 10-07-2015, from https://pure.tudelft.nl/portal/files/4477274/Silvio_Rodrigues_PhD_Thesis.pdf.

[167] Ros, M. C. (2015). Identifying the key barriers to large scale commercialisation of gravity based structures in the offshore wind industry. *Offshore wind industry review of GBSs*.

[168] Saanen, Y., & Rijsenbrij, J. C. (2007). Which system fits your hub? *Cargo Systems*.

[169] SanDiego-airport. (2006). Frequently asked questions - airport site selection program. Retrieved 22-02-2018, from https://web.archive.org/web/20060923214700/http://www.san.org/airport_authority/airport_site_selection/faq.asp#15.

[170] Schlee, J., & Pratt, R. M. (1970). Atlantic continental shelf and slope of the united states-gravels of the northeastern part. Tech. rep. Geological survey professional paper 529-H.

[171] Schleisner, L. (2000). Life cycle assessment of a wind farm and related externalities. *Renewable energy*, *20*(3), 279–288.

[172] Schmid, S. R., Hamrock, B. J., & Jacobson, B. O. (2014). *Fundamentals of machine elements: SI version*. CRC Press.

[173] Sheridan, B., Baker, S. D., Pearre, N. S., Firestone, J., & Kempton, W. (2012). Calculating the offshore wind power resource: Robust assessment methods applied to the us atlantic coast. *Renewable Energy*, *43*, 224–233.

[174] Sim, J., Park, C., et al. (2005). Characteristics of basalt fiber as a strengthening material for concrete structures. *Composites Part B: Engineering*, *36*(6-7), 504–512.

[175] Sincoff, M. Z., & Dajani, J. S. (1976). Planning and evaluation parameters for offshore complexes. *NAS CR-145040*.

[176] Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. (2017). The large scale impact of offshore windfarm structures on pelagic primary production in the southern north sea. *arXiv preprint arXiv:1709.02386*.

[177] Smith, C. B. (2007). Extreme waves and ship design. In *10th International Symposium on Practical Design of Ships and Other Floating Structures, Houston, USA*.

[178] SPARTA. (2017). Portfolio review 2016, no. march 2017.

[179] Statoil. (2017). Hywind, the leading solution for floating offshore wind power. Retrieved 17-07-2017, from https://www.statoil.com/en/what-we-do/hywind-where-the-wind-takes-us.html.

[180] Steimle, F. W., & Zetlin, C. (2000). Reef habitats in the middle atlantic bight: abundance, distribution, associated biological communities, and fishery resource use. *Marine Fisheries Review*, *62*(2), 24–42.

[181] Stevens, S. C., & Parsons, M. G. (2002). Effects of motion at sea on crew performance: A survey. *Marine Technology*, *39*(1), 29–47.

[182] Stuiver, M., Soma, K., Koundouri, P., Van Den Burg, S., Gerritsen, A., Harkamp, T., Dalsgaard, N., Zagonari, F., Guanche, R., Schouten, J.-J., et al. (2016). The governance of multi-use platforms at sea for energy production and aquaculture: challenges for policy makers in european seas. *Sustainability*, *8*(4), 333.

[183] Suleiman, B. M. (2000). *Identification of finite-degree-of-freedom models for ship motions*. Ph.D. thesis, Virginia polytechnic institute and state University.

[184] Swail, V., Ceccacci, E., & Cox, A. (2000). The aes40 north atlantic wave reanalysis: validation and climate assessment. In *6th International Workshop on Wave Hindcasting and Forecasting November*, (pp. 6–10).

[185] TAKEMURA, T., OCHIAI, M., & ENDO, S. (1999). Dynamic movement of pontoon type floating structure with flat plates. In *PROCEEDINGS OF CIVIL ENGINEERING IN THE OCEAN*, vol. 15, (pp. 65–70). Japan Society of Civil Engineers.

[186] Templeton, J. S. (2007). *Offshore Technology in Civil Engineering, Volume Two: Hall of Fame Papers from the Early Years*, vol. 2. ASCE Publications.

[187] Thomsen, J. B., Ferri, F., Kofoed, J. P., & Black, K. (2018). Cost optimization of mooring solutions for large floating wave energy converters. *Energies*, *11*(1), 159.

[188] Thomsen, K. (2014). *Offshore wind: a comprehensive guide to successful offshore wind farm installation*. Academic Press.

[189] Thoresen, C. A. (2003). *Port designer's handbook: recommendations and guidelines*. Thomas Telford.

[190] Thuc, P. (2017). Vietnam renewable energy development project to 2030 with outlook to 2050. Ministry of Industry and Trade, department of renewable energy.

[191] UNCTAD. (2015). Review of maritime transport 2015. Retrieved 22-01-2018, from http://unctad.org/en/PublicationsLibrary/rmt2015_en.pdf.

[192] Uraz, E. (2011). *Offshore Wind Turbine Transportation & Installation Analyses Planning Optimal Marine Operations for Offshore Wind Projects*. Master's thesis, University of Gotland, Visby, Sweden.

[193] Van Bussel, G., Henderson, A., Morgan, C., Smith, B., Barthelmie, R., Argyriadis, K., Arena, A., Niklasson, G., & Peltola, E. (2001). State of the art and technology trends for offshore wind energy: operation and maintenance issues. In *Offshore Wind Energy EWEA special topic conference*.

[194] van Leeuwen, S., Tett, P., Mills, D., & van Der Molen, J. (2015). Stratified and nonstratified areas in the north sea: Long-term variability and biological and policy implications. *Journal of Geophysical Research: Oceans*, *120*(7), 4670–4686.

[195] van Zuijlen, E., & de Vries, M. (2016). Q-meeting 14-12-2016. *Growth research in offshore wind*.

[196] Vanucci, D. (2011). Wp 3 - technologies state of the art. *ORECCA.*.

[197] Verbruggen, T. (2003). Wind turbine operation & maintenance based on condition monitoring wt-ω. *Final Report, April*.

[198] Versendaal, J. (2017). *Exploring the potential of the pre-assembled installation method for the installation of offshore wind turbines*. Master's thesis, University of Delft, Delft, Netherlands.

[199] Vis, I. F., & Ursavas, E. (2016). Assessment approaches to logistics for offshore wind energy installation. *Sustainable energy technologies and assessments*, *14*, 80–91.

[200] Vugts, J. H. (2013). *Handbook of Bottom Founded Offshore Structures: Part 1. General features of offshore structures and theoretical background*, vol. 1. Eburon Uitgeverij BV.

[201] Wang, C., & Tay, Z. (2011). Very large floating structures: applications, research and development. *Procedia Engineering*, *14*, 62–72.

[202] Wang, C., & Wang, B. (2015). Great ideas float to the top. In *Large Floating Structures*, (pp. 1–36). Springer.

[203] Wang, Z., Shi, J., Zhao, Y., et al. (2011). Technology roadmap, china wind energy development roadmap 2050. *International Energy Agency*.

[204] Welaya, Y. M., Elhewy, A., & Hegazy, M. (2015). Investigation of jack-up leg extension for deep water operations. *International Journal of Naval Architecture and Ocean Engineering*, *7*(2), 288–300.

[205] Werkgroep-Discontovoet (2015). Rapport werkgroep discontovoet 2015, 95.

[206] Westra, C. (2015). *Offshore wind, clean energy from the sea*. Chris Westra consulting bv. ISBN: 9789082300406.

[207] Whitehouse, R. (1998). *Scour at marine structures: A manual for practical applications*. Thomas Telford.

[208] Whitehouse, R. J., Harris, J. M., Sutherland, J., & Rees, J. (2011). The nature of scour development and scour protection at offshore windfarm foundations. *Marine Pollution Bulletin*, *62*(1), 73–88.

[209] Whitlock, R. (2017). Kriegers flak demonstrates rapidly falling costs for offshore wind. Retrieved 30-11-2017, from https://www.renewableenergymagazine.com/wind/kriegers-flak-demonstrates-rapidly-falling-costs-for-20161114.

[210] WindEurope. (2017). Floating offshore wind vision statement, june 2017. *Windeurope*.

[211] Windpower (2017). Wind farms vietnam. Retrieved 15-11-2017, from https://www.thewindpower.net/windfarms_list_en.php.

[212] Windpowermonthly (2017). Market status: Asia-pacific. Retrieved 15-11-2017, from https://www.windpowermonthly.com/article/1389248/market-status-asia-pacific.

[213] Working group no. 24, P. I. A. N. C. (1995). Criteria for movements of moored ships in harbours. *PIANC*.

[214] Zaaijer, M. B. (2003). Comparison of monopile, tripod, suction bucket and gravity base design for a 6 mw turbine. *OWEMES, ENEA, Naples*.

[215] Zhang, P., Ding, H., Le, C., Zhang, S., & Huang, X. (2013). Preliminary analysis on integrated transportation technique for offshore wind turbines. In *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, (pp. V008T09A072–V008T09A072). American Society of Mechanical Engineers.

Figures website references

[W1] 4COffshore. (2013). Jacket or lattice structures. Retrieved 23-02-2018, from http://www.4coffshore.com/windfarms/jacket-or-lattice-structures-aid5.html.

[W2] Almeida, R. (2012). Jumbo shipping conducts heavy lift wind farm installations at anholt. Retrieved 17-03-2018, from http://gcaptain.com/jumbo-shipping-conducts-heavy/.

[W3] Balkenende, F. (2017). Gigantische zeewuse vlag komt op het grootste kraanschip ter wereld. Retrieved 30-01-2018, from https://www.pzc.nl/zeeuws-nieuws/gigantische-zeeuwse-vlag-komt-op-het-grootste-kraanschip-ter-wereld~a408bb37/.

[W4] BallastNedam. (2018). Butendiek offshore windmolenpark. Retrieved 07-11-2017, from http://www.ballast-nedam.nl/projecten/butendiek-offshore-windmolenpark/.

[W5] Buss. (2017). Buss setting the stage for merkur offshore wind farm. Retrieved 6-12-2017, from https://www.offshorewind.biz/2017/10/09/buss-setting-the-stage-for-merkur-offshore-wind-farm/.

[W6] CWEEA. (2017). Construction starts on donghai bridge offshore wind farm. Retrieved 10-12-2017, from www.cweea.com.cn.

[W7] Databasin. (2018). Annual average offshore wind speed. Retrieved 02-03-2018, from https://databasin.org/maps/new#datasets=ff8b021f65c9442da3478530da345340.

[W8] Deepwaterwind. (2018). Block island wind farm. Retrieved 03-01-2018, from http://dwwind.com/project/block-island-wind-farm/.

[W9] DONG. (2017). Bigger, cheaper, greener. Retrieved 14-08-2017, from http://www.openocean.fr/fr/news/2017/03/21/vindeby-1991-2017-decommission-of-the-worlds-first-offshore-wind-farm/.

[W10] el Sawin, J., Seyboth, K., Sverrisson, F., Adib, R., et al. (2017). Renewables 2017 global status report. *Global Status Report renewable energy policy network for the 21st century*.

[W11] Firstsubsea. (2018). Cable protection system gallery. Retrieved 08-11-2017, from http://www.firstsubsea.com/products/renewables/cable-protection-system/cable-protection-system-gallery.html.

[W12] Futuna-Yachts (2018). Marine construction. Retrieved 02-04-2018, from http://www.futuna-yachts.com/construction/.

[W13] GCaptain. (2012). Maersk drilling, keppel, land ultra-harsh environment jackup contract with statoil. Retrieved 22-02-2018, from http://gcaptain.com/maersk-drilling-keppel-land/.

[W14] GOWEF. (2017). Overview offshore wind farms in germany. Retrieved 22-01-2018, from https://www.offshore-stiftung.de/en/media-library.

[W15] Guppo. (2017). Floating lands. Retrieved 20-2-2018, from https://gruppoingegneriadisistemaen.wordpress.com/floating-lands/.

[W16] Hazama. (2000). Naoetsu port breakwater caisson. Retrieved 10-02-2018, from http://www.ad-hzm.co.jp/english/works/japan/harbors/harbors_10.html.

[W17] Heavyliftnews. (2017). Video: Heerema's hermod and thialf: Birds eye view. Retrieved 30-01-2018, from http://www.heavyliftnews.com/news/video--heerema-s-hermod-and-thialf--birds-eye-view.

[W18] HSMoffshore (2017). Borssele alpha offshore high voltage substation - 700 mw. Retrieved 10-02-2018, from https://www.hsmoffshore.com/en/projects/offshore-renewables/borssele-alpha-offshore-high-voltage-substation---700-mw/.

[W19] IHC-VUYK. (2017). Vessel design. Retrieved 30-01-2018, from https://www.royalihc.com/en/services/design-and-engineering-services/vessel-design.

[W20] Kristiansen, T. (2013). Maersk tankers sells broström singapore. Retrieved 23-01-2018, from https://shippingwatch.com/secure/carriers/article5672921.ece.

[W21] MOCE. (2016). Van oord neemt bilfinger offshore wind over. Retrieved 18-03-2018, from https://maritiemnieuws.nl/73908/van-oord-neemt-bilfinger-offshore-wind-over/.

[W22] Nauticareport. (2013). Vanguard, il mostro che recupererà la concordia. Retrieved 20-05-2018, from https://www.nauticareport.it/dettnews.php?idx=6&pg=5704.

[W23] NOAA. (2018). Ecology of the northeast us continental shelf. Retrieved 02-03-2018, from https://www.nefsc.noaa.gov/ecosys/ecosystem-ecology/physical.html.

[W24] Parkins, J. (2012). Ardjuna sakti (lpg floating storage facility). Retrieved 12-01-2018, from http://www.concretetech.com/concrete-projects/ardjuna-sakti-lpg-floating-storage-facility.

[W25] S., P. (2017). More monster wind farms are set to loom over britain's coast but power will cost 40 Retrieved 22-01-2018, from http://www.dailymail.co.uk/news/article-4874812/More-monster-wind-farms-set-loom-coast.html.

[W26] SeaproofSolutions. (2018). Standard cps - universal design for easy installation. Retrieved 07-03-2018, from http://www.seaproof.com/cps/.

[W27] Ship-technology. (2016). Sleipnir semi-submersible crane vessel. Retrieved 01-02-2018, from https://www.ship-technology.com/projects/sleipnir-semi-submersible-crane-vessel/.

[W28] Siem. (2016). Siem wraps up nordsee one inter-array cable project. Retrieved 6-12-2017, from https://subseaworldnews.com/2016/09/06/siem-wraps-up-nordsee-one-inter-array-cable-project/.

[W29] Siemens. (2011). Bolted steel shell tower. Retrieved 10-12-2017, from https://www.energy.siemens.com/us/pool/hq/power-generation/renewables/wind-power/Bolted_Steel_Shell_Tower_brochure_EN.pdf.

[W30] Siemens. (2016). Siemens wind power presents first customized turbine transport vessel in esbjerg. Retrieved 03-05-2018, from https://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2016/windpower-renewables/pr2016120100wpen.htm&content[]=WP.

[W31] Statoil (2014). Aasta hansteen moving boundaries. Retrieved 10-02-2018, from https://www.statoil.com/en/news/archive/2014/08/26/26AugAastaHansteen.html.

[W32] van der Groot, S. (2015). Cig maritime technology. Retrieved 04-3-2018, from https://businessguide.offshorewind.biz/profiles/cig_maritime_technology.

