Concept design for floating offshore wind turbine installation with the Pioneering Spirit

A systems engineering approach

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TUDelft

Allseas

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by

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Preface

Dear Reader,

During my academic studies, my interest in offshore operations and renewable energy grew significantly. As a result, I was looking for a graduation project that would cover both aspects. I am very grateful for the fact that Allseas Engineering B.V. offered me the opportunity to conduct research involving the installation of floating wind turbines with the Pioneering Spirit. Throughout this thesis, I have been assisted by multiple supervisors from both the Delft University of Technology and Allseas, for which I want to express my sincere gratitude

First of all, I would like to thank Austin Kana for his supportive guidance. It was extremely helpful to have weekly meetings during which the progress, feedback and questions could be addressed. I would also like to thank Henk Polinder and Jesper Zwaginga for their critical questions and useful comments that allowed me to reflect on my work.

Furthermore, I would like to extend my heartfelt appreciation to André Steenhuis and Vera Terlouw for their consistent engagement and daily support. Apart from their involvement in the research, they also provided me with the privilege of attending a tour on the Pioneering Spirit, interesting symposia, and other activities for which I am very grateful. In addition, I would also like to thank all colleagues from Allseas' Naval Department for their support and joy.

Finally, I would like to thank my family, girlfriend, friends and fellow students for their conviviality, encouragement and help throughout this thesis.

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Abstract

Due to the growing demand for offshore wind energy and the increasing wind turbine sizes, a shortage of capable installation vessels is anticipated by 2024. Consequently, the utilisation of heavy-lift vessels, previously not employed for bottom-founded or floating offshore wind turbine installations, may become imperative to realise the offshore wind project pipeline. Therefore, this study analyses the technical and economic feasibility of installing floating wind turbines with the largest construction vessel in the world named the Pioneering Spirit. For this, the concept development stage of the systems engineering method was applied, consisting of three successive phases. Firstly, in the Needs Analysis phase, valuable insights regarding the operational environment were obtained, resulting in operational requirements for the concept design. Secondly, in the Concept Exploration phase, these requirements were used for generating multiple alternative concept options after which the most promising concepts were selected for further analysis through a trade-off analysis. Lastly, in the Concept Definition phase, the technical feasibility, workability and economic feasibility were evaluated for the selected concepts. The technical feasibility was assessed by creating storyboards for the different installation procedures, determining the stability of the barge named the Iron Lady for different load cases and providing technical descriptions of performed operations and required equipment. Furthermore, the workability was estimated by comparing statistical wave and wind data with the environmental limits for various operations obtained through literature, previous projects and a motion analysis model. Subsequently, with the storyboards and workability results, the economic feasibility was determined with a model that included estimations of the vessel and fuel costs for constructing a reference wind farm located at a variable distance to shore. Ultimately, it was found that Spar- and TLP-type floating wind turbines are of most interest for the concept design and that the Pioneering Spirit is in principle capable of installing the corresponding pre-assembled foundations and wind turbines relating to a capacity of 15 megawatt with a single-lift operation. Furthermore, this research gives valuable insights that extend beyond the initial scope of this paper. Since the performance implications of the selected concepts related to the workability assessment and economic feasibility study can directly be linked to specific design choices and limitations. This, in combination with the exploration of floating wind turbine installation with alternative lifting equipment, can be used to provide recommendations for future designs of purpose-built vessels in this sector. Finally, the methodology used in this study could be applied to evaluate the feasibility of other potential concepts for deployment in this area.

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Nomenclature

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Expression	Definition
H_s	significant wave height
T_p	wave peak period
r	yearly discount rate
$MaxSum$	total amount of weighting points
$MaxWeight$	maximum weighting factor
$MinWeight$	minimum weighting factor
n	number of selection criteria
GM	metacentric height
KB	distance between keel and centre of buoyancy
BM	metacentric radius
KG	distance between keel and centre of gravity
ρ_w	density of seawater
g	gravitational acceleration
L	vessel's hull length
B	vessel's hull breadth
D	vessels's draught
m_{tot}	total mass of Iron Lady including ballast and load
$m_{IronLady}$	dry weight of the Iron Lady
m_{load}	mass of the load
$m_{ballast}$	ballast weight
y_{CoG}	vertical position of the centre of gravity
m_i	mass of component i
$y_{CoG,i}$	vertical centre of gravity of component i
I_t	transverse moment of inertia of waterplane
S_z	spectral density of motion z
S_ζ	spectral density of a wave
z_a	amplitude of motion z
ζ_a	wave amplitude
ω	angular frequency
θ	angle of incoming wave
V_w	wind speed
N	number of installation cycles
$T_{loading}$	planned operational period for a single loading operation
$n_{loading}$	number of loading operations per installation cycles
$T_{mooring}$	planned operational period for a single mooring operation
$n_{mooring}$	number of mooring operations per installation cycles
$T_{unloading}$	planned operational period for a single unloading operation
$n_{unloading}$	number of unloading operations per installation cycles
$T_{installation}$	planned operational period for a single installation operation
$n_{installation}$	number of installation operations per installation cycles
$T_{unmooring}$	planned operational period for a single unmooring operation
$n_{unmooring}$	number of unmooring operations per installation cycles
T_i	planned operational period for operation i
n_i	number of operation i
$T_{total,cont.}$	total project duration for continuous installation procedures

Expression	Definition
$T_{total,in-cont.}$	total project duration for in-continuous installation procedures
$T_{oper.,cont.}$	total operational duration for continuous installation procedures
$T_{oper.,in-cont.}$	total operational duration for in-continuous installation procedures
$T_{trans.,cont.}$	total transportation duration for continuous installation procedures
$T_{trans.,in-cont.}$	total transportation duration for in-continuous installation procedures
$v_{sailing,IL}$	average sailing speed of Iron Lady
$v_{sailing,PS}$	average sailing speed of Pioneering Spirit
$T_{total,cont.,cor.}$	total project duration for continuous installation procedures corrected by workability
$T_{total,in-cont.,cor.}$	total project duration for in-continuous installation procedures corrected by workability
$T_{oper.,cont.,cor.}$	total operational duration for continuous installation procedures corrected by workability
$T_{oper.,in-cont.,cor.}$	total operational duration for in-continuous installation procedures corrected by workability
$T_{trans.,cont.,cor.}$	total transportation duration for continuous installation procedures corrected by workability
$T_{trans.,in-cont.,cor.}$	total transportation duration for in-continuous installation procedures corrected by workability
$T_{oper.,cont.,cor.,spar}$	total operational duration for continuous installation procedures for spar foundations corrected by workability
$T_{oper.,in-cont.,cor.,spar}$	total operational duration for in-continuous installation procedures for spar foundations corrected by workability
$T_{oper.,cont.,cor.,WTG}$	total operational duration for continuous installation procedures for WTGs corrected by workability
$T_{oper.,in-cont.,cor.,WTG}$	total operational duration for in-continuous installation procedures for WTGs corrected by workability
$\eta_{i,spar}$	workability of operation i for spar installation procedures
$\eta_{i,WTG}$	workability of operation i for WTG installation procedures
$T_{trans.,cont.,cor.,spar}$	total transportation duration for continuous installation procedures for spar foundations corrected by workability
$T_{trans.,in-cont.,cor.,spar}$	total transportation duration for in-continuous installation procedures for spar foundations corrected by workability
$T_{trans.,cont.,cor.,WTG}$	total transportation duration for continuous installation procedures for WTGs corrected by workability
$T_{trans.,in-cont.,cor.,WTG}$	total transportation duration for in-continuous installation procedures for WTGs corrected by workability
$\eta_{trans.}$	workability of transportation
$C_{total,cont.}$	total installation cost for continuous installation procedures
$C_{total,in-cont.}$	total installation cost for in-continuous installation procedures
$C_{vessel,cont.}$	total vessel cost for continuous installation procedures
$C_{vessel,in-cont.}$	total vessel cost for in-continuous installation procedures
$C_{fuel,trans.,cont.}$	total transportation fuel cost for continuous installation procedures
$C_{fuel,trans.,in-cont.}$	total transportation fuel cost for in-continuous installation procedures
$C_{fuel,oper.,cont.}$	total operational fuel cost for continuous installation procedures
$C_{fuel,oper.,in-cont.}$	total operational fuel cost for in-continuous installation procedures
s_{barge2}	distance at which a second barge is required to enable continuous installation
$T_{available}$	available time for barge to return fully loaded at the wind farm location
$dayrate_{vessel,i}$	day rate of vessel i
$n_{vessel,i}$	number of vessel i
$\dot{m}_{fuel,trans.,PS}$	fuel consumption during transport for the Pioneering Spirit
$\dot{m}_{fuel,trans.,IL}$	fuel consumption during transport for the Iron Lady
$\dot{m}_{fuel,trans.,tug}$	fuel consumption during transport for a tug

Expression	Definition
P_{fuel}	fuel price
$\dot{m}_{fuel,oper.,PS}$	fuel consumption during operation for the Pioneering Spirit
$\dot{m}_{fuel,oper.,IL}$	fuel consumption during operation for the Iron Lady
$\dot{m}_{fuel,oper.,tug}$	fuel consumption during operation for the Pioneering Spirit
$C_{total,cont.,cor.}$	total installation cost for continuous installation procedures corrected by workability
$C_{total,in-cont.,cor.}$	total installation cost for in-continuous installation procedures corrected by workability
$C_{vessel,cont.,cor.}$	total vessel cost for continuous installation procedures corrected by workability
$C_{vessel,in-cont.,cor.}$	total vessel cost for in-continuous installation procedures corrected by workability
$C_{fuel,trans.,cont.,cor.}$	total transportation fuel cost for continuous installation procedures corrected by workability
$C_{fuel,trans.,in-cont.,cor.}$	total transportation fuel cost for in-continuous installation procedures corrected by workability
$C_{fuel,oper.,cont.,cor.}$	total operational fuel cost for continuous installation procedures corrected by workability
$C_{fuel,oper.,in-cont.,cor.}$	total operational fuel cost for in-continuous installation procedures corrected by workability
$C_{fuel,oper.,cont.,cor.,1}$	total fuel cost during loading, mooring, unloading, installation and unmooring operations for continuous installation procedures corrected by workability
$C_{fuel,oper.,in-cont.,cor.,1}$	total fuel cost during loading, mooring, unloading, installation and unmooring operations for in-continuous installation procedures corrected by workability
$C_{fuel,oper.,cont.,cor.,2}$	total fuel cost during waiting on good weather for continuous installation procedures
$C_{fuel,oper.,in-cont.,cor.,2}$	total fuel cost during waiting on good weather for in-continuous installation procedures
$T_{available,cor.}$	available time for barge to return fully loaded at the wind farm location corrected by workability
s	distance of wind farm site to shore
$m_{CO2-emission,cont.}$	total CO2-emission for continuous installation procedures
$m_{CO2-emission,in-cont.}$	total CO2-emission for in-continuous installation procedures
$m_{CO2-emission,cont.,cor.}$	total CO2-emission for continuous installation procedures corrected by the workability
$m_{CO2-emission,in-cont.,cor.}$	total CO2-emission for in-continuous installation procedures corrected by the workability

List of Abbreviations

Abbreviations

Abbreviation	Definition
FOW	floating offshore wind
GHG	greenhouse gas
BFOWT	bottom-fixed offshore wind turbine
TRL	technology readiness level
CRI	commercial readiness index
FOWT	floating offshore wind turbines
LCOE	levelised cost of electricity
CAPEX	capital expenditures
OPEX	operational expenditures
AEP	annual energy production
FIV	foundation installation vessel
WTIV	wind turbine installation vessel
SE	systems engineering
RAO	response amplitude operator
MSL	mean sea level
TLP	tension leg platform
AHT	anchor handling tug
ROV	remotely operated vehicle
DP	dynamic positioning
TLS	topside lift system
JLS	jacket lift system
FLU	forklift unit
CTC	centre-to-centre
MHS	main hoist system
GRS	grillage system
MH	main hoist
UB	upper main hoist block
LB	lower main hoist block
DS	driven sheaves
FGR	fixed grillages
AGR	adjustable grillages
SFB	strand fixation beam
HPU	hydraulic power unit
ICB	interconnection beams
SWL	Safe Working Loads
WTG	wind turbine generator
CoG	centre of gravity
MPMSA	most probable maximum single amplitude
DOF	degree of freedom
MW	megawatt
GW	gigawatt
MGO	marine gas oil

1
Introduction

This chapter will serve as an introduction to this thesis and the floating offshore wind (FOW) energy sector. It points out the opportunities and problems that are related to this relatively novel technology. Thereafter, the research objectives are formulated followed by a description of the systems engineering method that will be used in this research. Furthermore, the research questions and initial scope will be defined. Finally, the outline of this paper is given.

1.1. Problem Description

General

The importance of the energy transition has become increasingly evident in recent years. Global warming, as a consequence of greenhouse gas (GHG) emissions, has resulted in the melting of ice caps, the rising of the sea level, wildfires, extreme droughts, and severe storms [80]. This will most likely have adverse effects on the global ecology, economy, and communities. To fight global warming, a reduction of these GHG emissions has to be realised. However, it is expected that the global primary energy and electricity demand will increase in the coming decades as can be seen in Figure 1.1 *[93][53]*. Therefore, to abate GHG emissions, the already existing transition efforts to renewable energy sources together with other innovative solutions, such as carbon capture and storage, have to be accelerated. Multiple agreements have been made internationally. In the European 2030 climate and energy framework, some key targets are to reduce greenhouse gas emissions by at least 40% and realize a 32% share for renewable energy by 2030 *[2]*. Additionally, the Paris Agreement is a global treaty and aims to become carbon neutral by 2050 *[85]*. Regarding the transition to renewable energy, several options are available with varying maturity of technology such as hydro, wave, solar, and wind *[17]*.

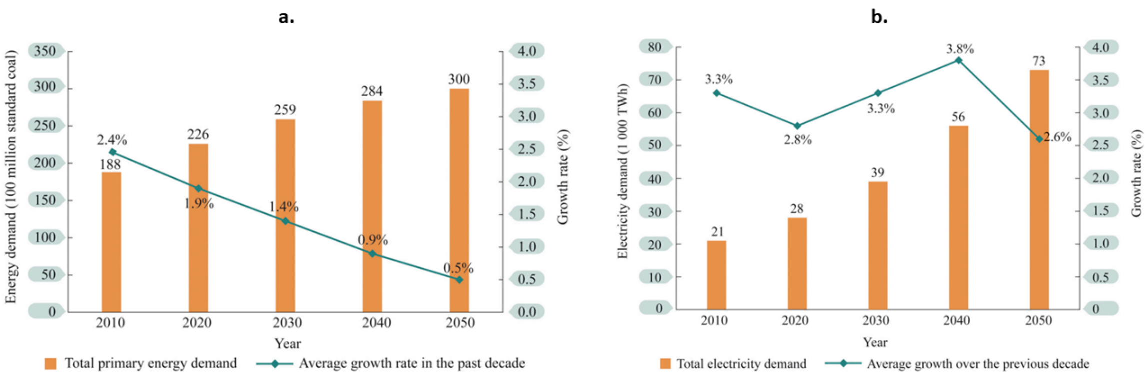


Figure 1.1: Total primary energy (a.) and electricity (b.) demand outlook *[53]*

Wind energy is expected to play a major role in this energy transition. According to *[27]*, the share in the global primary energy supply for wind energy is expected to reach 13% by 2050, making it the second largest renewable energy source in the future. Wind energy can be generated onshore as well as offshore. The latter has great potential because wind resources are stronger and more consistent when moving further offshore, it is possible to transport bigger wind turbines at sea than by road, there will be less visual and noise pollution for the surrounding environment, a large part of the global population is living near coastal areas, and the sea is a huge and empty space where a large number of wind farms can be developed *[5] [86]*. On the other hand, the construction and maintenance of offshore wind farms is a complex and expensive process with harsh environmental conditions *[60]*. Within the offshore wind energy market, floating wind energy is an auspicious source for the future. It has been estimated that approximately 80% of the global offshore wind resource potential is located in water depths exceeding 60 meters *[89]* (Figure 1.2). Bottom-fixed wind turbines become less technical, economical and logistical feasible in water depths greater than 60 meters *[32]*. Therefore, this potential in global wind resources is most likely going to be utilised by floating wind turbines.