[W33] VBMS. (2018). Van oord neemt bilfinger offshore wind over. Retrieved 18-03-2018, from http://www.vbms.com/en/equipment/tools.

[W34] Vesseltracking.net (2018). Biggest oil tankers overview. Retrieved 22-01-2018, from http://www.vesseltracking.net/wp-content/uploads/2016/05/biggest-oil-tanker-side.png.

[W35] Westfield. (2017). Fixed platform. Retrieved 26-02-2018, from http://westfieldenergy.com/markets/oil-gas/oil-gas-fixed/.

[W36] Yauck, J. (2009). Turning great lakes wind into energy. Retrieved 14-1-2018, from https://bayviewcompass.com/turning-great-lakes-wind-into-energy/.

A. ECN offshore port concept

Besides conventional methods of installation, the market requires innovative concepts to make the installation cost low and more importantly, reduce the risk. To encourage such concepts, three ideas are proposed as part of an "Innovation Project" within ECN. As part of the three innovations, the first innovation proposes to build an offshore harbour. The nacelle, blades and tower are transported by feeder vessels and stored at the offshore harbour. Then the components are assembled, parallel to this, the installation vessel picks up complete turbines and installs them in sets of two.
The installation of the turbine is a single lift application, the Huisman shuttle vessel is used in this research. This innovative concept is simulated using the "ECN install tool" and results are compared to the reference case. The reference case is a jack-up which is able to transport all the components needed for 6 turbines. The ECN Tool was built within the Far and Large Offshore Wind Programme (FLOW) with due consultation with IHC Merwede and Van Oord. Parameters like distance to shore, limiting wave height and installation time are varied for the innovative and for the reference case. A more detailed explanation on the processes for the reference case and innovative concept can be found in [46].

Critical notes

As previously mentioned, the scope of this research using the "ECN Install tool" is the logistical profit of such an innovative concept. No attention is paid to economical or technical feasibility. It is arguable whether some operations conducted in this research are technical feasible, examples are:

- The Huisman shuttle vessel is a concept, it has not been build and it is not sure that it can lift such a turbine smoothly on the foundation.
- It is assumed that the assembling work is not limited by weather conditions.
- The harbour is a floating pontoon structure, the loads caused by components and equipments on the foundation of the structure are not limited by a certain maximum weight for storage.

Despite these critical notes about the technical assumptions in this research, the results are very promising, even when a delay occurs in this innovative process caused by a technical limitation.

Results

As mentioned in the introduction there are three parameters varied, the distance to shore, the limiting wave height and the installation time. The influence of the wave height on the duration of a turbine installation is relatively small, the other two varied parameters show about similar results. When varying the distance to shore from 35 until 150 kilometers, nearly the same results are generated as when the installation time of one single lift is increased from 3 hours to 9 hours. The scenario in which the distance to shore is varied can be seen in figure A.1. In the reference case the limiting significant wave height and the duration of the single lift have the same value as in the innovative case when the distance to shore is varied. Respectively 2 meters and 5 hours. The potential of an offshore port during the installation of a wind turbine is clear. When selecting the distance of 85 kilometers to shore, the results are displayed in figure A.2.

It should be noted that foundation installation can also be installed from such an offshore port. The only difference is that the foundations have to be piled according to the conventional way and the Huisman vessel cannot be applied in this case.

An important note was made during the meeting with Ashish Dewan, one of the researchers. The cycle time of the reference case concerned the cycle time in 2015 for the turbine installation, currently the cycle time is lower. Considering the distance to shore, the relative fastest cycle time was generated by the Gemini wind farm according to Ashish Dewan. One wind turbine was installed in approximately 2 days.

Reference wind farm: Turbines

Distance [km]	Start Date	End Date	Duration Total [days]	Duration work [days]	Delay total [days]	Delay weather [days]	Delay shift [days]
35	5-Aug	7-Mar (next year)	3.90	1.77	2.13	1.421	0.710
85	5-Aug	8-Mar (next year)	3.91	1.95	1.96	1.439	0.524
150	5-Aug	14-Mar (next year)	4.25	2.19	2.06	1.491	0.571
Innovation Turbines: Single lift with Hs=2 m T=5 hrs							
35	5-Aug	4-Sep	0.62	0.53	0.09	0.069	0.025
85	5-Aug	4-Sep	0.78	0.69	0.09	0.069	0.024
150	5-Aug	5-Sep	0.99	0.90	0.09	0.069	0.087

Figure A.1: Variation of distance to shore and comparison between reference case and innovative concept

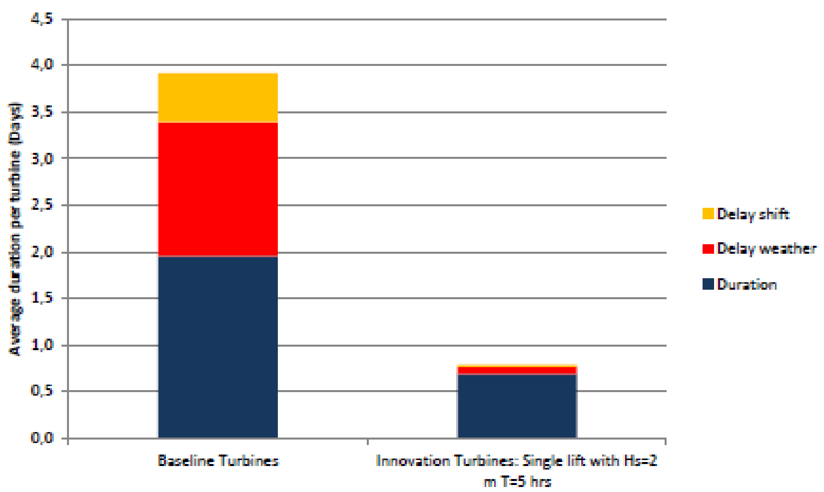


Figure A.2: Average duration and delay per installed turbine

B. Foundation overview

In paragraph 1.1.1 an overview is provided of six wind turbine foundations. Three of them are fixed and three of them are floating, however there are more types of foundations commonly used. The five fixed foundation types listed in figure B.1 represent 97% of all offshore wind foundations. The remaining 3% consist of triple foundations and floating foundations. A triple foundation is similar to a tripod foundation, despite that the three legs are longer [206].

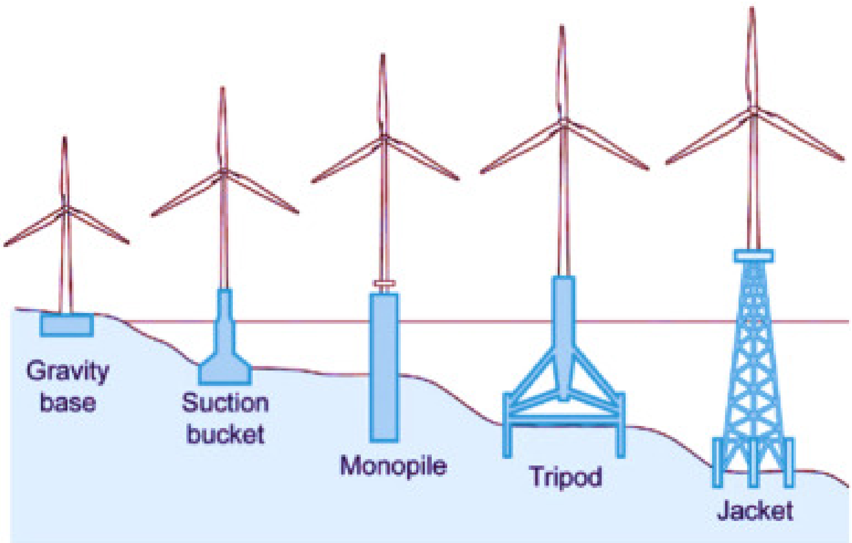


Figure B.1: Common fixed foundations [138]

The three main concepts for floating foundations are displayed in figure B.2. However variants on these exist, including a barge platform or a single platform mounting multiple turbines. A clear visualisation of the three most promising floating foundations is presented below.

Figure B.2: Main floating foundation concepts [69]

When the components of the turbine are installed on top of the monopile, it looks as follows:

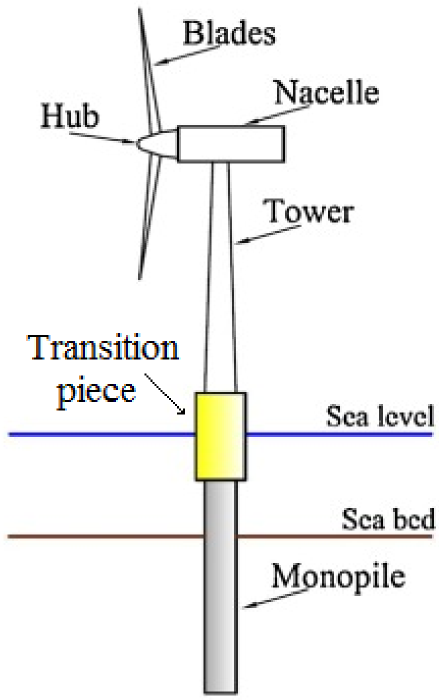
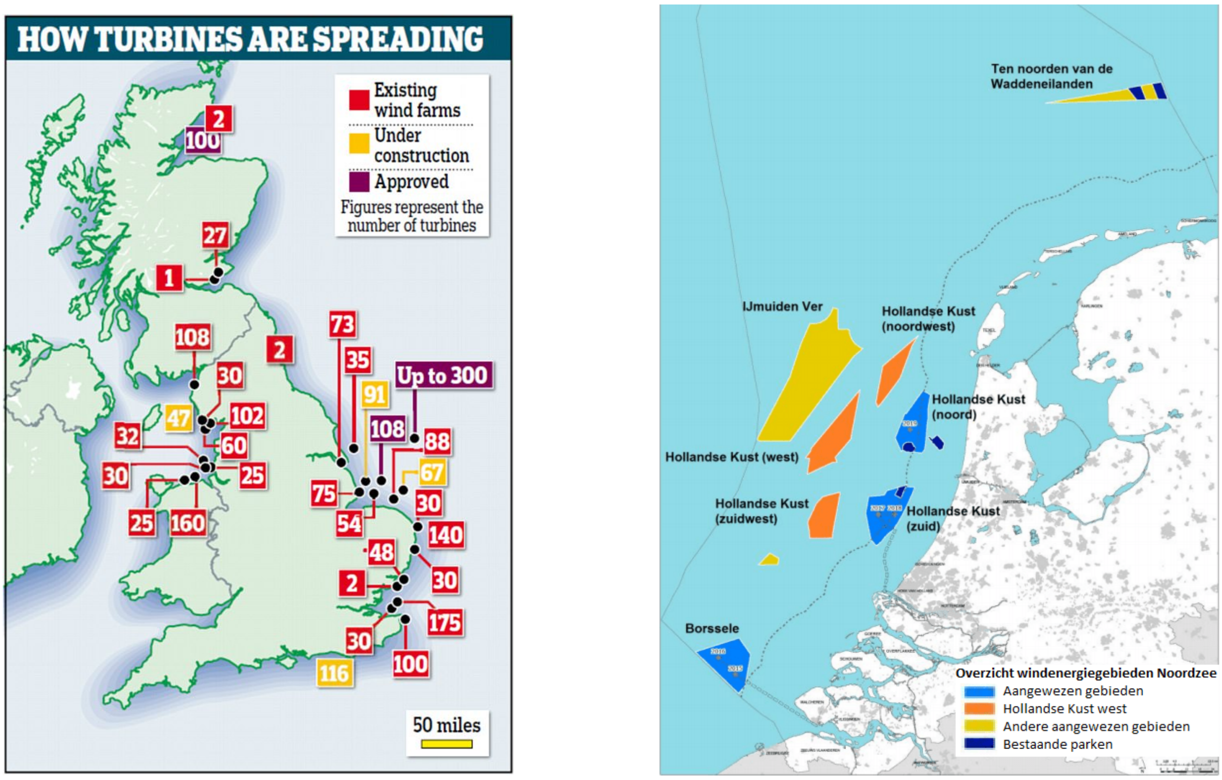


Figure B.3: Fully installed turbine and monopile [40]

C. Continental market potential

The potential offshore wind market of Europe and North America is explained in the main report. Additional visualisations regarding operational offshore wind areas in Europe are presented in appendix C.1. Appendix C.2 elaborates on the potential of floating foundations in Europe. Because Asia and South America are analysed by the same approach, only a summary is displayed in the main report. The background of this summary is available in appendices C.3 and C.4.

C.1 North Sea



(a) UK wind farm status at 09-2017 [W25]

(b) Netherlands wind farm status at 07-2017 [121]

Figure C.1: Wind farm status in the North Sea

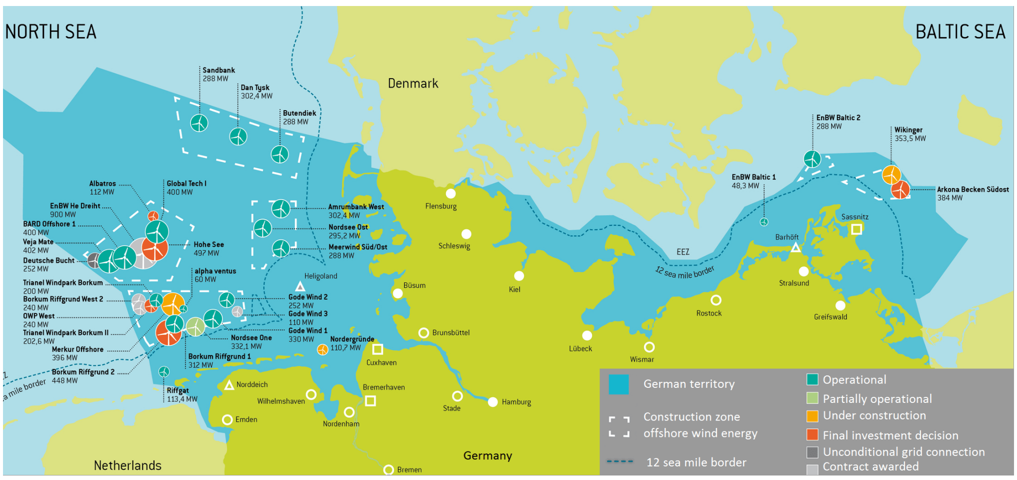


Figure C.2: Germany wind farm status at 07-2017 [W14]

C.2 Floating foundations Europe

The three main aspects that determine the low potential outlook for floating foundations in Europe are elaborated in this section.

The potential offshore wind area in Europe is accounted for 80% by water depths larger than 60 meter. These offshore areas provide a total potential of 4.000 GW for floating wind capacity. 60 meter is the break-even point of floating foundations and fixed foundations by the year 2030 [95] [109]. However the deep water potential of just the North Sea, already exceeds the current EU's electricity consumption four times [5]. 20% of the offshore wind resource area in Europe, is in a water depths less than 60 meter. This area is already nearly sufficient, to fulfil the energy consumption in Europe.