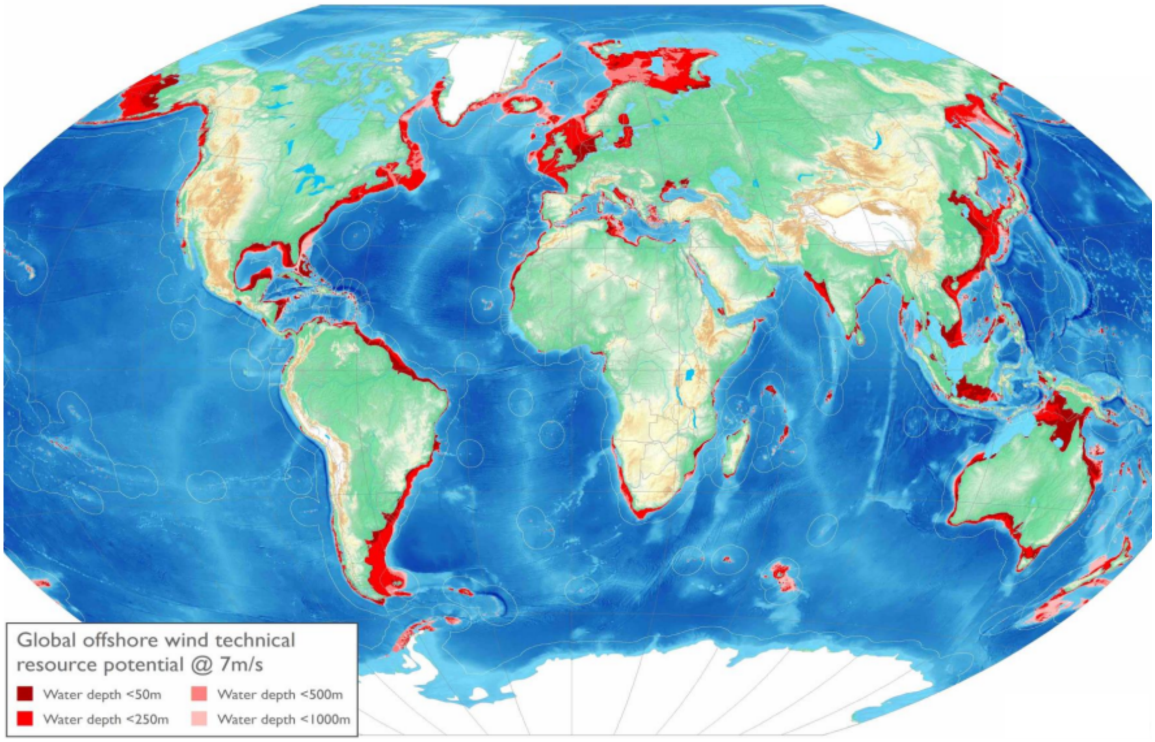


Figure 1.2: Global offshore technical wind resource potential *[9]*

In comparison to onshore or bottom-fixed offshore wind turbines (BFOWTs), the floating offshore wind sector is less industrialised and matured *[19][20]*. Currently, it is in the pre-commercial phase with only a few operational floating wind farms worldwide *[91]*. Some examples of these operational wind farms are the 25 megawatt (MW) Windfloat Atlantic Windfarm located offshore Portugal, the 30 MW Hywind Windfarm and the 50 MW Kincardine Offshore Windfarm Ltd. located offshore Scotland *[19]*. Furthermore, numerous floating wind turbine concepts and installation methods exist with varying Technology Readiness Levels (TRLs) and Commercial Readiness Indices (CRIs) *[34]*. The installation method and strategy depend on multiple factors such as port facilities, foundation design, vessel availability and more. Regarding vessel availability, it is expected that there will most likely be a shortage of wind and foundation installation vessels as a result of, for example, the growing demand and increasing turbine sizes *[24][42]*.

Growing Demand

The first identified challenge is the growing demand for offshore wind turbines as a result of the energy transition objectives. According to *[27]*, it is estimated that the total floating wind energy capacity will grow from 0.1 gigawatts in 2020 to approximately 300 gigawatts in 2050. This will mean that even with the newest 14 megawatts GE Haliade-X *[94]* wind turbine approximately 688 floating offshore wind turbines (FOWTs) have to be installed each year from 2020 to 2050. Furthermore, it is also estimated that the installed bottom-fixed offshore wind capacity will increase from 35 gigawatts in 2020 to 1544 gigawatts in 2050. This will put additional pressure on the availability of offshore wind turbine installation vessels because some floating vessels can install both BFOWTs and FOWTs. However, conventional jack-up vessels that are used for BFOWT installation are not suitable for FOWT purposes *[26]*.

High Levelised Cost of Electricity

As mentioned before, the FOW technology is less mature and commercialised in comparison to onshore and bottom-fixed wind energy. This results in a higher Levelised Cost of Electricity (LCOE) as can be seen in Figure 1.3. Therefore, a reduction of the LCOE is required to make FOW more attractive *[31]*. This reduction of the LCOE is expected to be realised during the upcoming decades (Figure 1.3). The LCOE is an important measure for making investment decisions because it gives an indication of the competitiveness of energy sources *[52]*. The LCOE depends on multiple factors such as the project lifetime, capital expenditures (CAPEX), operational expenditures (OPEX), the annual energy production (AEP), and the discount rate *[52]*. A possible reduction of the LCOE can be achieved by looking at the installation process of FOWTs.

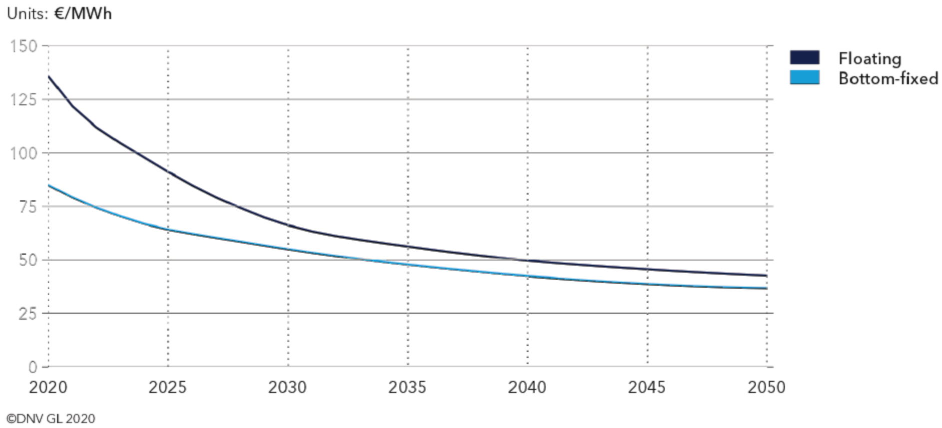


Figure 1.3: LCOE outlook comparison between fixed and floating offshore wind turbines *[20]*

Wind Turbine Development

The offshore wind energy technology is in continuous development resulting in wind turbine designs with higher capacities and increasing sizes. According to *[43]*, it is expected that wind turbines with 15 to 20 megawatts capacity will enter the offshore market between 2025 and 2030. In Figure 1.4, the global weighted average and expected turbine dimensions are represented. Research by the US Department of Energy found that the LCOE of a wind farm, when using a 20 megawatt wind turbine for the development of a 2.5 gigawatt wind power plant, can be reduced by 23% relative to the global average turbine and wind farm size in 2019 *[71]*. However, it is uncertain whether larger turbine sizes will reduce costs in reality. For this to be proven, companies developing these new technologies should design, develop and test prototypes *[21]*. Still, wind turbine developments in the past decades would indicate that increasing turbine sizes will most likely be a matter of time *[28]*. This would require improved features of the installation vessels.