Floating offshore wind foundations will allow countries like: Norway, Portugal or Spain to enter the offshore wind industry [210]. So there seems a potential market for the floating foundations, where the first floating wind farm (Hywind) became operational in 2017. Though the currently installed capacity is only 30 MW with five spar bouy foundations combined with a 6 MW turbine.
Interviewed parties are elaborated in chapter 3. The interviewed persons and the most recent published reports are on the same page regarding the future of floating foundations. Floating cost reductions will expand the market for offshore wind somewhat, but will not enable floating to compete with fixed foundations where these are feasible [95]. According the interviews, the floating foundation installation needs to be more developed to become costparity, in particularly the cable laying and anchoring.

The third aspect is that countries who have a geographically unfavorable location for offshore wind, will invest in other RES and not in the offshore floating wind market. There are only eight floating wind farms with more than 3 MW capacity, planned for construction.

C.3 Asia

In Asia there are six countries with plans to join, or extent the offshore wind market before the year 2030. These countries are: China, Japan, Taiwan, South Korea, Vietnam and India [140]. For each country the renewable energy share of the total amount of energy generated, is determined by a literature analysis. In this way an indication can be provided on the level of intention of their offshore wind targets. Also for Asia the offshore wind capacity will be indicated for the year 2030 by prognoses of organisations, associations and commissions in the offshore wind market.

Climate targets

China is the country with the highest energy generation in the whole world, so their renewable energy target is important for the sustainability of planet earth. The 2030 target of China is to generate 20% of their energy by RES [70] [85]. The renewable energy generation target of Japan is a little higher, they aim a share of 23% by RES in the year 2030. The target of Vietnam is the lowest of all six countries taken into account, their target is 10% of renewable energy generation by 2030 [190]. The RES share of South Korea is 20% by 2030 [148], while Taiwan aims to generate 25% of their energy by RES [21] in 2030.
The highest share of renewable energy generation of the six considered countries belongs to India, their target is 35% by 2030 [76]. A high RES target only corresponds to a lot of renewable energy generation when their is a high amount of energy consumption. In Asia the energy consumption will rise with 30%

from 2018 until 2030 [136]. This increase has a positive influence on the offshore wind market by 2030.

Offshore wind capacity

As for Europe and North America the offshore wind potential capacity is determined by recently published reports that provide an indication for the year 2030. This is more reliable than looking at the offshore wind farm projects in the pipeline, since most of the planned projects are canceled. China is currently market leader in Asia. In 2016 China was second world wide with the annual offshore capacity installation, only Germany had a higher capacity [140]. Indications show that China has 65 GW of installed capacity in 2030 and in 2050 this coincides with 200 GW, of which 50 GW is installed far from the shore [203].

Japan is expected to have 10 GW of offshore wind energy by 2030 and it relies heavily on floating foundations, since this represents 4 GW [71] [104]. Japan has a favorable geographical shape for offshore wind because there is a lot of coastline. This argument also holds for Taiwan and this is confirmed by the expectation of three times as much offshore as onshore wind energy in 2030. Taiwans offshore capacity by 2030 is indicated to be 4 GW [21]. Despite that this argument also holds for South Korea, their expected installed capacity by 2030 is only 2.5 GW [155]. Where Taiwan expects more offshore energy than onshore energy by wind, in India this is completely different. Onshore there is 185 GW expected by 2030, while offshore this is only 3 GW [76].

No published reports concerning the offshore wind capacity distribution of Vietnam by 2030 between onshore and offshore were found. Therefore, the current distribution between onshore and offshore capacity installed is assumed to stay constant. There is currently two times as much offshore wind operational as onshore [212] [211]. It is widely published that the wind capacity of Vietnam by 2030 equals 6 GW [71], so the offshore capacity installed by 2030 is 4 GW.

Offshore wind conditions

In comparison to China and in a lesser extent also to Japan, the four other countries have a low market potential for offshore wind. Therefore their conditions are combined to one common condition, which accounts for 13,5 GW. Using the database of 4COffshore, the average distance to shore and water depth for the potential wind farms is determined. The same approach is applied as for Europe and North America. The combined countries have an average distance to shore of 23 kilometer and an average water depth of 28 meter.

For Japan the average distance to shore is only 7 kilometer and the average water depth just 17 meter. In Japan there is a limited area of shallow water, this area is currently and in the next few years projected for near shore wind farms. Despite that Japan relies on floating wind farms in the future, currently there are only 4 small potential floating wind farms projected. In 2050 it is expected that the fixed and floating foundations have an equal share in installed capacity [104]. For China the average distance to shore of potential wind farms is 22 kilometer and the water depth 14 meter. No floating projects are in the pipeline.

The average of the highest 5% of China's potential wind farms, is 56 kilometer for the distance to shore and 27 meter for the water depth. In Japan the average of the highest 5% is 35 kilometer for distance to shore and 70 meter of water depth. This 70 meter of water depth is about 4 times as high as the average for all the potential wind farms in Japan. This high increase can be explained by the fact that the highest 5% represents 4 floating wind farms and 1 wind farm with fixed foundation. For the combined countries the highest 5% leads to a distance to shore of 45 kilometer and a water depth of 41 meter. These values are just as for all calculated conditions, based on the weighted capacity of the wind farm.

The average wind farm size of the potential wind farms in Japan is 180 MW and the average turbine size is 8 MW. For China the average wind farm size is 300 MW and the turbine size 10.4 MW. The numbers holding for the potential wind farms for the clustered countries are 230 MW for the average wind farm size and 6 MW for the average turbine size. These values of the average turbine size are all composed by a weighted average to the wind farm capacity.

C.4 Brazil and Australia

Outside Europe, North America and Asia, there are no countries listed in the several reports that show offshore wind capacity indications by 2030. Another possibility is to look at projects that are in the pipeline. The same approach is used as for the offshore wind conditions for the other three continents. Brazil and Australia are the only countries that are known to have projects in the pipeline [1].

The wind farm Asa Branca in Brazil, which is being planned by the local company Eolica Offshore since 2002 [166], is expected to have a 12 MW pilot ready by 2017 and a demonstration project by 2018. However a major obstacle in Brazil is the government and onshore wind developers [119]. Nonetheless, the project is aimed to reach a total installed power of 11.2 GW in the next 20 years. But since the project keeps being delayed and because no single report mentions Brazil as a market player by 2030. The Brazilian offshore wind market is not taken into account in this research.

In Australia, the government is currently considering a 2 GW offshore wind farm request [1]. However, the arrangement of all the required permits is not the only hindrance. Vessels have to be chartered all the way from Europe or Asia and all the other components also have to be shipped around the world, which increases the costs. The lack of an established supply chain makes it hard for offshore wind generation to come anywhere close to the price of onshore projects in Australia. Since no report mentions Australia as a market player by 2030 and because there is no single construction planned. Australia is not taken into account as a market potential for offshore wind.

A visualisation of the average conditions and the capacity by 2030 is provided in figure 2.6. The conditions of US Atlantic and the EU are comparable, as are the average conditions in Asia.

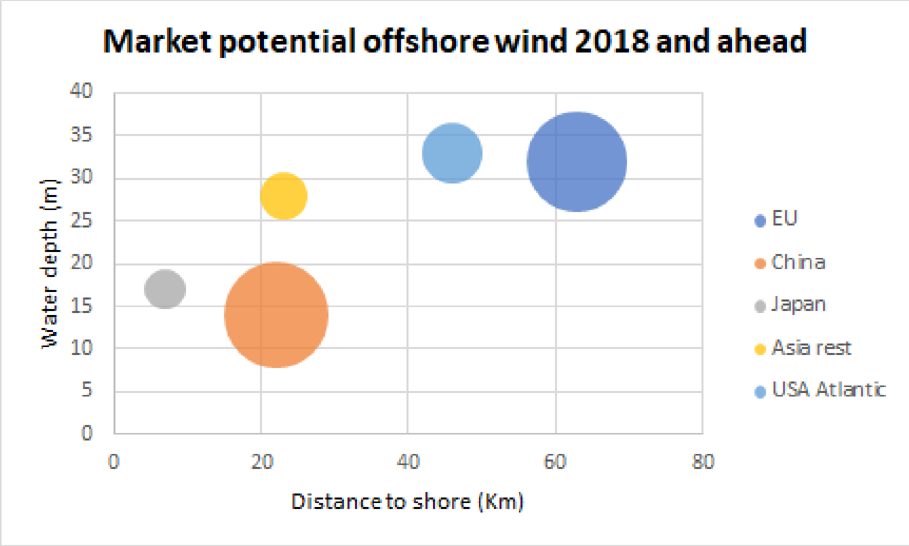


Figure C.3: Capacities and average conditions from 2018 and ahead, projects planned, approved and under construction

D. Interviews

The companies that are interviewed can be found in table D.1.

Table D.1: Interviewed companies and job titles

Interview	Company
1	Siemens wind power
2	SIF group
3	VolkerWessels Boskalis Marine Solutions
4	VolkerWessels Boskalis Marine Solutions
5	Vuyk Engineering
6	Vuyk Engineering
7	van Oord
8	ECN

Together these companies were responsible for laying over 1500 cables, the installation of more than 250 foundations, placing the scour protection for more than 15 offshore wind farms and the installation of over 200 wind turbines. They were also responsible for the manufacturing of 70% of the wind turbines and 23% of the foundations in Europe. These are just the numbers for which they were responsible, the involvement in similar projects shows even higher numbers. So, besides the installation of the substation the construction phase is represented very well. Also the design of the vessels and equipment and the engineering of marine operations are represented by the companies. The general process of research and development phase is interviewed as well.

Interviewing more companies is difficult due to rivalry and the limited number of players in the Dutch market. The additional value is questionable since the interviewed companies already have a large market share. Five of the Eight interviewed persons have a job title with manager, this can contribute to the level of the interview.

E. Demand prioritisation

This appendix elaborates on the location of the demands in figure 4.2. For all six demands the value for a profit effect and the value for adaptability is succinctly explained.

Deep water port near the wind farm

Despite the large resource potential of floating foundations, the forecast of this technology has a low potential as explained in section 3.4. Though when there are more deep water ports available, the potential of a spar-buoy foundation improves. The availability of deep water ports does not increase the profits of a project, it provides an opportunity of wind farm projects for a new market. This could lead to profits for the industry and government.

It is not possible to dredge onshore ports to a depth of 80 to 100 meter, to enable the construction of spar-buoy foundations. Large ports, like the port of Rotterdam, guarantee a water depth of 26 meter. However, an onshore deep water port requires a natural water depth in the order of 80 meter. Besides a port in a fjord these are not available, so an offshore port is required. As explained in section 5.1, these have not been constructed so far and will therefor be hard to accomplish.

Decrease rental costs of the installation vessel

The transport and installation of wind turbines accounts for 19% of the CAPEX and 10% of the life cycle costs. The major part of the costs within these processes are caused by the day-rate and rental period of the vessels. Decreasing the rental period of the vessels will have a significant influence on the profits of the project.

A small optimisation in the logistics of the vessels could already save a few million. This could be created by for example: better weather forecast, more available onshore ports, a higher workability or a faster lifting system. However, optimisations that lead to large adjustments in the logistics are difficult to adapt.

Though an high influential adjustment in the logistics requires a different approach and will be more difficult to adapt.

Usage of one installation vessel and a cheap feeder system

The LCOE of offshore wind at the U.S. Atlantic coast will drop significantly when one installation vessel can be used for transport and installation. This also stimulates the development of the offshore wind market.

When it is legitimate to sail with a non U.S. flagged installation vessel from U.S. port to U.S. port, or when the vessel industry in the U.S. develops rapidly, it is possible to use one installation vessel for the construction of an U.S. offshore wind farm. Both scenarios are not plausible to occur the coming years. A feeder system to supply the offshore installation vessel has been used once in the U.S. offshore wind market. Therefore, optimisations in this feeder system are expected.

A shelter with loading facilities

This demand comes from the installation phase, that only has an influence of a few percent on the life cycle costs. The savings would be a few trips from the project location to the shore, so this saving is limited.

The required shelter makes it possible to load cargo to the smaller installation vessels. In particular the support vessel, cable laying vessel and the fall pipe vessel. When there is a shelter, the feeder vessel can unload the cargo to the smaller installation vessels. Another possibility is to unload the cargo to a platform, where it is stored. The latter requires a crane on the platform, since the feeder does not have this. This demand requires only a loading capability of the platform and and therefore scores a 7 on integration.

A smaller installation support vessel

The installation support vessel is used to place the required equipment for the inter-array cable laying on the transition piece. It also functions as a sleeping accommodation for the offshore crew during several installation phases. Removing the sleeping accommodation from the support vessel, decreases the CAPEX of this vessel. Though this is a relatively low decrease in comparison to the decrease of the OPEX for a shorter rental period of the installation vessel.

Construction of a support vessel without a sleeping accommodation is easy. However, a new offshore sleeping accommodation has to be constructed and therefore the integration is reduced to the score of 7.

Ease the transport of the tower

The profit effect of this demand is based on the transport tower not visiting the onshore port. This shortens the transport of the tower to the offshore site, though this transport vessel has to be capable of installing the tower or an offshore platform has to be constructed. Both possibilities have a negative effect on the profit of this demand.

Vessels from the manufacture location have to sail a longer distance and then install multiple towers. The jack-ups from the onshore port still have to install the nacelle and blades. This can be integrated within the transport and installation phase, although it is a challenge to find an agreement between all involved parties.

F. Sand volume

This calculation shows the quadratical increase of sand volume needed when the water depth increases linear. It is important to notify that this is the minimum amount of sand possible, additional sand needed for erosion is not take into account. The following assumptions in the calculation are made:

- The water depth in the first case is 50 meter and in the second case 100 meter
- The internal friction angle of saturated sand is 30°
- The island has a surface area of 50 x 100 m at the water level. These lengths are chosen to act as a minimal area of the port.

The volume of the island is calculated as a truncated pyramid. The volume of the small 'truncated' pyramid is subtracted from the big pyramid. A visualisation is displayed in figure F.1, where the water depth is equal to 'h' in figure F.1. It has to be kept in mind that the port consists of a rectangular surface area instead of a square. The height 'x' in figure F.1 is a non existing height above the island, however its value is needed for the calculation.
It is assumed that at the water level (light gray area in figure F.1), the width of the surface is 50 meter, so half the width is 25 meter. Half the length is 50 meter, this leads to a diagonal of 56 meter at the water level. The vertical angle in the corner is 30°so with the use of the tangent it is calculated that the height of x is 32 meter.