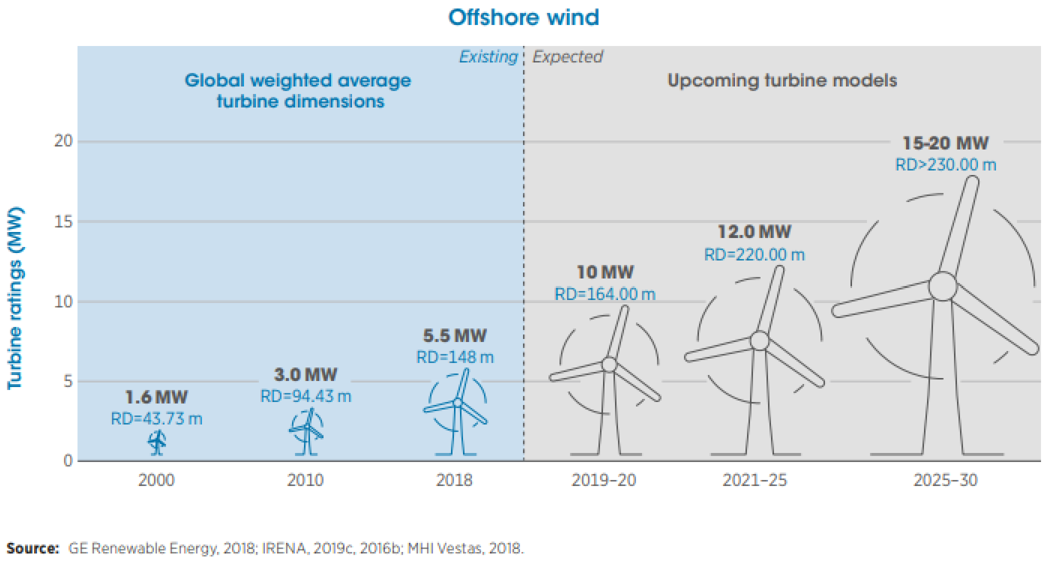


Figure 1.4: Existing and expected wind turbine capacity and size *[43]*

Installation Vessel Shortage

For the installation of FOWTs, different vessels are required. Typical vessels that may be necessary are anchor handling tugs, remotely operated underwater vessels, cable lay vessels, towing tugs, barges and heavy-lift vessels *[26]*. According to multiple articles, a worldwide shortage is expected of different vessel types that are required for offshore wind development. For example, a shortage of Foundation Installation Vessels (FIV) and Wind Turbine Installation Vessels (WTIV) for the offshore wind pipeline in Poland and other Baltic Sea countries is already expected by 2024 and 2025 *[35]*. Furthermore, the US offshore wind target to deploy 30 gigawatts of offshore wind by 2030 is also in danger. According to *[72]*, the availability of WTIV is posing the highest risk for achieving the US target. Finally, it is estimated that the demand for installation vessels that are capable to install wind turbines larger than 9 megawatts, which were not available on the market in 2019, will reach 62 vessels in 2030 and the lead time of both FIVs and WTIVs is approximately 3-4 years *[24][35]*. To summarise, the increasing turbine sizes, the long lead times for new installation vessels, the need for a lower LCOE, and the growing demand for both BFOWTs and FOWTs will most likely result in a shortage of installation vessels worldwide.

Objective Allseas

Allseas Group S.A. currently owns the largest construction vessel in the world named the Pioneering Spirit which was commissioned in 2014 and is shown in Figure 1.5. It has unique capabilities compared to other, more conventional vessels. The vessel was constructed for pipelay and heavy-lift operations. In recent projects, the Pioneering Spirit has installed a total of four offshore transformer substations for the wind energy market off the coast of western Europe *[63]*. Additionally, due to the growing interest and demand for offshore wind turbines, the expected shortage of capable installation vessels, and the increasing foundation and wind turbine sizes, Allseas is also looking into opportunities to enter the offshore wind turbine installation market with the Pioneering Spirit. The company is currently exploring the possibilities to install monopiles for bottom-fixed offshore wind turbines. However, the floating offshore wind energy market could also enable opportunities to enter the floating offshore wind installation sector.

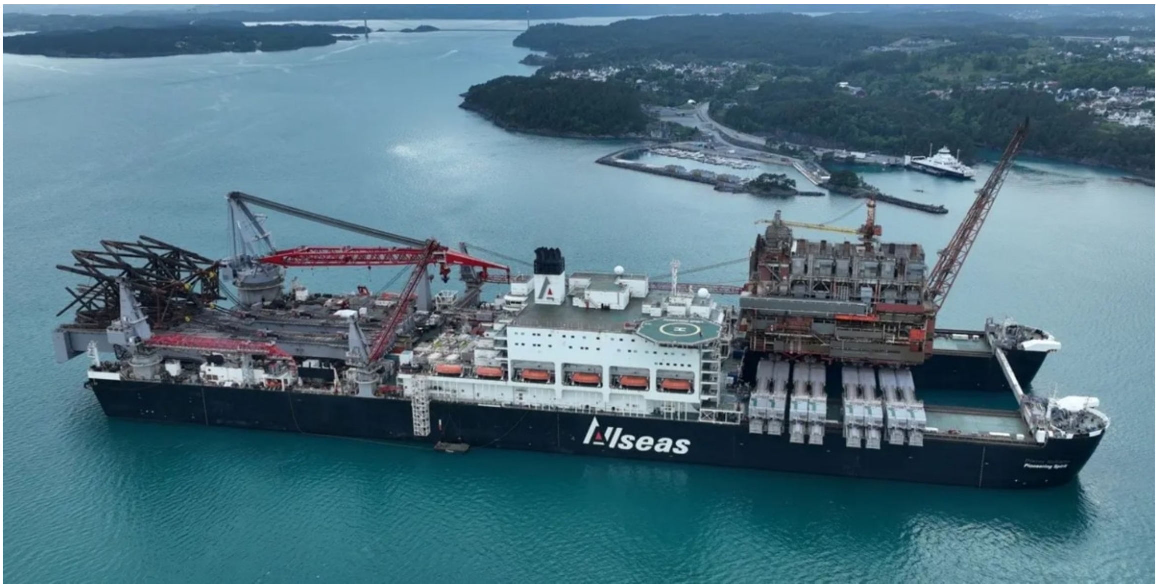


Figure 1.5: Pioneering Spirit transporting a decommissioned topside and jacket, courtesy of Allseas

1.2. Research Objective

The main objective of this research is:

To design a feasible concept for installing floating offshore wind turbines with the Pioneering Spirit and assess its economic feasibility and workability.

To achieve the main objective, multiple sub-objectives have been formulated:

1. The first sub-objective is to *obtain a list of operational requirements for the concept design, and get an overview of the characteristics of the Pioneering Spirit and the installation location* - **Chapter 2 and 3 (Literature Study - Needs Analysis)**

2. The second sub-objective is to *design multiple alternative feasible concept designs for the installation of floating offshore wind turbines with the Pioneering Spirit and make a selection based on their performance.* - **Chapter 4 (Thesis - Concept Exploration)**

3. The third sub-objective is to *visualise the installation procedures of the selected concept designs and assess their technical feasibility, workability and economic feasibility.* - **Chapter 5 (Thesis - Concept Definition)**

1.3. Systems Engineering

The conceptual design of the Pioneering Spirit for installing floating wind turbines may include multiple interacting miscellaneous components that are cooperating to achieve the main research objective. These components can be related to the sea fastening, transportation, loading, and installation of the FOWTs. Therefore, an approach that supports the design process of such complicated systems is considered crucial in order to come up with a well-thought-out concept.

According to *[77]*, the function of systems engineering (SE) can be defined as: "To guide the engineering of complex systems". Moreover, several key characteristics of the systems engineering method are that it is an iterative model and focuses on the internal and external factors of a system, it combines quantitative and qualitative aspects for decision-making, and the system design and development requires multiple engineering disciplines. Eventually, the goal of the method is to develop a system that can be put into operation and satisfies the necessary requirements and objectives. For this reason, systems engineering is considered a promising method for the design of a feasible concept to install floating offshore wind turbines with the Pioneering Spirit.

1.3.1. Life Cycle Model

The systems engineering life cycle model describes the design, development, operation and support process of a complex system as can be seen in Figure 1.6 *[77]*.

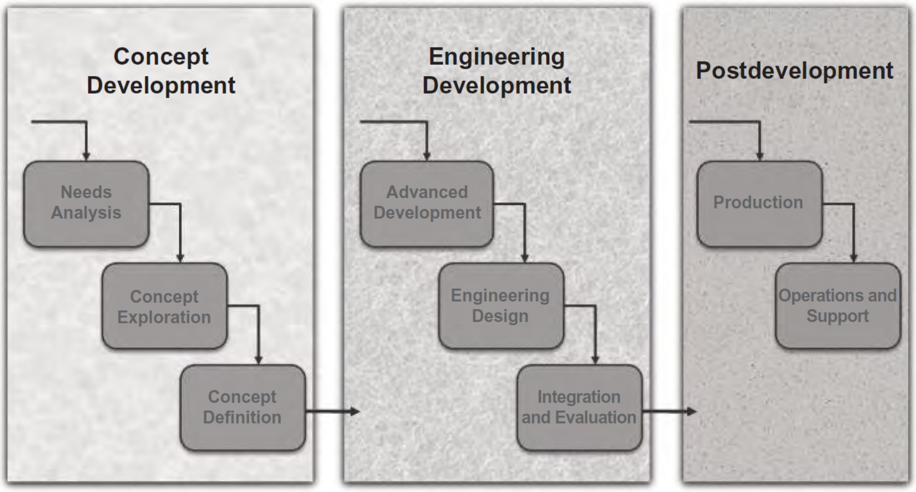


Figure 1.6: Systems engineering life cycle model *[77]*

The life cycle model can be separated into three stages that are described below:

- **Concept Development:** This stage comprises three successive phases and represents the analysis and planning to identify the need for a new system that is feasible, explores potential concepts that satisfy certain operational requirements, and makes a decision for a specific superior concept design based on the system's performance.

- **Engineering Development:** This stage also consists of three successive phases and includes the engineering process of the chosen concept so it can perform the specified functions in a physical environment with a design that can be manufactured economically and operated successfully.

- **Postdevelopment:** The last stage with two successive phases describes the process after the system development in which unforeseen problems arise that need urgent resolution.

When going through the different phases, the system steadily materialises. The scope of the analysis shifts from a system level during the needs analysis to a part level during the engineering design phase. For this thesis, only the concept development stage is taken into account because the final output of this stage is a superior concept design for which the workability, and technical and economic feasibility can be analysed. Subsequently, a decision can be made on whether or not to continue with the engineering development and post-development stages for the selected system concept. However, this should be included in another research. Therefore, only the concept development phase will be described in more detail below.

1.3.2. Concept Development

The concept development stage can be subdivided into three phases: needs analysis, concept exploration and concept definition. The different phases describe a set of activities that transform the inputs of a phase into certain outputs. A visual representation of the concept development phase can be seen in Figure 1.7. The phases succeed each other, meaning that the outputs of the first phase can be used as inputs for the second phase and the same applies to the third phase. However, within and between phases iteration can be done.

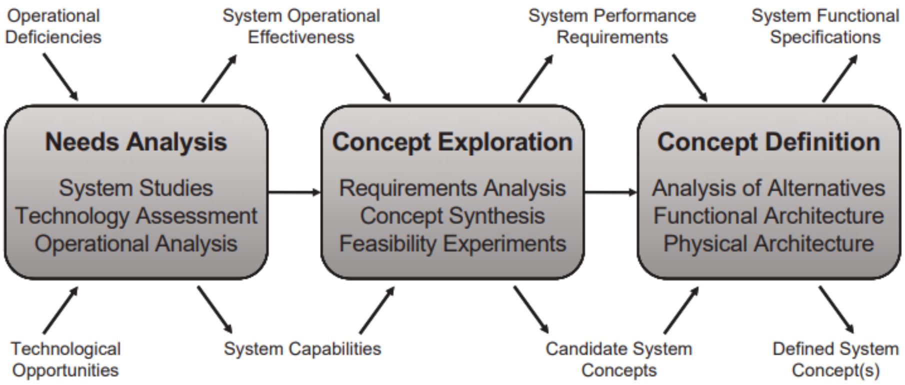


Figure 1.7: Inputs and outputs of the different phases in the concept development stage *[77]*

Needs Analysis *[77]*

The needs analysis identifies the need for a new system. This could be the consequence of a deficiency in a current system (need-driven) or a technological development that is superior to already existing systems (technology-driven).

By studying the operational characteristics of the new system to meet the formulated need, the necessary capabilities and functions can be determined. Thereafter, a possible system that could comply with the aforementioned capabilities and functions has to be specified that can be assumed to be affordable and feasible (*System Capabilities* in Figure 1.7).

Eventually, the output of the needs analysis is a set of qualitative operational requirements that broadly describe the objective of the new system when it is developed and in operation (*System Operational Effectiveness* in Figure 1.7). The requirements should be clear, complete, consistent, and feasible.

Concept Exploration *[77]*

In the concept exploration phase, the previously determined operational requirements from the needs analysis phase are further analysed to provide specificity and completeness. This will result in a more detailed list of operational requirements, an operational concept, and an operational context.

This detailed set of elements is then transformed into a list of performance requirements which define what different operations should be performed by the subsystems but not how these should be executed (*System Performance Requirements* in Figure 1.7).

Finally, the performance requirements should be integrated into multiple alternative feasible concept designs including sub-components (*Candidate System Concepts* in Figure 1.7).

Concept Definition *[77]*

The concept definition phase starts with trying to make the system performance requirements from the previous phase as quantifiable as possible.

After a multi-criteria trade-off analysis, in which the importance of different performance requirements is evaluated by assigning weighting factors to these requirements, a superior concept can be selected (*Defined System Concept* in Figure 1.7).

Ultimately, a list of functional specifications can be formulated describing completely and concisely all the functions the system must perform (*System Functional Specifications* in Figure 1.7).

The approach taken in this research is based on the concept development stage of the systems engineering method. However, because of mostly time constraints, some iterations may not be performed and variations in the design process may be observed throughout the entire concept development stage. This could result in deficiencies in the system that are encountered in a later phase but are not revised. However, deficiencies will be mentioned in the conclusion or discussion.

1.4. Research Question

The main research question that corresponds with the main research objective is as follows:

What is the feasibility and workability of floating offshore wind turbine installation with the Pioneering Spirit?

The feasibility in this context can be divided into economic feasibility and technical feasibility. These are defined as follows:

- **Technical feasibility study:** Technical feasibility includes checking for accessibility to technical resources and applications within the organization. If the resources already exist, you must then determine if the technical team can customize the technology into new working systems for the project. Not only do you need the correct technical resources, but the equipment also needs to be evaluated to ensure it has the proper hardware and software for the proposed plan *[41]*.

- **Economic feasibility study:** Economic feasibility allows the company to determine the cost and benefits analyses, which helps provide decision-makers with a list of potential economic benefits to the organization. They need to know the total cost, including accidental expenses, so that during the project, they may be able to anticipate any potential unforeseen monetary challenges *[41]*.

- **Workability:** A workability assessment combines the offshore environment, the marine spread dynamic behaviour and the operational procedure into one simulation model which will give insight in the environmental risk of the operation *[92]*.

To answer the main research question, multiple sub-questions have been formulated:

1. *What are the different operational requirements that the concept design should be capable of accomplishing based on aspects relating to the main drivers, constraints and procedures of floating offshore wind turbine installation with the Pioneering Spirit?* - **Chapter 2 and 3 (Literature Study - Needs Analysis)**

2. *What are alternative feasible concept designs that comply with the operational requirements, how can the performance of these concepts be evaluated and compared, and which concepts are the most promising?* - **Chapter 4 (Thesis - Concept Development)**