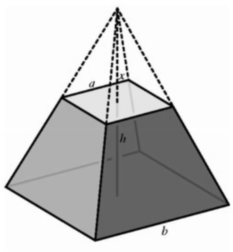


Figure F.1: Volume of the pyramid

The volume of the big pyramid can be calculated as follows:

$$\begin{aligned} V &= \frac{1}{3} * length * width * height \\ &= \frac{1}{3} * (100 + ((50/30) * 100 * 2)) * (50 + ((50/30) * 100 * 2)) * (32 + 50) \\ &= 4.5\, million\, m^3 \end{aligned}$$

The volume of the small pyramid can be calculated as follows:

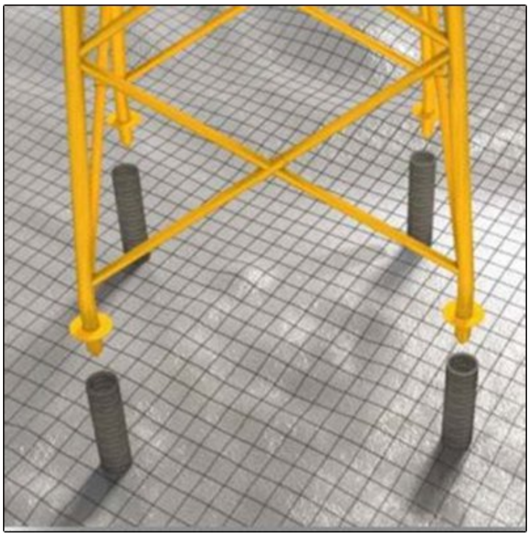
$$\begin{aligned} V &= \frac{1}{3} * 100 * 50 * 32 \\ &= 50.000\, m^3 \end{aligned}$$

So the total volume of the island is about 4.5 million m^3 of sand with a water depth of 50 meter. With the same approach the total volume of the island is calculated with a water depth of 100 meter. The volume of sand is 24.2 million m^3, so for an increase of 50 meter of water depth the volume of sand increased about 20 million m^3.

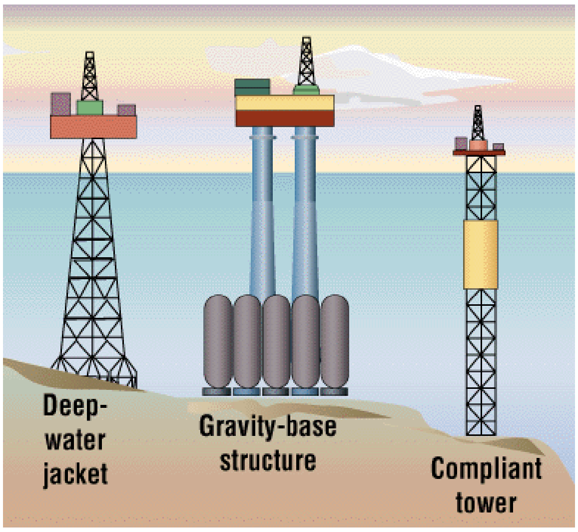
G. Port conditions

G.1 Fixed structures

The gravity based structure and guyed tower are compared to the jacket structure in paragraph 6.2.7. An overview of these structures is provided and also the installation technique of a jacket is displayed below.



(a) Pre installed piles for jacket installation [W1]



(b) Fixed platform options [W35]

Figure G.1: Fixed platform installation and comparison

G.2 Overtopping

A fixed structure does not experience motions and it has other requirements regarding a protected work environment. The overtopping manual gives maximum overtopping discharges, to be used for the design of hydraulic structures where waves could overtop. When the port concept is a fixed structure, the overtopping values of the manual can be applied as a limit for safe working conditions. The thresholds in table G.1 are based on the analysis of wave overtopping perceived by port engineers to be safe.

To calculate the amount of wave overtopping over a vertical structure the following equation is used [67]:

$$\frac{q}{\sqrt{gH_s^3}} = a * e^{-b\frac{R_c}{y*H_s}} \tag{22}$$

In which:

R_c (m) = (structure) freeboard

q ($m^3/m/s$) = specific discharge

a,b (-) = emperical coefficients

y (-) = geometrical parameter

H_s (m) = significant wave height

g (m/s^2) = gravity acceleration

Table G.1: SLS for overtopping [161]

Hazard type and reason	Mean discharge q (l/s/m)	Maximum volume Vmax (l/m)
Trained crew, well shod and protected, expecting to get wet; overtopping flows at lower levels only, no falling jet, low danger of fall from walkway.	1 - 10	500
Trailers driving at low speed, overtopping by pulsating flows at low flow depths, no falling jet, vehicle not immersed.	10 -50	100 - 1000
Damage to equipment and components	0,4	

G.3 Baulk timbers

Metal is placed over the baulk timber so the load is distributed more uniformly. Trailers can jack up underneath the tower and transport it to the quayside. A top view of the baulk timber is presented in figure G.2.

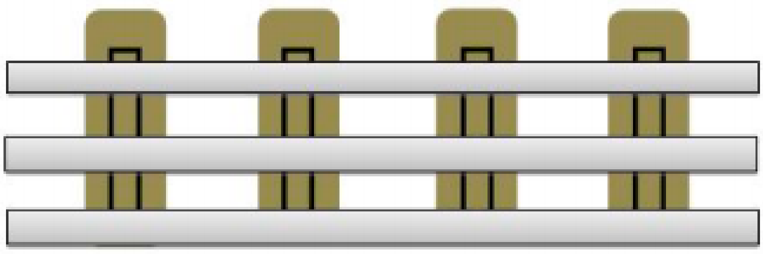


Figure G.2: Storage of the tower [72]

G.4 Buoy locations

The wave spectra of ten locations are taken into account for determining the workability. The location with similar conditions as the average construction in 2030 is indicated by a black dot.

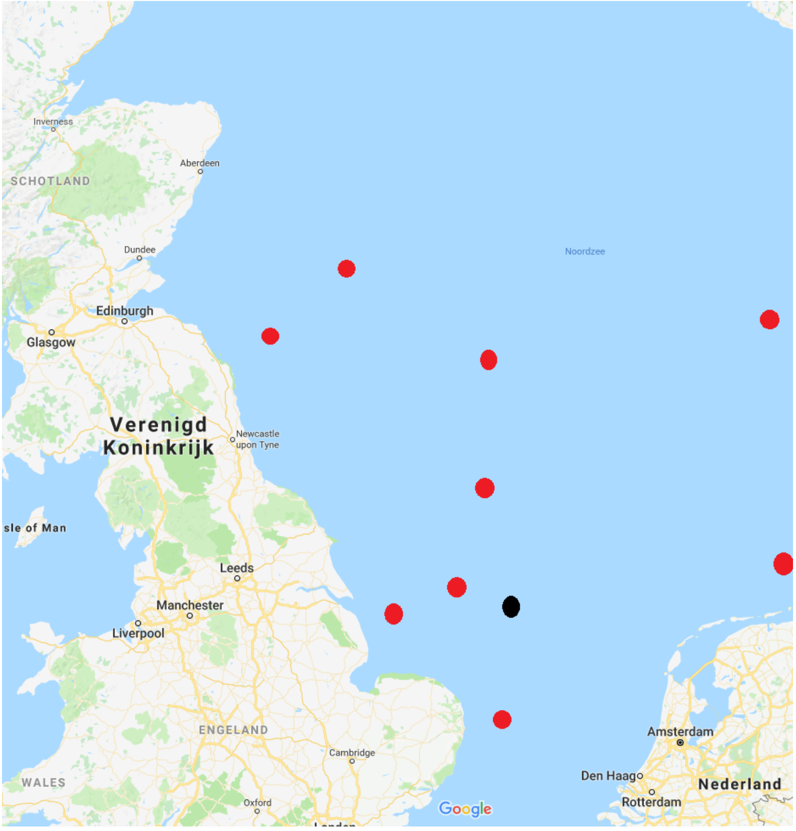


Figure G.3: Buoys taken into account

G.5 Vertical loads

This section elaborates on the vertical loads that are taken into account in the design of the port. These values correspond to a minimum load that has to be withstand by the port at all times. It is assumed that the load is uniformly distributed over the deck area of the port. The total load is equal to 12.600 ton, equivalent to 123.606 kN.

- Two 1300 ton cranes satisfy according an expert in the crane lifting market[37]. For the unloading of the feeder a smaller lift capacity satisfies, but for the flexibility of the activities this is also a 1300 ton crane.
- Five turbines of 12 MW, each turbine has a total weight of 1600 ton[38]
- One accommodation including 50 persons, estimated to weight 2000 ton

[37] Largely depending on the type of crane, a 900 ton crane can lift 900 ton at an altitude of 3 meter and a 1300 ton crane can lift 900 ton at an altitude of 10 meter. The radius of the crane has an exponential influence on the lifting capacity

[38] Extrapolated, based on the the weight of a 4,6,8 and 10 MW turbine. These weights and dimensions are not published, since for a 10 MW turbine this is confidential information.

H. Port design

H.1 AQWA

This section elaborates on the motion response calculated by AQWA, of which the basics are described in paragraph 6.1.2.

Finite elements

The result of the barge drawing created in Rhino is exported to Ansys. Modifications to the drawing can be done and the next step is to make a mesh. The submerged panels are displayed by blue, the panels above the waterline have a ligth brown color.

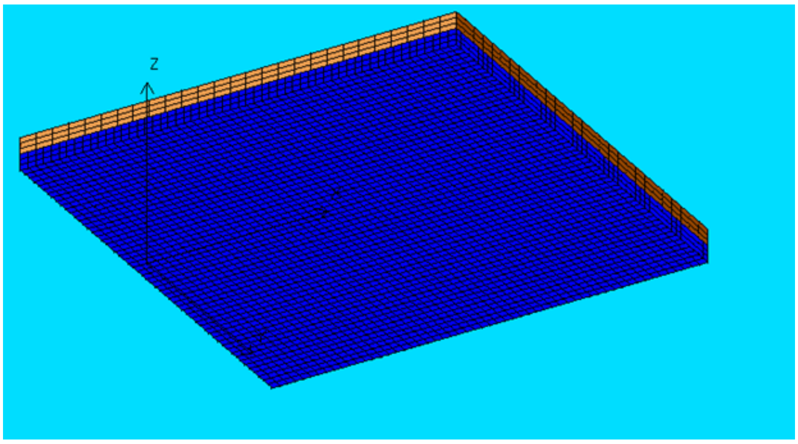


Figure H.1: Barge in Ansys

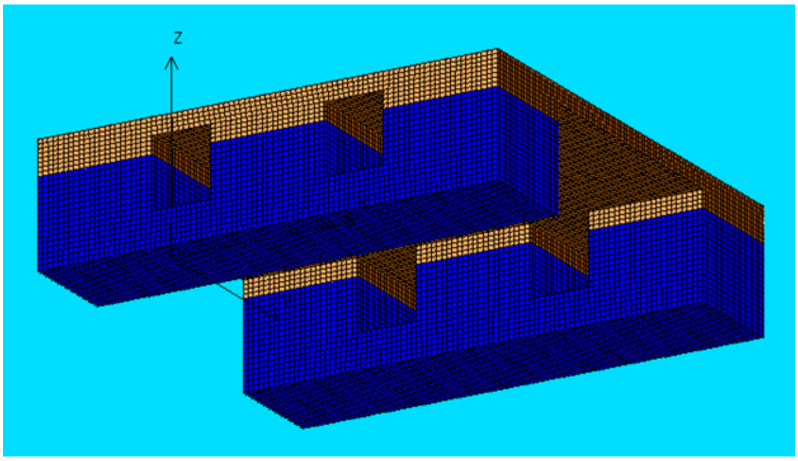


Figure H.2: Semi-submersible in Ansys, without the deck

Additional information on AQWA

A few variables have to be defined before the AQWA simulation can start. The water depth is set to 40 meters, the water density, draught and the gravitational constant have to be inserted and the center of gravity is demanded. The latter depends on the vessel weight and the cargo, in relation to their distance to the reference level. A mesh width of 1.5 meter is selected for the submerged panels and a larger width for the panels above the waterline. The MPM factor is applied to the significant motion

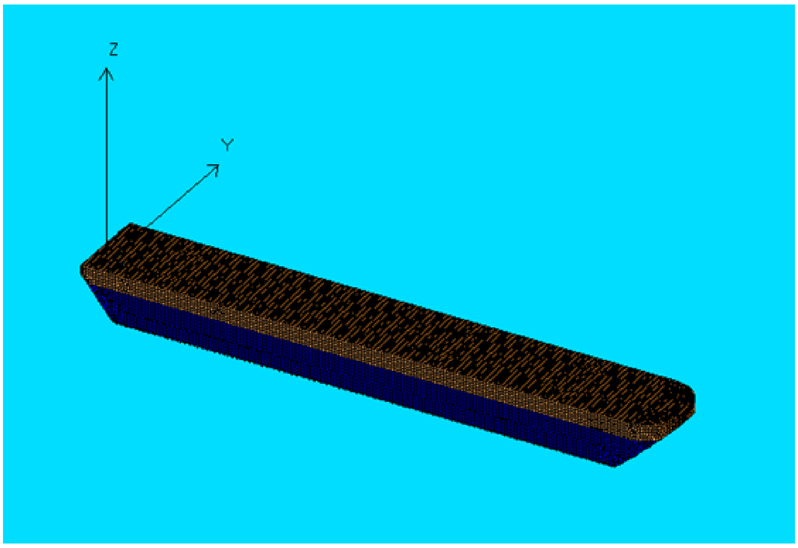


Figure H.3: VLCC in Ansys

amplitudes, which are determined by AQWA. This factor takes into account that the Hs only occurs for three hours, although the MPM value is still exceeded in 33% of the cases. Mooring systems are not integrated in the AQWA simulation.

Damping

The applied damping formula is developed by Yoshiko Ikeda. It takes into account the viscous damping and results in a value for κ. After the AQWA simulation this value can be determined, next AQWA is ran again but now using this damping coefficient. The second incoming wave is damped by a certain percentage. For example, the κ value of the barge is equal to 0.036. So when inserting this in AQWA before the second simulation, a consecutive incoming wave is damped by 3.6%. In this way the waves are damped by AQWA, so the barge itself is not damped, but the waves are.
In some cases damping can not be taken into account. When certain criteria are not achieved, based on the determined hydrostatic and hydrodynamic conditions of the simulated structure. For example, the ULCC has a large length. The waves within the spectrum are not long enough to damp the ULCC in its length direction, which is required for pitch. The applied Ikeda formula for non-dimensional viscous damping is as follows:

$$\kappa_e = \frac{d^3 \cdot \omega_0}{\pi \cdot g \cdot B \cdot \overline{GM}} \cdot \left\{ H_0{}^2 + \left(1 + \frac{\overline{OG}}{d}\right) \right\} \cdot \left\{ H_0{}^2 + \left(1 + \frac{\overline{OG}}{d}\right)^2 \right\} \cdot \phi_a \cdot \omega$$

Figure H.4: Ikeda damping [97]

In which the H_o represents a ratio between the beam and the draught. The ϕ_a depends on the MPM factor used and the motion of the structure.