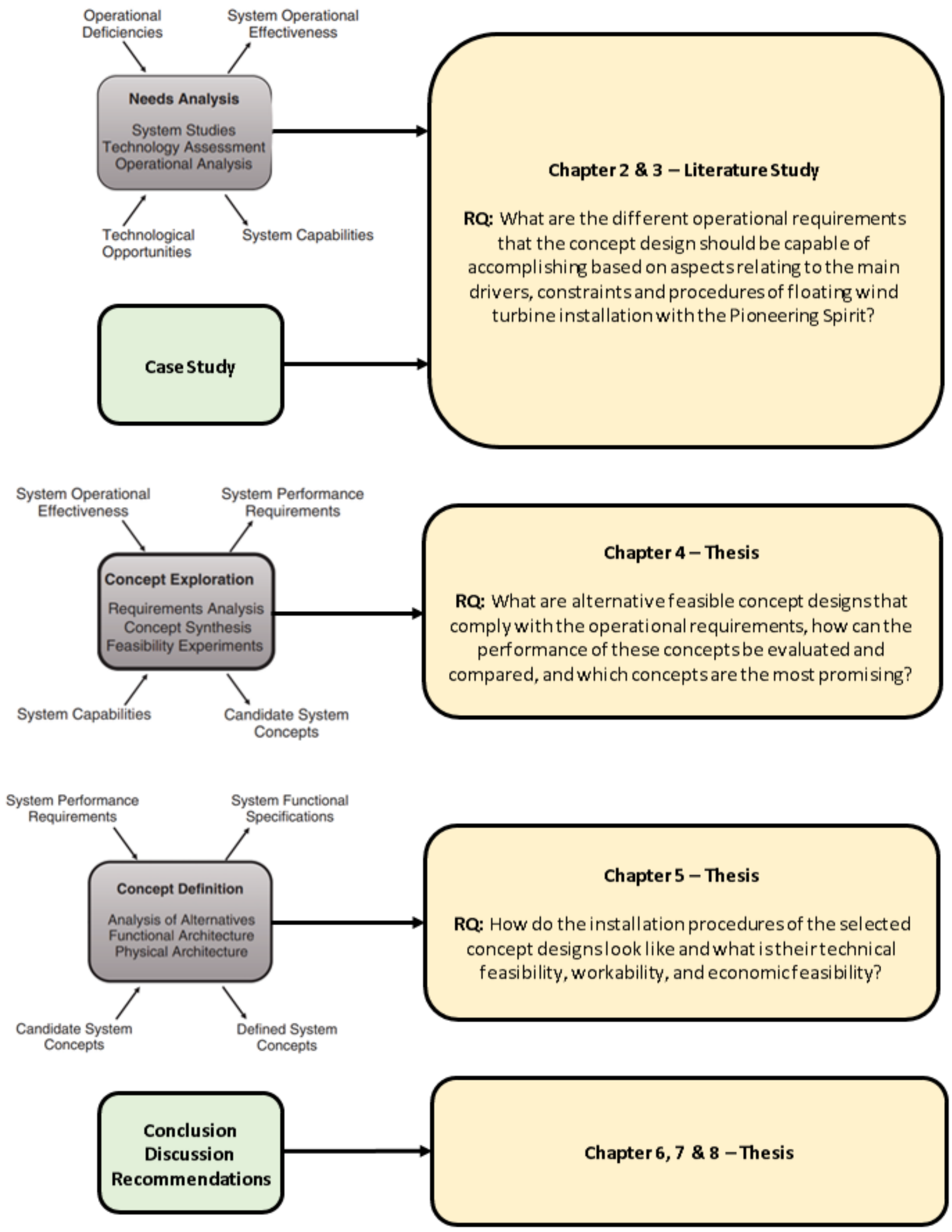
3. *How do the installation procedures of the selected concept designs look like and what is their technical feasibility, workability, and economic feasibility?* - **Chapter 5 (Thesis - Concept Definition)**

1.5. Initial Scope

The following initial boundaries and assumptions are defined for this research:

- The Pioneering Spirit will be used to install the floating offshore wind turbines.
- The required port facilities are present for assembling and loading the floating offshore wind turbine components onto the Pioneering Spirit or a feeder barge.
- Only the main floating offshore wind turbine concepts are considered.
- All the required components for the foundations and wind turbines are present at the port and no supply chain issues are considered.
- Only offshore operations are included in this research, thus the load-out of the wind turbines or foundations from the port onto a feeder barge or the Pioneering Spirit is left out of the analysis.

1.6. Outline


Operational Deficiencies
System Operational Effectiveness
Needs Analysis
System Studies
Technology Assessment
Operational Analysis
Technological Opportunities
System Capabilities
Case Study
Chapter 2 & 3 – Literature Study
RQ: What are the different operational requirements that the concept design should be capable of accomplishing based on aspects relating to the main drivers, constraints and procedures of floating wind turbine installation with the Pioneering Spirit?
System Operational Effectiveness
System Performance Requirements
Concept Exploration
Requirements Analysis
Concept Synthesis
Feasibility Experiments
System Capabilities
Candidate System Concepts
Chapter 4 – Thesis
RQ: What are alternative feasible concept designs that comply with the operational requirements, how can the performance of these concepts be evaluated and compared, and which concepts are the most promising?
System Performance Requirements
System Functional Specifications
Concept Definition
Analysis of Alternatives
Functional Architecture
Physical Architecture
Candidate System Concepts
Defined System Concepts
Chapter 5 – Thesis
RQ: How do the installation procedures of the selected concept designs look like and what is their technical feasibility, workability, and economic feasibility?
Conclusion
Discussion
Recommendations
Chapter 6, 7 & 8 – Thesis

2

Floating wind installation

This chapter aims to provide the necessary information regarding floating offshore wind turbine installation to answer the first sub-question from Chapter 1: "What are the different operational requirements that the concept design should be capable of accomplishing based on aspects relating to the main drivers, constraints and procedures of floating offshore wind turbines installation with the Pioneering Spirit?". First, the different stages of the offshore wind farm development life cycle will be described. Thereafter, the main drivers are introduced for the development of a new concept design to install floating offshore wind turbines. Furthermore, the different dominant floating wind foundation concepts are explained followed by an overview of various conventional and conceptual installation vessels and strategies. Finally, the findings of the aforementioned topics are formulated and a set of operational requirements is defined.

2.1. Offshore Wind Farm Development

Normally, the life cycle of an offshore wind farm can be divided into five stages (Figure 2.1). These stages are shortly described below to give an understanding of the different operations during the development of an offshore wind farm.

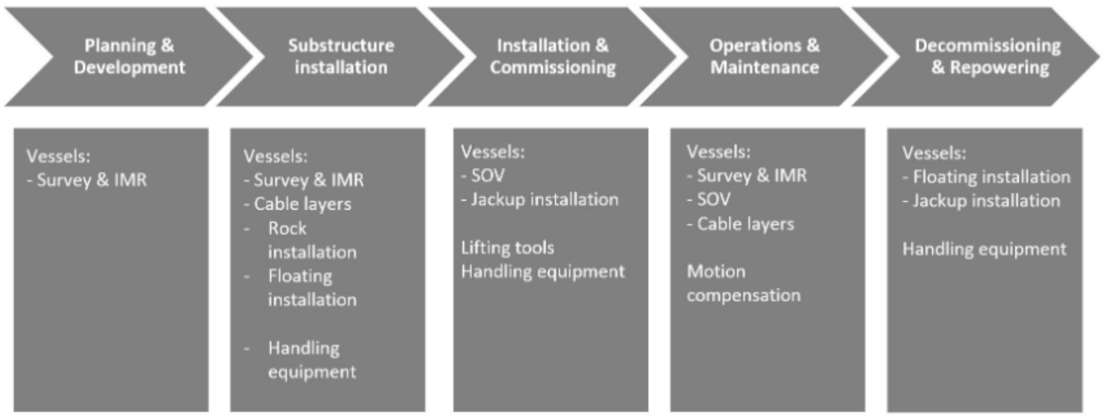


Figure 2.1: Lifecyle of an offshore wind farm *[4]*

1. **Planning and Development:** refers to the assessment of installation locations with regard to environmental conditions such as the metocean data and bathymetry. When a location has been determined, a detailed application is made about the project planning, utilised equipment, impact on the surrounding environment and other aspects which will be submitted to the local government.

2. **Substructure Installation:** after the application is approved by the local government, the installation process of the substructures can begin. The substructure of a floating offshore wind turbine consists

of an electrical infrastructure, a mooring system which comprises the anchors, mooring lines and connectors, and a floating foundation. These components have to be manufactured and transported to the wind farm site which is simultaneously prepared before the installation operation can start. The Installation and Commissioning phase begins when the floating substructure is coupled to the mooring lines and electrical cables.

3. **Installation and Commissioning:** when the substructure is installed, the wind turbine can be placed on top of it. Before this can be realised, the wind turbine components have to be manufactured, transported and assembled. However, some floating wind turbine types can be fully-assembled at a port and installed by towing tugs.

4. **Operations and Maintenance:** after the wind turbines are fully installed and operational, the fourth stage begins. The operational lifetime of offshore wind turbines is generally 20 years or more. This stage includes the monitoring and (un-)scheduled maintenance of all the wind farm components during the operational lifetime.

5. **Decommissioning and Repowering:** Finally, in stage five it has to be decided whether the offshore wind farm will be decommissioned or repowered. The life cycle starts again if the wind farm is repowered.

This research focuses on designing a concept for the installation process of FOWTs with the Pioneering Spirit. Therefore, the Planning and Development, Operations and Maintenance, and Decommissioning and Repowering phases are left out of the analysis. Subsequently, only parts from the Substructure Installation and the Installation and Commissioning phase are included. Typical operations that are time-consuming during these two phases are the loading of the vessel at a port, transit to the installation location, unloading if necessary (e.g. when using a feeder barge), installation, sailing to the next turbine location, and transit from the installation location back to the port *[14]*. To reduce the installation cost, it is necessary to optimise these operations. The loading, transportation, unloading and installation processes are described in more detail below.

Loading and Securing

When the first wind turbine or foundation is assembled at a harbour as much as is in accordance with the installation strategy, the loading process of the partly- or fully-assembled components from a port side onto a vessel can start. In this research, it is assumed that the essential port facilities for the assembly and loading of the wind turbines and foundations are available (e.g. water depth, cranes, and storage area). The components can be loaded onto a feeder barge or directly onto the Pioneering Spirit until the full loading capacity is reached. According to *[50]*, the feeder barge is often excluded in the case of wind turbines, because it is only necessary when the movement of the installation vessel needs to be reduced or the optimal loading capacity is not achieved with a single vessel. Another argument could be that the depth at the quayside of a port is too shallow for the installation vessel to enter the harbour, this constraint is however excluded in this research as is also stated in the initial scope. Each component has to be properly secured so cargo loss or damage during transit can be avoided *[82]*. Lower costs could be achieved when the loading phase is efficiently executed. This means that shorter waiting times for the feeder barge or Pioneering Spirit are preferable. When the full loading capacity of the feeder barge or the Pioneering Spirit is reached, it can start with the transportation phase. The loading capacity of a vessel depends on the available deck space, loading configuration, and pressure resistance of the deck surface *[87]*.

Transportation

During transportation, it is important that the vessel and the cargo remain stable. Forces as a result of environmental conditions such as waves, wind and current can act on the vessel or the cargo. This could have an effect on the stability of the vessel as well as the cargo. The overall stability of a vessel and its cargo depends mostly on the environmental conditions, weight distribution, sea-fastening equipment, and the wind turbine and vessel characteristics. Since the Pioneering Spirit is able to transport topsides and jackets with a weight of 48000 and 20000 tonnes respectively, the stability of the Pioneering Spirit is assumed to be within the safety boundaries. According to *[48]*, the excessive accelerations and vibrations of transported offshore wind turbine components should be limited by reducing vessel motion and using sea fastening equipment like transport frames and racks. The cost that is related to the transportation phase can be reduced by optimising the loading capacity and transit speed *[87]*. Also, the distance between the port and the installation location is an important factor regarding transportation costs.

Unloading

The unloading operation is only applicable when a feeder barge is used. As mentioned in the loading and securing paragraph, a feeder barge is mainly used when the loading capacity or stability of the installation vessel is insufficient. Also, other factors such as the water depth at a port, fuel consumption, transit speed, or the day rate of a vessel may influence this decision. However, it can be expected that feeder barges are inferior with respect to the loading capacity or vessel stability in comparison to the Pioneering Spirit because these vessels are generally smaller. Yet, typical benefits of smaller vessels are lower day rates and reduced fuel consumption. Normally, feeder vessels are unable to unload the cargo because no lifting equipment is mounted on the deck. Therefore, the unloading of fully or partly assembled wind turbine components has to be performed by the lifting equipment of the installation vessel. Important factors during this operation are the vessel capabilities (e.g. lifting tools, dynamic positioning and motion compensation systems, and sea-keeping capabilities).

Installation

After the installation vessel is loaded with the fully- or partly-assembled wind turbines and arrives at the wind farm location, it can start with the installation phase. Since both the floating wind turbine and installation vessel can move, excellent dynamic positioning and motion compensation systems are most likely needed. Also, gripping tools can be very helpful for this process. Potential factors that could influence the installation time are the logistics on the deck of the vessel, sea-keeping capabilities, installation strategy, and available installation equipment.

2.2. Main Drivers and Barriers

Floating offshore wind energy has very good potential for realising the carbon-neutral goals of 2050. Not only because it is estimated that 80% of the total offshore wind resource potential is located in deeper waters, where the wind is generally stronger and more consistent, but also because floating wind energy is expected to be very competitive in comparison to other renewable energy sources. However, at the moment there exist only a few small-scale wind farms worldwide. The drivers and barriers of floating offshore wind energy are key factors that influence its deployment. Therefore in this section, the main drivers and barriers will be identified. First, a general overview of the drivers and barriers is presented. Thereafter, the key drivers and barriers for this thesis are identified and discussed in more detail.

2.2.1. General

According to *[83]*, the drivers and barriers for floating offshore wind deployment can be divided into four categories: Technical, Economic, Political and Social (See Figure 2.2). This research will focus on the Technical and Economic drivers and barriers because these are expected to be the most important for the design of a new concept.

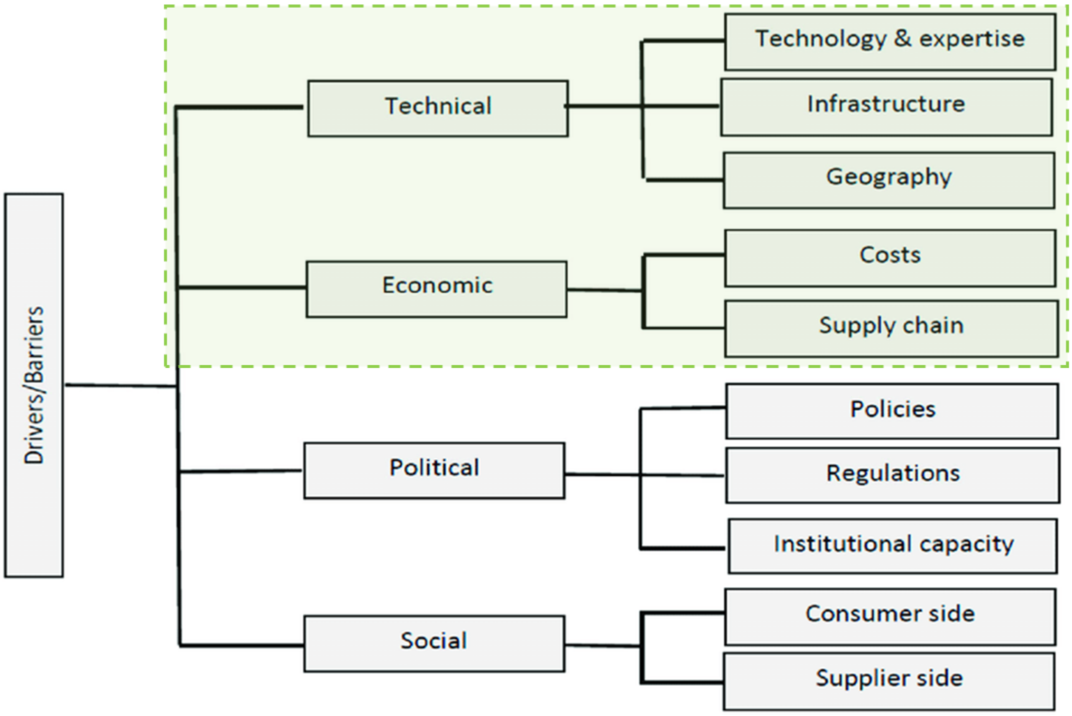


Figure 2.2: Drivers and barriers for FOWT deployment *[83]*

Technical

Technical drivers and barriers can be attributed to technology and expertise, infrastructure or geography. The technology and expertise is comprised of the design, fabrication, installation, operation and maintenance of turbines, floating foundations, moorings, anchors and electrical interconnections. The infrastructure includes the requirements of the power grid for the transmission of energy to consumers, and the requirements of port facilities for assembling and loading of the floating wind turbines. Finally, geography refers to the environmental conditions such as the metocean data and bathymetry which are key parameters for the installation and design of the floating offshore wind turbines.