H.2 Barge motions

The results of the heave motion for the barge with dimensions 133 x 133 x 10 meter is as follow:

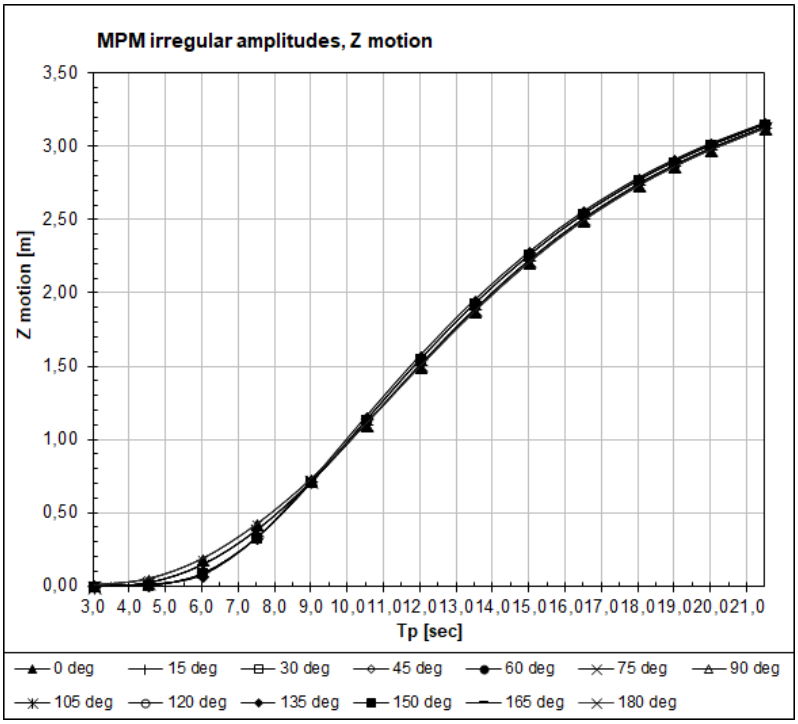


Figure H.5: Barge movement in heave direction

H.3 Thickness validation single barge

The thickness of the concrete walls of the single barge are validated in this paragraph. There are three walls that experience forces, the deck, the bottom and the four vertical side walls. A simple representation of the deck, bottom and vertical side walls is to schematise it as a beam that is fixed at both ends. The maximum moments at the end of the beam can be determined by a rule of thumb. This is displayed in figure H.6. The initial assumption as stated in paragraph 6.2.1, is an overall wall thickness of 0,75 meter.

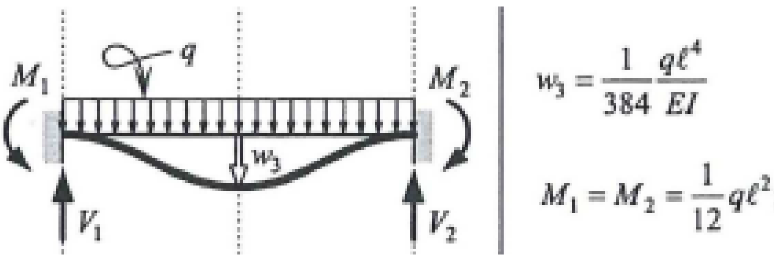


Figure H.6: Moment formula on two fixed ends [137]

The bottom has to deal with the upward water pressure. The weight of the platform and the additional three loads, do not act as counter weight since there is air between the loads and the water pressure. However, when the draught of the barge is determined, the amount of water can be calculated which is required to achieve the aimed draught. The depth of the barge should be at least 10 meter, due to the boundary conditions of the draught and the freeboard. The draught that is determined with a wall thickness of 0,75 meter, a height of 10 meter and a load plus lightweight, is 5,3 meter. For case 1 the width is 100 meter and the length 175 meter as can be seen in table 6.3. The highest moments occur in the length of 175 meter and with 6 sections in this length, this leads to a length of 29,2 meter.

$$q_{water} = draught * \rho_{seawater} * gravitationalconstant = 5.3 * 1,025 * 9,81 = 53\, kN/m$$

$$M_1 = M_2 = \frac{1}{12} * q_{water} * l^2 = \frac{1}{12} * 53 * 29,2^2 = 3749\, kNm$$

The concrete is exposed to sea water and the largest part is persistently submerged, this requires class XS2 [137]. In the Euopean standard 206 on concrete, it can be found that this class is related to characteristics of concrete class C35/45. The reinforcement percentage should be between 0,21 and 2,49. A percentage of 1 is assumed. However after a few calculations this is increased to 2% because 1% let to an average wall thickness of over 1 meter. It is reinforced with the most frequently used steel type B500B, this equals 270 [137]. The effective thickness can be calculated by the following formula:

$$270 = \frac{M_{max}}{b * d^2 * f_{cd}} \tag{23}$$

$$d = \sqrt{\frac{3749}{1 * 270 * 30}}$$

With:
d = effective thickness (m)
Mmax = maximum moment at the ends (kNm)
b = cross sectional width (m)
f_{cd} = compressive strength (MPa)

The effective thickness of the bottom, required to cope with this maximum moment by the water pressure is 0.68 meter. The concrete cover is based on an exposure classification of XS2 with an additional 50%. Using a concrete cover of 50 mm or 75 mm, is a negligible contribution to the total costs. However, this small addition of 25 mm can have a positive influence on the life time of the barge. The relation between effective thickness and thickness is the following:

$$d = t - (c + 1/2 * \phi) \tag{24}$$

$$t = 680 + (75 + 1/2 * 32)$$

With:
d = effective thickness (mm)
t = thickness (mm)
c = concrete cover (mm)
ϕ = steel bar diameter (mm)

The required thickness of the bottom is 771 mm. A similar approach is used to calculate the thickness of the deck. Though the loads, are the loads that the deck has to endure. These loads are divided by the surface area of the entire pontoon to calculate the bending moment. The weight of the platform consist of the concrete walls with an assumed thickness of 0,75 m. Also two large cranes, five turbines and the accommodation are taken into account. The maximum moment at the ends of the beam are lower than for the bottom. This leads to a wall thickness of 340 mm for the deck.

The length of the beam of the side walls is equal to the draught of the barge. Also the q force is different since this is equal to:

$$\int_0^h \rho g h \, dh \tag{25}$$

In which h represents the draught. The load on the side wall is distributed as shown in figure H.7, where point A is located at the bottom of the barge and point B at the water level.

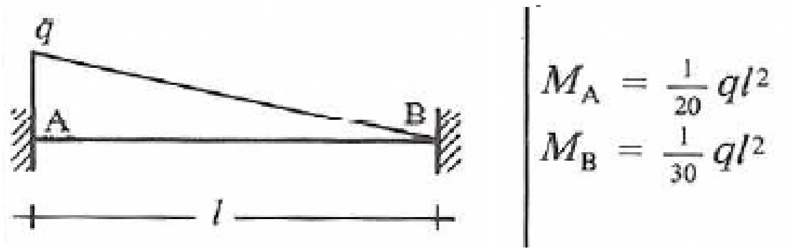


Figure H.7: Moment formula on two fixed ends for the side wall [137]

The required average thickness for the side walls is smaller than the average thickness of the deck and bottom. An assumption is made that the wall thickness of side walls is similar to the lowest thickness of the deck or bottom. Vertical inner walls are placed to reduce the span width. The thickness of the vertical inner walls is half the thickness of the side walls. Some cases have a thicker deck because an input variable is varied, this leads to an unneccesary thickness of the side walls and vertical inner walls. Therefore, for all cases, the thickness of the side walls and the vertical inner walls are equal to the determined thickness of case 1 in table 6.3.

The average wall thickness after the first iteration is 0,48 m and the freeboard is 4,7 meter. The next step is to conduct the calculation for the required thickness with an average wall thickness of 0,48 meter instead of 0,75 meter.
This results in a required wall thickness of 0,45 meter and the last iteration leads to an average wall thickness of 0,44 meter. The deck has a thickness of 0,34 meter and the bottom of 0,64 meter.
The freeboard is 6,6 meter and the draught is 3,4 meter. This is below the boundary condition of 5 meter. Therefore the required weight of added water is calculated, this is equal to 28.286 ton, equivalent to 1,7 meter of water within the single barge. This increases the draught to the required minimum of 5 meter and a freeboard of 5 meter. The wall thickness is still 0,44 meter, since the added water acts as a counter weight to the increased draught and corresponding load on the lower bottom.

H.4 Thickness validation catamaran

The catamaran barge has different dimensions and behavioural properties as the single barge. Therefore the approach to calculate the wall thickness deviates from the single barge. The five general boundary conditions and the two boundary conditions specifically stated for the barge are similar for the single barge and catamaran barge. Though boundary condition number seven is only valid for the catamaran type and boundary condition number 5 is irrelevant for the catamaran barge.

1. Offshore structure has to be at least suitable for a water depth range of 30 to 50 meter.
2. A minimum surface area of 17.500 m^2.

3. A minimum vertical load of 12.600 ton.
4. A freeboard between five and ten meter.
5. A port concept consist of a maximum of two port components.
6. A minimum draught of five meter is required.
7. The air gap of the catamaran is at least five meter above the water level. This makes boundary condition number three irrelevant.

Wall thickness

There is one main difference between the deck thickness calculation in comparison to the single barge. The 50% middle area of the deck has no supporting barge below it. This area is shown in orange in figure H.8.

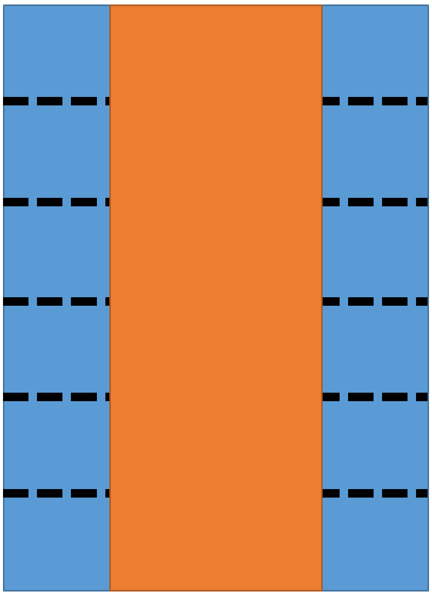


Figure H.8: Top view of the catamaran barge

The single barge consist of 36 sections created by vertical inner walls, six in longitudinal and six in lateral direction. The catamaran barge consist of twelve sections, six sections for both barges in longitudinal direction. This is shown by the black dotted lines in figure H.8. The length of a section is still longer as the width of a section. This is governing in the determination of the moments that occur in the deck of the barge. The deck area on the left and right side of the barge, indicated by blue in figure H.8 endure 50% of the vertical loads. The wall thickness is calculated by a similar approach as for the single barge. The orange area endures the other 50% of the loads, which leads to a thicker deck for this area.

With a barge depth of 10 meter and an assumed wall thickness of 0,75 meter, this leads to a draught of 7,9 meter and a corresponding freeboard of 2,1 meter. The required average wall thickness is 0,67 meter and the air gap is 1,2 meter. So the depth of the catamaran is increased by 3,8 meter, to satisfy boundary condition number 7 and the wall thickness is decreased to 0,67 meter.
After this iteration, the depth of the barge is decreased from 13,8 meter to 13,2 meter, because the air gap is 5,6 meter and the wall thickness is decreased to 0,65 meter.

After this second iteration, the wall thickness is constant and equivalent to 0,65 meter. Though the depth of the barge can be decreased by another 0,2 meter because the air gap is 5,2 meter.

Comparing the final result as presented in figure 6.3 in paragraph 6.2.1 of the single barge with the catamaran type, there are a few striking aspects.

- The draught of the catamaran barge is over five meter, this requires a higher depth than 10 meter to satisfy the boundary condition of the minimum air gap. As a consequence the lightweight of the catamaran type is 5% higher.
- The KG value of the catamaran barge is higher. This is because there is no supporting bottom of the catamaran in the orange area of figure H.8. Additionally the deck is thicker because, there are no vertical inner walls to reduce the span width.

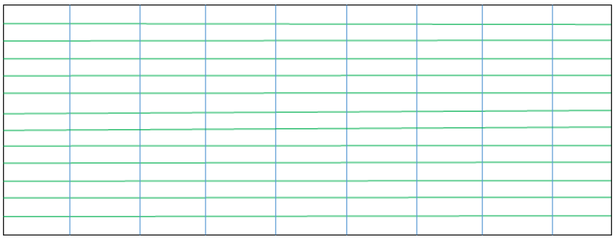
In conclusion of the catamaran barge, other materials should be considered because applying concrete requires more material for the catamaran barge as for the single barge.

H.5 Steel validation catamaran

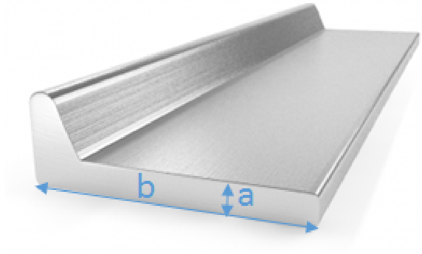
In the previous appendix it is determined that other materials as pre stressed reinforced concrete should be considered as a material for a catamaran barge. In this section a similar calculation is conducted and as a result the amount of required steel is calculated. This could increase the feasibility of applying a catamaran barge as a port component. Because the draught of a barge made from steel will be smaller than 5 meter and satisfy the boundary condition without increasing the depth of the barge. Water tanks have to be created, this is similar as for most cases of the single barge in table 6.3. The goal of this section is to determine the lightweight of the catamaran barge made from steel. In practice, a common wall thickness is 2 centimeter for a large vessel, though calculations are conducted to analyse this for the catamaran barge.

The first step is to understand how the steel is placed and constructed in the barge. The hull consist of an outer plate and beams with a Holland profile (HP), also known as a bulb flat. These are placed in the length of the barge to handle the load on the outer plate. These HP beams transfer the load to the girders, which are placed in lateral direction of the barge. When we look from the inside of one of the two barges to the outer wall, a zoomed in visualisation as shown in figure H.9a is the view. The green lines are the HP, the blue lines correspond to the girders and the black line is the edge of our view and consist of multiple plates.
The weight of all three elements has to be determined for both barges and for the deck. In figure H.9b a HP is shown in which a is the thickness and b is the height of the HP. An indicative picture of a small ship in figure H.10a shows an example of a ship construction. The green HP lines in figure H.9a, corresponds to the beams in longitudinal direction of the ship in figure H.10a. Girders area a form of stiffeners, these are connected to the outer plate and cross the HP beams. In figure H.10b a sketch of a girder is displayed.

For the HP, the girders and the outer plates, the weight is determined. A typical distance between the HP's is 700 mm and between the girders this is 2800 mm, these are used as a start value. Increasing this dimension will decrease the amount of girders and HP's needed. On the other hand, the used HP's

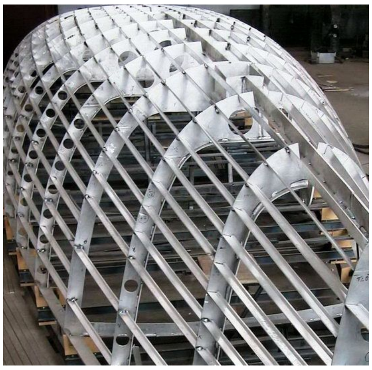


(a) Side view from inside

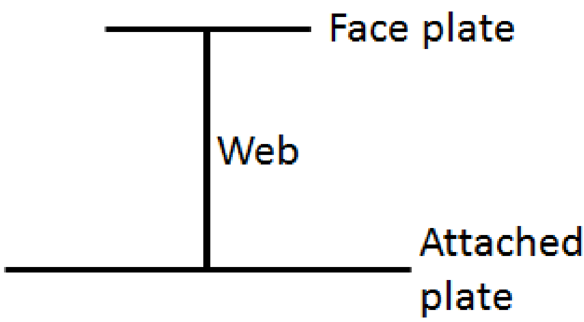


(b) HP profile

Figure H.9: Steel construction of a barge



(a) Ship construction without outer plate [W12]



(b) Girder

Figure H.10: Steel used in barge

and girders have a larger dimension when the distances are increased. These values can be iterated to achieve a lower amount of steel needed for construction.
The load for the five sides of the barge that are under the water line is based on the water pressure for a draught of 5 meter. However, the effective load is only for a height of 700 mm. The maximum moment on the barge is derived in a similar way as shown in figure H.7. For a draught of 5 meter and a span width of 2800 mm a moment of 3 kNm is present. With a cross-section classification of class 2, corresponding to plastic theory, the following formula is applied to determine the plastic modulus [137]:

$$M_{pl} = \frac{W_{pl} * f_y}{Y_{M0}} \tag{26}$$

In which:
W_{pl} (mm^3) = section modulus
f_y (N/mm^2) = yield stress (355)
Y_{M0} = material factor (1,0)

The section modulus is equal to $65*10^3$ mm^3. Using the Polytechnisch Zakboek, the corresponding dimensions of the HP can be determined [120]. This is a thickness of 8 mm, a height of 140 mm and the weight is equal to 10,9 kg/m. So per unit length the weight of a HP is is 10,9 * 0,7, which is 7,6 kg. The total length of HPs in both barges is calculated and multiplied by the weight, this equals 190 ton for the starboard, port side and floor. A similar approach for the bow and stern side of both barges is applied with a different unit length and provides 15 ton. The deck has HP dimensions of 80 x 6 and the total ton of HP for the deck is 125. The entire weight of the HP's is 330 ton.

The outer plate thickness is in the order of the thickness of the HP, a thickness of 10 mm is applied. For the entire body of the catamaran, this leads to a weight of 2450 ton. As can be seen in figure H.10b, the girder consist of three elements. Each of these has a certain thickness and a breadth or height. The thickness is assumed similar as to the outer plate, which is 10 mm. The breadth of the face plate is assumed similar as the height of the HP and the breadth of the attached plate is twice the breadth of the face plate. The height of the web is equal to twice the breadth of the attached plate, which equals 560 mm.
Based on these dimensions, each girder has a weight of 98 kg/m and is placed every 2800 mm in longitudinal direction. For the entire catamaran barge the weight of the girders is equal to 650 ton. This provides a total weight of 3600 ton for the entire catamaran barge.

If a stiffener is required to strengthen the construction in horizontal direction, it is called a stringer and not a girder. The dimensions of a stringer are smaller, though there are more of them required as for the girder. It is assumed that a stringer is not required for the catamaran barge due to the draught of just five meter which provides limited stresses for a large barge. with a surface area of 30.659 m^2, this equals 0,12 ton/m^2 and an average thickness of 15 mm. This is smaller than the commonly applied thickness in the ship building industry of about 30 mm.
An explanation for this is the small load and low draught of the barge. Decreasing the length between the girders to 2500 and the spacing between the HP's to 650, has a negligible influence since similar standard dimensions of the HP, girders and outer plate are then recommended by the guiding tables with all the dimensions for steel. A saving of nearly 10% is feasible in comparison to the applied dimensions in this section. However, this 10% could be outweighed by not applying typical dimensions for the HP, girder and outer plate. Also the 10% is negligible in relation to assumptions that are made in this calculation. Therefore this optimisation is not used as a comparison to the concrete catamaran barge.

H.6 Catamaran approach

The derivation of the stability and natural oscillation from the single barge. The four main differences are summed up below:

- To determine the distance of BM, the moment of inertia (I) at the waterplane area (A_{wp}) is demanded. First the moment of inertia through its center is determined, just as for the single barge. But then Steiner's theorem[39] (parallel axis theorem) is added to determine BM, this does not hold for BMI. This relates to the moment of intertia about another axis at distance d away from the centre. For each barge of the catamaran the following formula is applied: $I+A_{wp}*d^2$ [19] [143].
- To determine the oscillation period, the mass moment of inertia is demanded. For the roll motion, this is different for the catamaran barge than for the single barge. There are two methods to determine the mass moment of inertia of the deck. Equation 28 can be multiplied by the mass of the deck of the barge, or the mass moment of inertia can be calculated as shown

[39] Explained in the lecture notes of Offshore Hydromechanics (OE4630) TU Delft

in paragraph 6.1.2 which is applied to the single barge. Both methods provide a similar answer. The mass moment of inertia of the floaters is calculated by equation 27. The radius of gyration (k) is multiplied by the weight of the floaters [143].

$$k^2 * m + d^2 * m \tag{27}$$

Where:

$$k_{xcxc} = \frac{\sqrt{3b^2 + 3h^2}}{6} \tag{28}$$

In which:
h (m) = height of barge
b (m) = width of one barge
k (m^2) = radius of gyration about the centroidal axis

- The added mass is different for the catamaran barge as for the single barge. In figure 6.5 the added mass formula for a single barge shows two multiplications within the brackets. The width of the barge is multiplied by the distance of the underwater mass to the centre of gravity. The same applies to the second multiplication with the draught. The single barge formula is translated into the added water mass formula per unit length as shown in figure H.11. The orange area indicates the added mass.

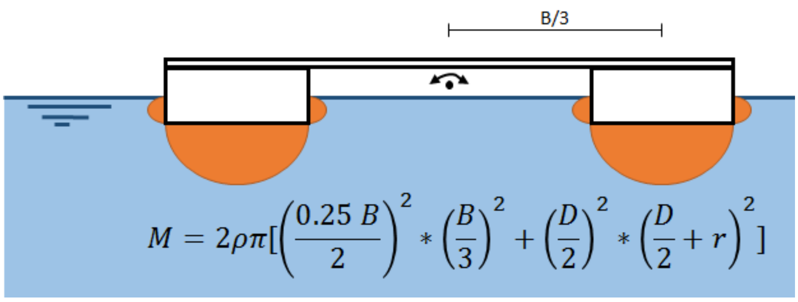


Figure H.11: Added water mass for catamaran barge in roll direction

- The width is half the width of the single barge, except for the deck. This factor of a half comes back in for example the values of BM, KG, draught and the spring terms.

H.7 Semi-submersible derivations

In this appendix a visualisation of this type of structure is provided and the derivation of the added mass of a semi-submersible is explained.

H.7.1 Semi-submersible impressions

The specifications of three semi-submersibles are analysed. Thialf is the largest existing semi-submersible. The Sleipnar and OOS Zeelandia are semi-submersibles which are in the design phase, but when constructed exceed the dimension of the Thialf semi-submersible.

(a) Thialf at Rotterdam [W17] (b) Sleipnir [W27]

Figure H.12: Two large semi-submersibles

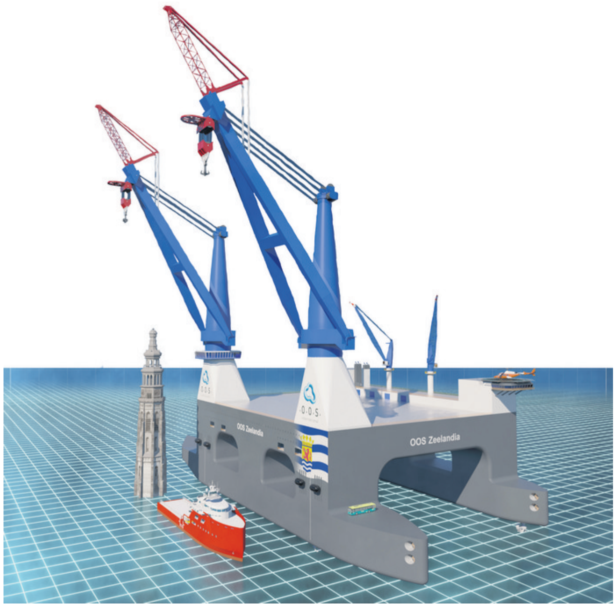


Figure H.13: Size impression of the OOS Zeelandia [W3]

H.7.2 Semi-submersible added mass

The equations and visulations of the added mass in figure 6.5 are valid for a semi-submerged structure. In combination with the equations of a submerged structure as shown in figure H.14, the added mass formula for a semi-submersible structure is derived. However, multiplying the added mass below CG by (5/2) results in an added mass that is to high. Intermediate results showed that this added mass does not correspond to the values provided by AQWA.
It was questionable to see the floater and column depth that was submerged as fully submerged, instead of analysing the entire semi-submersible as a semi-submerged structure. The latter is confirmed by an intermediate test in AQWA concerning the added mass. So the added mass in figure H.14 is not valid for a semi-submersible.

The applied methodology to derive the added mass formula is similar for heave, roll and pitch. The added mass surface area in a 2D visualisation is determined and this is multiplied by the Steiner term.

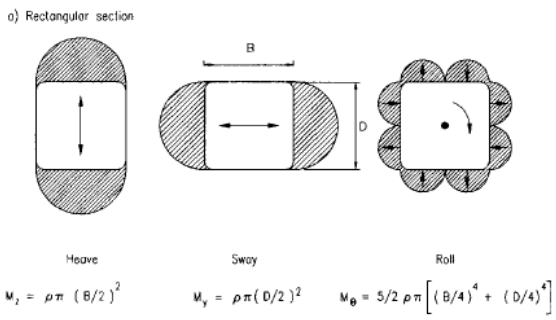


Figure H.14: Rough 2D estimate of added mass for a rectangular fully submerged structure [11]

This term is equal to the length of the centroid distance of the surface area to CG. So far, this is similar as for the barge methodology. But the unit length for pitch and roll is different as to the barge. For pitch, the unit length is twice the column width and for roll there are two different unit lengths. One unit length equals three times the length of the column, and the other unit length is the total length minus three times the column length. This difference in unit length is required because the added mass is different for the length that has a column and for the length that has no column. So the roll added mass actually consist of two separate equations.
To ease the understanding of this derivation, a visualisation is provided for the pitch added mass in figure H.15. The added masses that has the same distance to CG have a similar number in the figure., this is indicated by the dotted line and only drawn once for each number to present an indication.

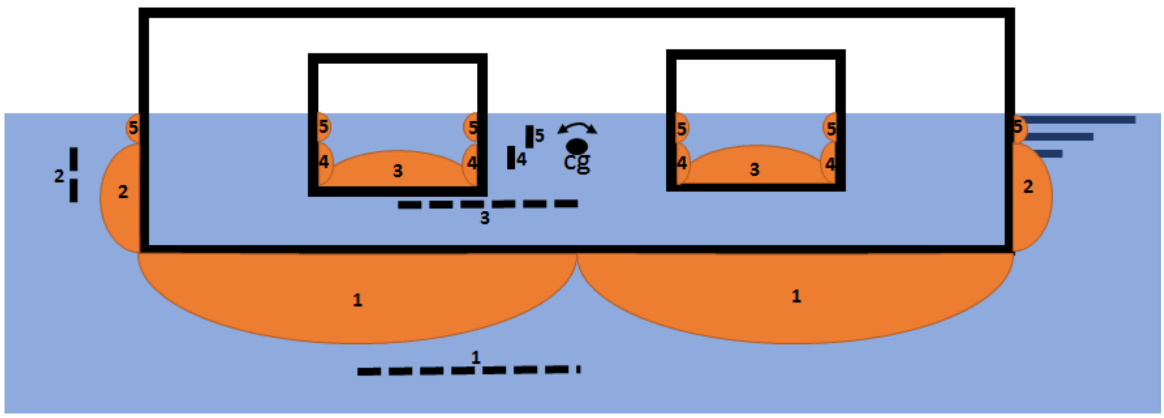


Figure H.15: Rough estimate of pitch added mass for a semi-submersible

The determination of the added mass surface area and the length to CG of each centroid point of the surface area results in equation 29. For the roll motion a similar approach is applied, though the side view is different and the unit length is equal to the explanation as stated in the text above figure H.15. The numbers in figure H.15 corresponds to the consecutive order of the five multiplication terms of the added mass.

$$Added\ mass\ pitch = B_c * 2 * \pi * \rho * \begin{pmatrix} (\frac{L_f}{2})^2 * (\frac{L_f}{4})^2 + (\frac{CG}{2})^2 * (\frac{CG}{2})^2 + \\ \frac{(L_f - 3L_c}{2})^2 * (\frac{L_f}{4})^2 + (\frac{CG - H_f}{1})^2 * (\frac{CG - H_f}{2})^2 \\ + (\frac{T - CG}{2/3})^2 * (\frac{T - CG}{2})^2 \end{pmatrix} \quad (29)$$

In which:

B_c = width of column

L_f = Length of floater

L_c = Length of column

H_f = Depth of floater

CG = Center of gravity

T = Draught

H.8 Semi-submersible motions

The most probable maximum motion response of the semi-submersible in a Jonswap wave spectrum is provided in this appendix. The motion response in roll and heave are based on a Hs of 4,5 meter.

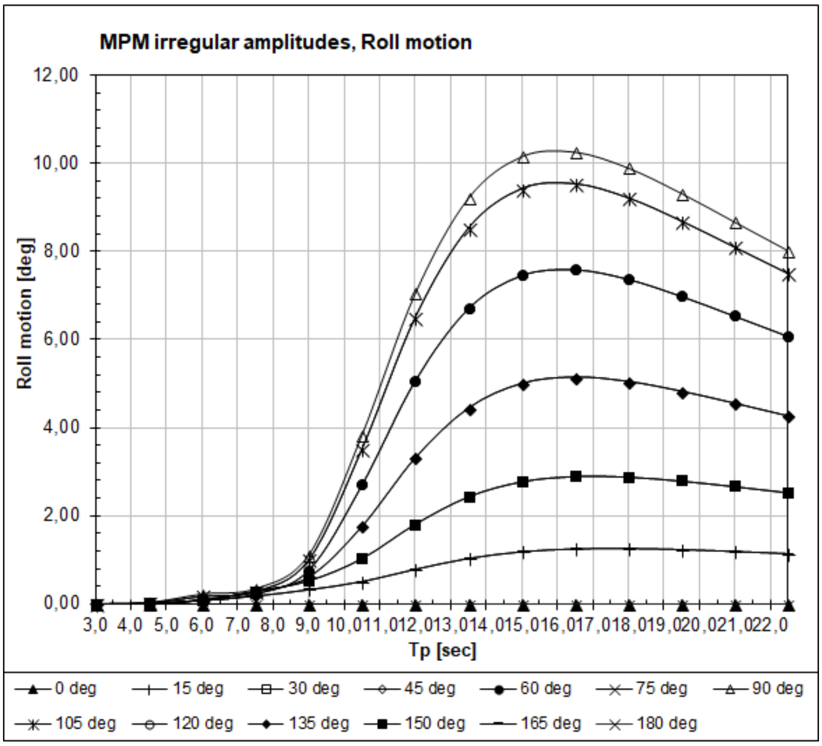


Figure H.16: Motion response of the semi-submersible in the roll direction

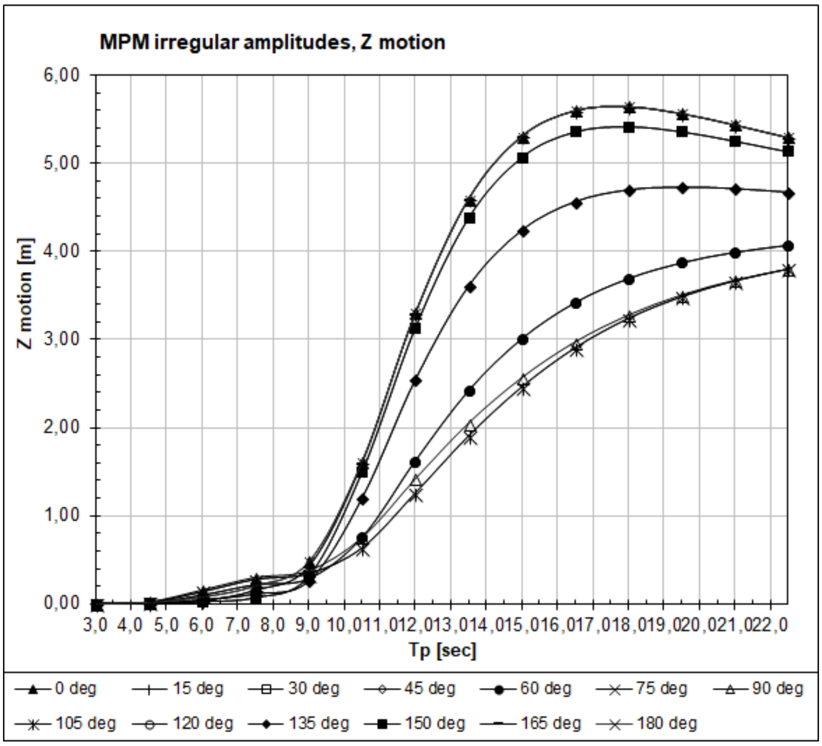


Figure H.17: Motion response of the semi-submersible in the heave movement

H.9 VLCC properties

The most probable maximum motion response for the ULCC in pitch and heave are displayed in this appendix.

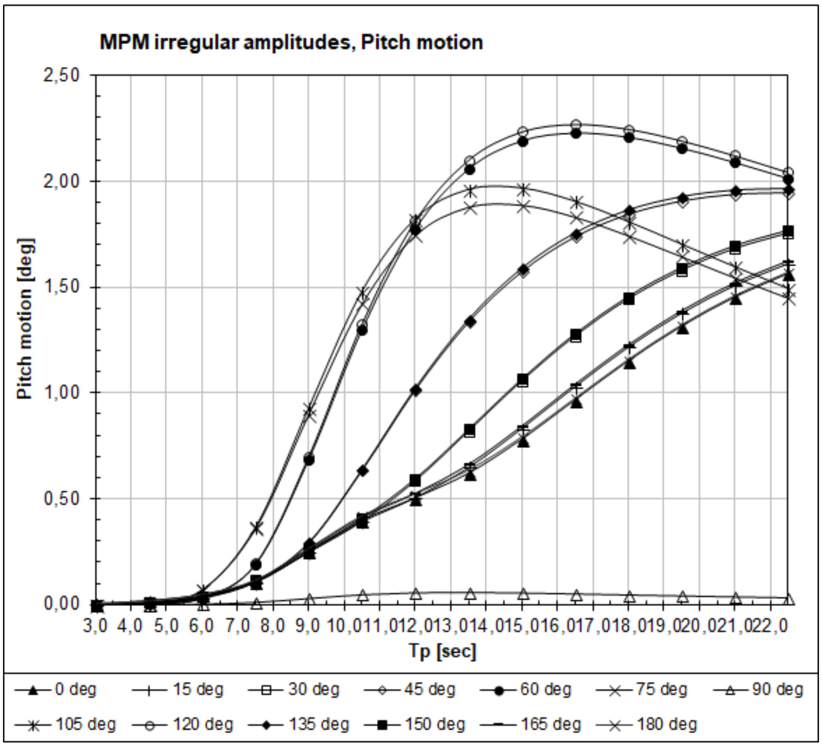


Figure H.18: The response in pitch direction of a VLCC

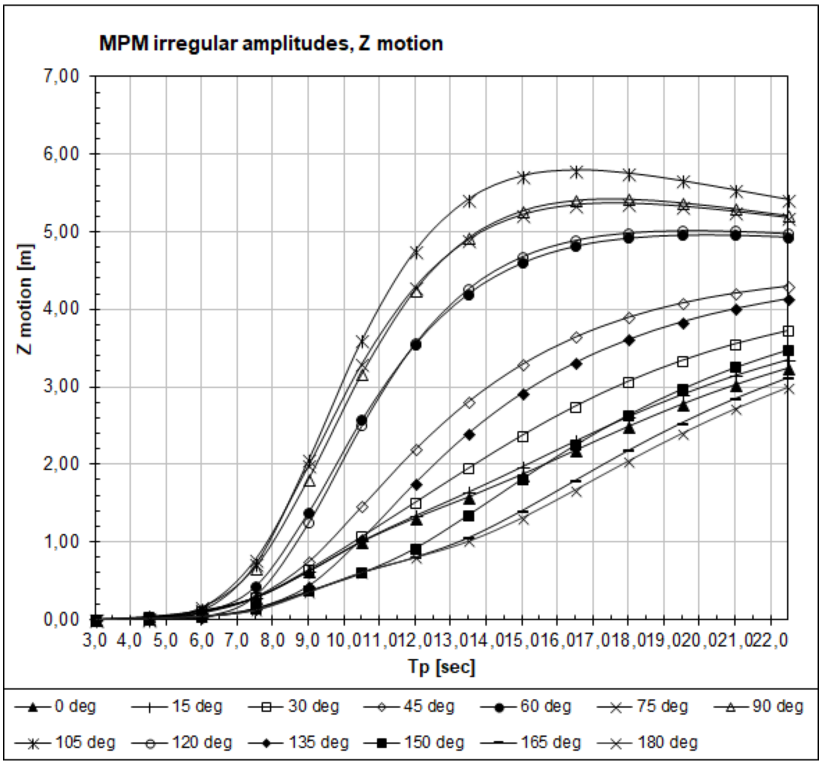


Figure H.19: The response in heave movement of a VLCC

H.10 Construction costs barge

The indirect costs and the uplift costs that lead to the multiplication factor of the direct costs are based on the parameters as shown in figure H.1. The parameters listed below are the main contributors to relate the direct costs and total costs [9].

Table H.1: Indirect and Uplift costs

	Parameter	Percentage of direct costs
Indirect costs	Design	6
	Temporary site facilities	3
	Staff on construction site	4
	Supervision by client on site	1.5
Uplift costs	Insurance	1.5
	Overehad	5
	Risk	5
	Profit contractor	15

I. Logistical model

This appendix elaborated on the logistical model which is developed to calculate the logistical savings. The last section of this appendix shows the visualisation for two of the four logistical concepts.

I.1 Flowchart

With this flowchart it gets clear how the total costs are determined for the feeder vessel, offshore port and the JUB and their corresponding equipment and labour for all three of them. But the flowchart in figure I.1 is a simplistic representation of the logistical model. It does not take into account where each turbine is located for each hour in time. There is also no division within the multiple activities of the platform, while in the real simulation model the platform consists of multiple activities that are monitored.
All parameters represented in the right box of figure I.1, start with the value 0. Except the letter 'p' which is to be determined prior to the simulation, in the example in paragraph 7.1.1 this is 100. The amount of turbines onshore are assumed to be equal to this as soon as the model starts, however in practice this will be supplied throughout the process.

The flowchart monitors the process every hour. When a box in which a single or multiple, '+1' is displayed for i,j or k is passed, the next hour starts. The total amount of hours a vessel or port is active, is the addition of all the '+1' for each particular vessel or port. This leads to a period in which the vessels and port are active and the corresponding total costs The onshore port is due to simplicity not displayed in figure I.1.

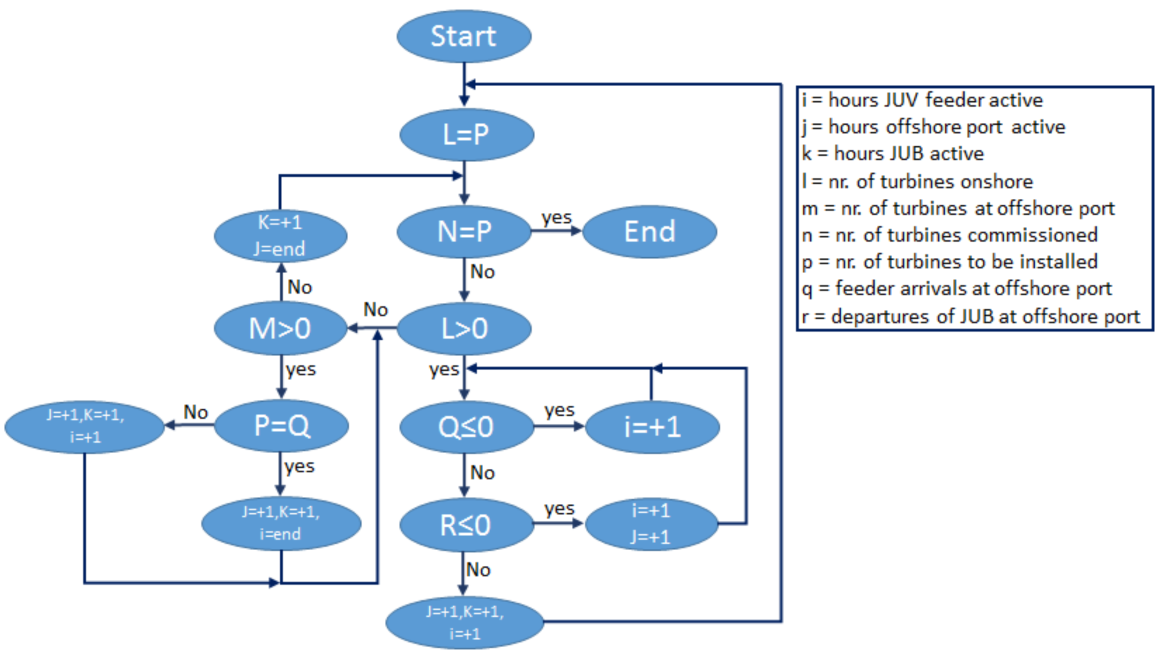


Figure I.1: Simplistic visualisation of the logistical model

I.2 Input parameters

The input parameters that have a substantial influence on the costs are briefly mentioned in paragraph 7.1.2. These four input parameters are explained into more detail in this section and in the end of this section an overview is provided of all input parameters.

Turbines

There are 100 wind turbines installed with each a capacity of 12 MW. In table 2.2 it can be seen that installing a 12 MW turbine by the year 2030 is a conservative approach, since the average turbine size in Europe and US Atlantic is around 13 MW. The weight of the blades increases linear with capacity, while the weight of the nacelle, hub and tower are more related to a quadratical increase with the capacity. After a verification in the market the 12 MW weight of the entire turbine is 1614 tonnes. The distribution is as follows:

Weight and power	8MW	10MW	12MW	14MW
Nacelle and hub (tonnes)	350	420	504	605
Rotor (tonnes)	120	150	188	235
Tower (tonnes)	550	715	930	1209

Figure I.2: Weight and power of a turbine

Day-rate vessels

The day-rates are determined based on the maximum carrying capacity, maximum sailing speed of the vessel and when present, the lifting capacity. After a small questionnaire in the market the day-rates for several vessels became insightful. A general formula is created based on the day-rates, this is shown below. The advantage of a general applicable formula is that when varying one of the three parameters, the day-rate is automatically adjusted.

- **Feeder vessel:** carrying capacity * 15 + sailing speed * 750
- **Installation vessel:** carrying capacity * 30 + lifting capacity * 20 + sailing speed * ((carrying capacity + lifting capacity)/3)
- **Barge:** carrying capacity * 3 + sailing speed * 500

A barge has low multiplication numbers for multiple reasons: no jacking capability, availability, design and construction. As an example, a feeder vessel with a maximum sailing speed of 20 km/h and a carrying capacity of 1814 tonnes, has a day-rate of:

$$1814 * 15 + 20 * 750 = €42.210$$

Distance to shore

The average distance to shore by 2030 in Europe and US Atlantic is approximately 70 km. However, currently offshore wind farm projects of 200 km to shore are planned and of more than 100 km to shore are already commissioned. As is stated in paragraph 2.3 the highest 5% of the wind farms planned in the coming years is 153 km. Since the offshore port has more potential with a longer distance to shore of the wind farm projects and the increase of distance to shore shows an exponential trend over the years. An optimistic, but plausible distance to shore of 175 km is used as input for the base case.

Delay due to environmental conditions

The limiting significant wave height for the activities of all three vessel types is shown in table 7.1. The significant wave height is the only weather condition taken into account in the model since this is more limiting for shipping than wind or currents. Weather data of the Dutch coastal waters is available for free and the weather data of the years 2014 and 2015 is used as input. The border of the Dutch coastal water is at a distance to shore of approximately 100 km, instead of the aimed 175 km. Therefor the limitation of the vessel to the significant wave height is lowered by 0,5 meter, so the wave height of 100 km to shore coincides more accurate with the aimed wave height of 175 km to shore. As an example, the limiting significant wave height for the installation vessel when sailing is 3 meter. So in the model this is set to 2,5 meter.

There are more input parameters of which the value is fixed for all five logistical analyses. An overview of the remaining input parameters that are not described in this paragraph can be found in figure I.3. These values are fixed for the base case and the related results.

Group	Variable	Unit	Costs	Number	Value
Wind turbine	Power of wind turbine	MW			12
	Number of wind turbines			100	100
	Weight Nacelle + hub	Tonnes		504	504
	Weight Rotor	Tonnes		180	180
	Weight Tower	Tonnes		930	930
Assembling	Tower & 2 blades + nacelle/hub	Hours		5.0	5
	Tower + a blade & 2 blades +nacelle/hub	Hours		6.0	6.0
	Tower & nacele/hub + 1 blade	Hours		4.0	4.0
Period of time	Loading one turbine at onshore port	Hours		2	2
	Unloading one turbine at offshore port	Hours		2	2
	Loading one turbine at offshore port	Hours		2	2
	Assembling of components	Hours		5	5
	Transit in terminal of components	Hours		0.5	0.5
	Installation including jacking time per turbine	Hours		20	20
	Offshore transfer of one turbine	Hours		15	15
	Offshore transfer of two turbines	Hours		21	21
Distances	Distance onshore and offshore port	Km			175
	Distance offshore port and wind farm	Km			5
Costs	Cranes fixed costs	€/project	50000	3	150000
	Assembling offshore crane day rate	€/day	4000	1	4000
	Loading crane day rate offshore	€/day	15000	1	15000
	Loading crane day rate onshore	€/day	15000	1	15000
	Self driving trailers onshore	€/day	4000	2	8000
	Self driving trailers offshore	€/day	6000	2	12000
	Labour costs onshore	€/hour	20	25	500
	Labour costs offshore	€/hour	25		
	Labour at offshore port	people		10	250
	Labour at JUV	people		5	125
	Labour at JUB	people		10	250
	Labour at barge	people		10	250
	Fuel costs JUV/JUB	€/day	13000		
	Fuel costs Feeder	€/day	10833		
	Fuel costs Barge	€/day	15167		
	Port onshore with assembling	€/day	2740	1	2740
	Port onshore without assebling	€/day	1644	1	1644
	Port onshore fixed costs	€/project	150000	1	150000

Figure I.3: The verified and fixed input parameters for the logistical model

Most of the fixed values showed in the figure above depend on other input values that are not visible.

For example the port rent depends on the surface area, the fuel costs depend on the current market price and the capacity of the wind farm depends on the demanded power.

I.3 Additional assumptions

As explained in paragraph 7.1.2, five major assumptions are made. A lot of minor assumptions support the major assumptions, fixed input parameters and logistics within the model. These minor assumptions are listed below:

- The JUB requires 10 people who are continously working on the activities. The duration of a work shift is eight hours and the salary is based on a yearly salary of €65.000 per crew member [6]. So in total there are 30 people working on the JUB. The barge feeder and fast feeder require 5 people who are continuously active. At the onshore port 25 people are working for eight hours and there are three shifts a day.

- When equipment is not used during the rental period, it still has to be paid. The transport of equipment is not taken into account.

- To take into account the acceleration and deceleration near the ports,the sailing speed of the vessels is multiplied by 0,9. A higher sailing speed requires a longer stopping distance, this is accomplished by the same multiplication for all vessels.

- The port area is rented twelve days before the transport process starts and three days after the last turbine components left the port. When assembling is conducted at the onshore port, the required surface area is 200 meter wider. A port without assembling has a surface area of 500 m * 300 m.

- The total period of the process is the range between the start of loading the first feeder and the commissioning of the last turbine.

- A continues use of a jack-up installation vessel requires 10 tonnes of fuel per 24 hours [37]. This is equal to 11000 liter of fuel a day and with the current rate of €1,20/L the costs are determined. The feeder vessel uses 5/6 of this quantity since its weight is a lot lower, but the sailing speed is higher. A barge uses 4/6 of the fuel of a JUB because its sailing speed is very low.

- A continuous back-up storage of at least one turbine is required at the offshore port. The percentage of days without a back-up shows the risk that the JUB has to wait. The percentage of days without a back-up is determined from the arrival of the first turbine components, until the departure of the last turbine components.

- The jacking up and down of a vessel takes about nine hours, the installation of the turbine on top of the transition piece takes another eleven hours due to a high level of accuracy. A transfer of a single turbine between two vessels offshore takes six hours, however an additional nine hours is required for the jacking up and down of the vessels.

- When the unloading of the feeder and loading of the installation vessel has to be paused due to weather restrictions, this paused period is multiplied by 1,5. It takes some time to put the process on a hold and to start the process up again. When between arrival and departure of the port the limiting HS does not occur, the feeder vessel and the installation vessel do not use the jacking system. This factor 1.5 also represent the possibility of a wind velocity that limits the unloading or installation, while the limiting Hs does not occur.

- Working shifts are 12 hours a day, as commonly applied in the offshore market.

I.4 Start date of the project

The offshore port has to be used for multiple offshore wind farm projects as explained in the scope of this research. A single offshore wind farm project is modeled in EXCEL and this project is therefore copied and repeated multiple times. So the project should represent an average weather condition throughout the lifetime of the port. To determine this average weather condition six start dates are applied as the input value and the corresponding results for two logistical concepts is determined. The two logistical concepts are the reference case and the concept with the transport to the offshore port by a feeder.

Again, the three varying parameters are the sailing speed, carrying capacity and the start date of operation of the second vessel, if present in the logistical concept. The two boundary conditions related to the logistical model are satisfied and an optimum value for the total costs and amount of installation days is determined. By calculating the optimum, only the sailing speed and start date of the second vessel are modified. Increasing the carrying capacity of the feeder leads to high costs for satisfying the boundary condition of a maximum of five turbines stored.
The results for several start dates are shown in table I.1. The selected start date of the project is the first of February because this shows approximately average weather conditions. It can also be seen that the weather conditions mainly affects the duration of the project and to a smaller extent the total costs. This can be explained by the performed optimisation, in which the total costs are given more value than the installation days.

Table I.1: Duration and costs per project for several start dates

	One JUV for transport and installation		Transport by a fast feeder and installation by a JUB		Difference	
Start date	Installation days	Total costs (€ Million)	Installation days	Total costs (€ Million)	Installation days	Total costs (€ Million)
01-02	170	42.1	145	19.1	25	23.0
01-04	159	38.6	125	13.5	34	25.1
01-06	158	39.6	121	13.3	37	23.7
01-08	195	48.6	180	26.9	15	21.7
01-10	202	50.9	199	32.6	3	17.7
01-12	196	48.6	183	27.6	13	21.0

I.5 Logistical visualisation

As stated in paragraphs 7.2.1 and 7.2.4 two of the four logistical concepts are not visualised in the main text, because the results look similar as other concepts. These two concepts are shown on the next page.

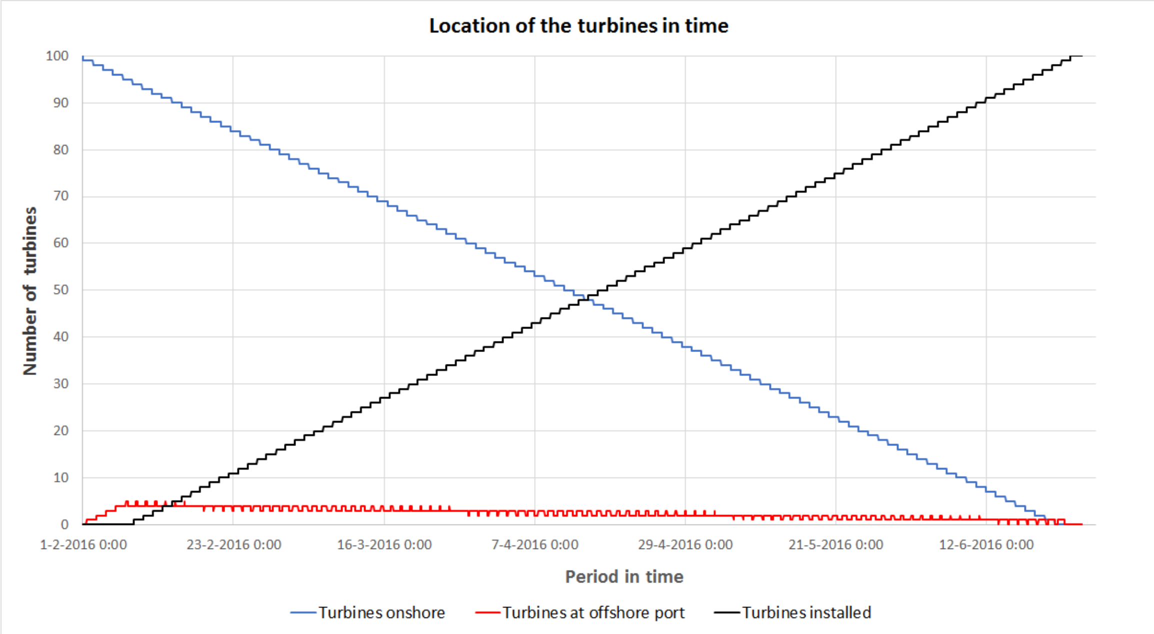


Figure I.4: Transport by a fast feeder vessel and installation by a JUB

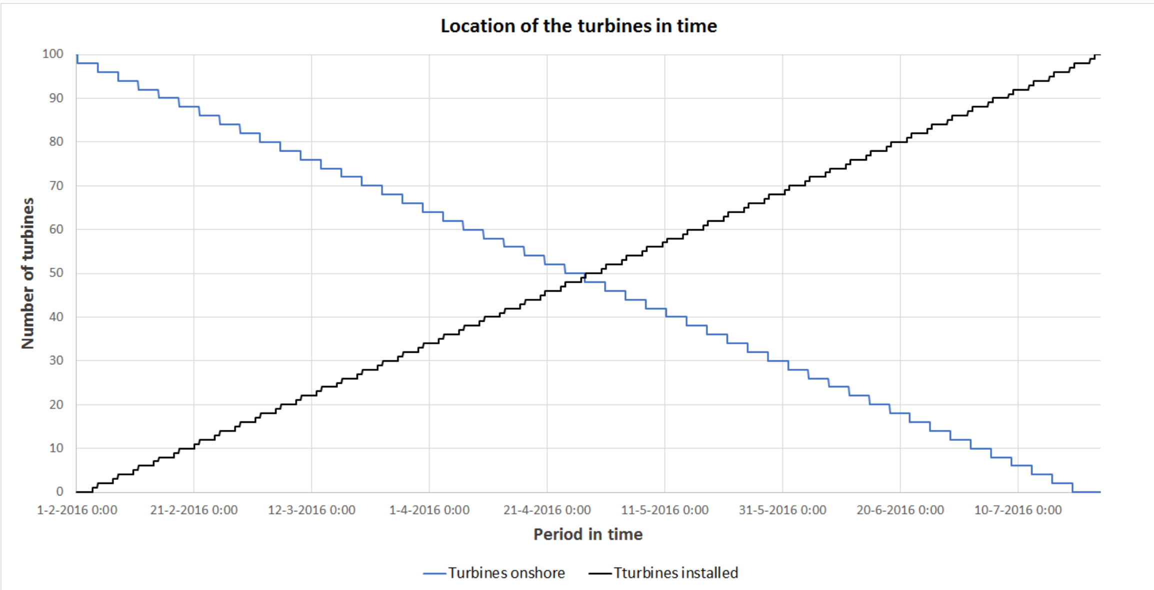


Figure I.5: Offshore transfer of turbine components between JUV and JUB

I.6 Delay by ECN Install tool

The project start on the first of February, the time overview of the project can be seen in figure I.6. It clearly shows the substantial contribution of the weather conditions to the delays, specifically in the month of February.

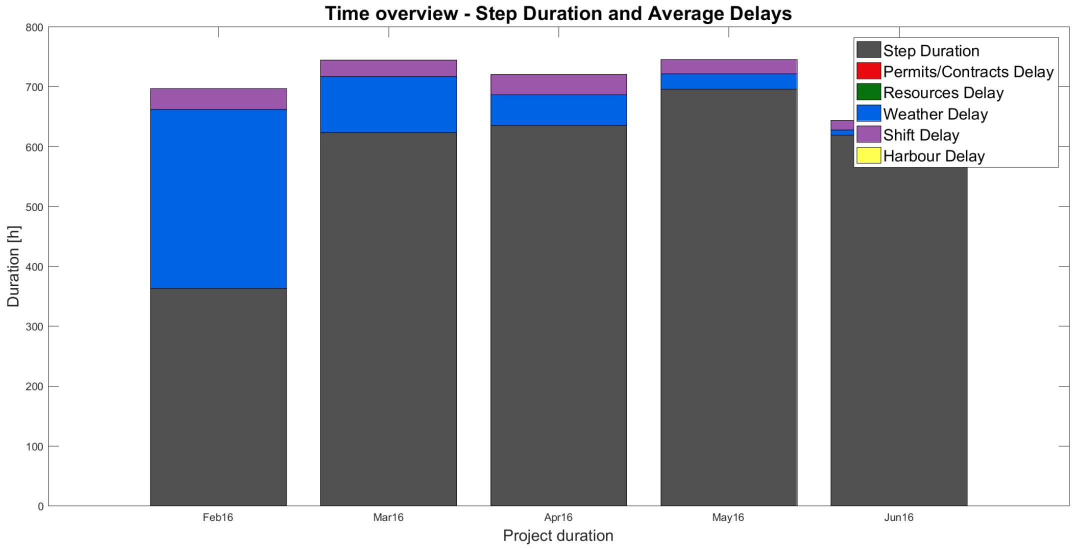


Figure I.6: Time overview of the ECN Install simulation.

J. Cash flows

This appendix contains supporting visualisation to understand the discounted cash flows of two off-shore port concepts.

J.1 Discounted cash flow

A visualisation of the discounted cash flows for the port concept of a barge and the port concept of the barge and small jack-up is shown in this appendix.

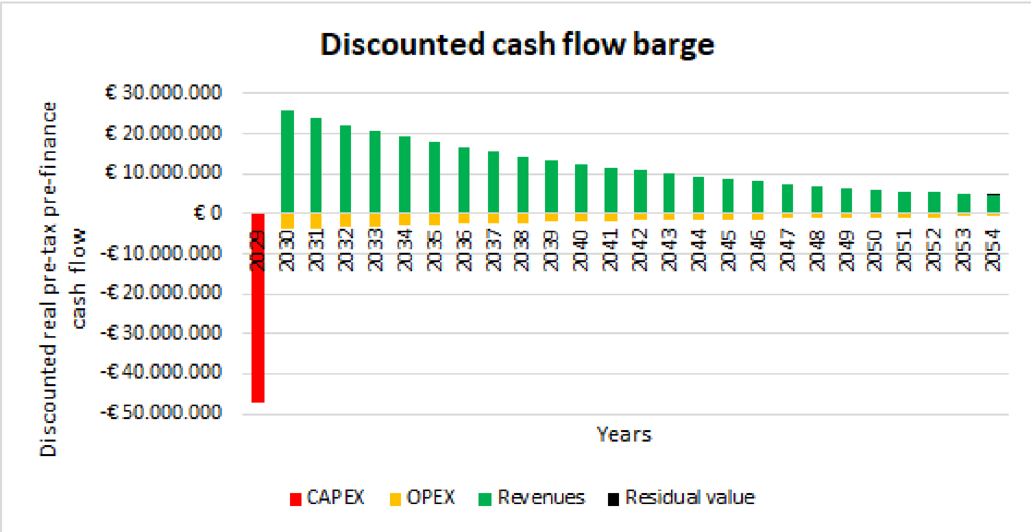


Figure J.1: Discounted cash flow barge port concept

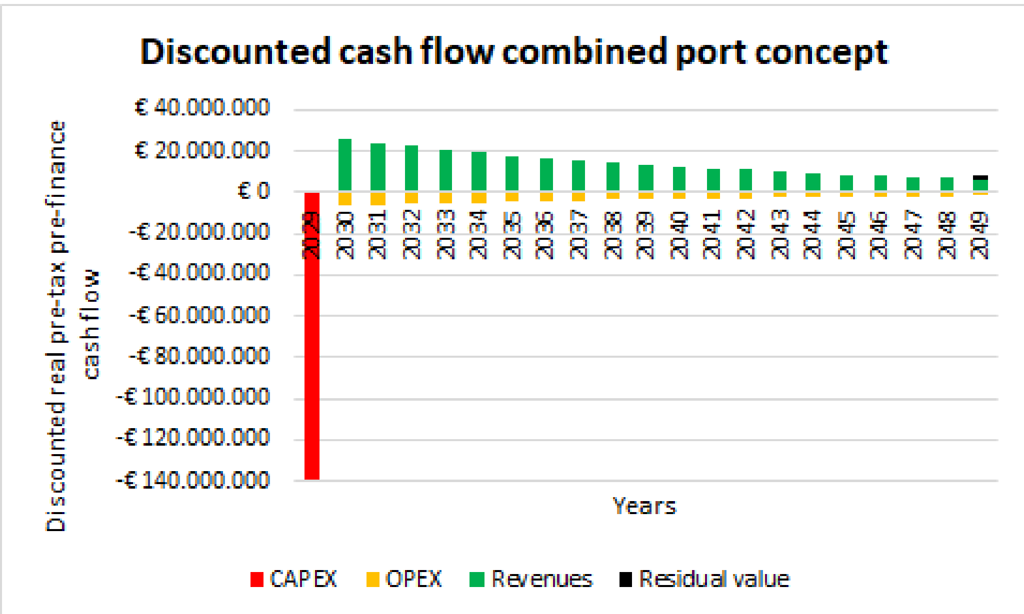


Figure J.2: Discounted cash flow barge and small jack-up barge

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