Economic

The economic drivers and barriers can be attributed to the supply chain and the costs for the development of FOWTs. For the supply chain, it is important that the different components for a floating offshore wind turbine can be manufactured near the preferred installation location to avoid excessive transportation costs. The costs for FOW development consist of CAPEX and OPEX. For measuring the relative cost of energy production, the levelised cost of LCOE can be calculated.

2.2.2. Levelised Cost of Electricity

The LCOE can be interpreted as the minimal price at which the energy must be sold in order to make no financial loss on a developed energy plant during the whole life cycle. It is used to measure the competitiveness of a specific energy source compared to other sources. Therefore, it is of utmost importance that the lowest possible LCOE must be achieved. Currently, floating offshore wind energy has a relatively high LCOE value in comparison to bottom-fixed and onshore wind. However, it is expected that these LCOE values will converge over the upcoming decades as mentioned in Chapter 1. According to *[56]*, the LCOE can be defined as the total cost during the lifetime (see Section 2.1) of an energy production plant divided by the total energy production and taking the present value evaluation into account. The equation for calculating the LCOE is depicted below.

$$LCOE = \frac{\sum_{i=1}^{T}(CAPEX_i + OPEX_i)(1+r)^{-i}}{\sum_{i=1}^{T} AEP_i(1+r)^{-i}} \tag{2.1}$$

is the cost of developing or providing non-consumable parts for the product or system

In this equation, the CAPEX corresponds to the capital expenditures and accounts for all the cost made during the development of a floating offshore wind farm. The OPEX refers to the operational expenditures that include all the costs relating to the operational and maintenance phase during the full lifecycle of a floating offshore wind farm. The AEP comprises the annual energy production. In this equation, "i" represents the year of the investment or energy generation, starting from year one to year "T", and "r" is the yearly discount rate. The breakdown of the LCOE for a floating offshore wind farm is depicted in Figure 2.3.

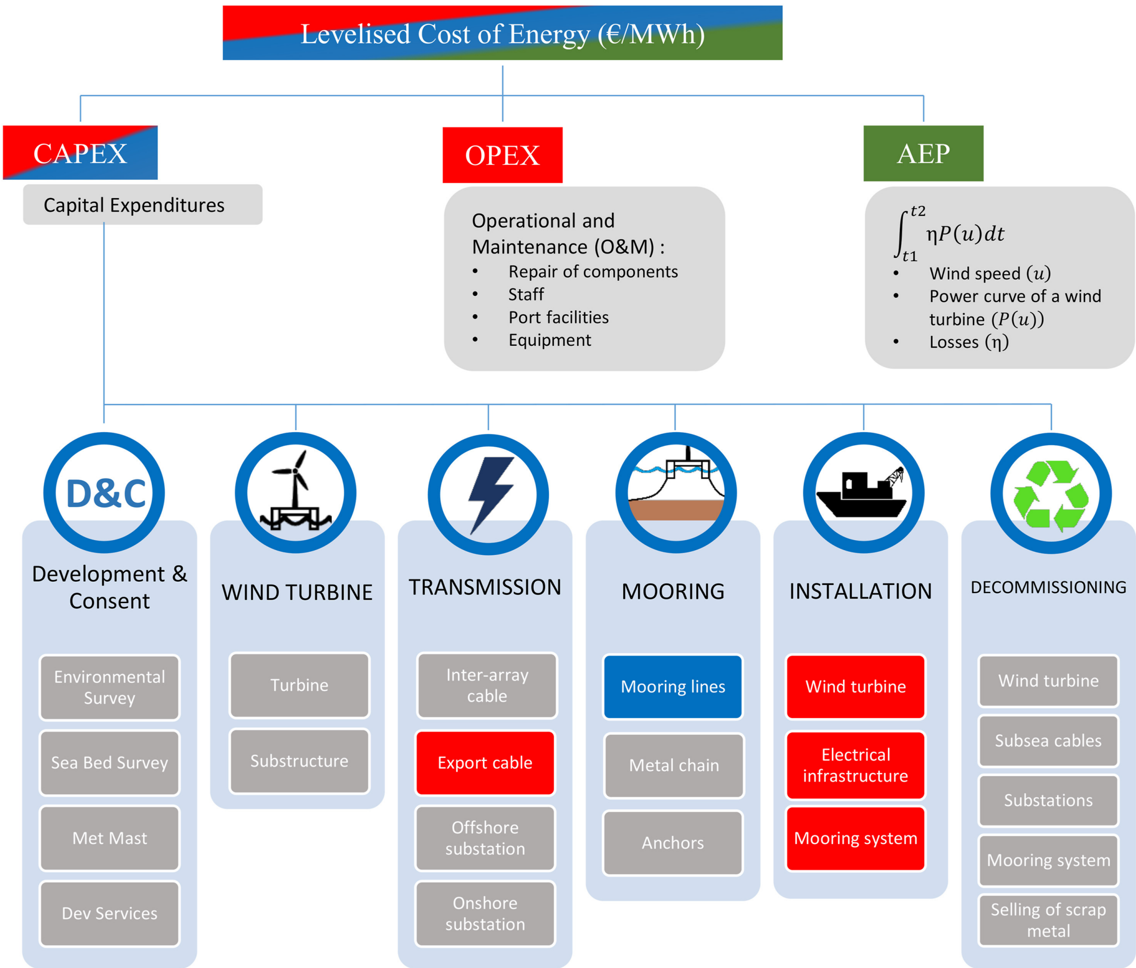


Figure 2.3: Levelised cost of electricity breakdown for a floating offshore wind farm *[56]*

In the figure above, grey indicates that the cost is site-independent, red means that it is site dependent and blue denotes that it is dependent on the water depth. However, it is questionable if these color representations are correct since the type of anchor or substructure could also be dependent on water depth or installation site for example. A representation of the component level contributions to the LCOE for a floating wind reference project with 75 8-MW semi-submersible FOWTs (total capacity of 600 MW) and an operating life of 25 years can be seen in Figure 2.4.

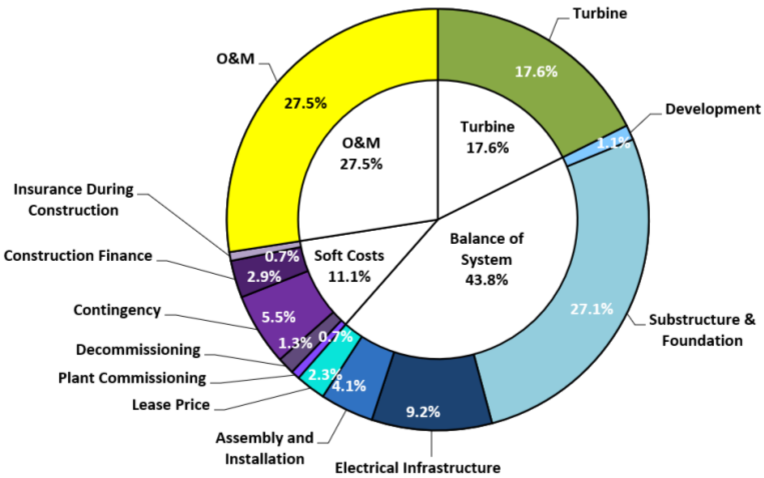


Figure 2.4: LCOE breakdown of a floating wind reference project with an operating life of 25 years *[75]*

This research focuses on the objective to reduce the LCOE by designing a concept for the installation of floating wind turbines with the Pioneering Spirit. Hence, it is not relevant to include all the cost contributions in the economic assessment of the different concepts. Therefore, the economic feasibility will be evaluated by comparing the total installation cost for a floating wind farm reference project.

2.2.3. Technology Readiness Level and Commercial Readiness Index

To assess the maturity of a particular technology, the TRL measurement system can be used. It consists of a scale from 1 to 9, representing the technologies from the lowest to the highest maturity level respectively. The TRL can be evaluated for different types of technologies and can be used to follow its progress or to support its development. Technological risks can be reduced by using the TRL system. However, it does not account for the commercial uncertainty regarding the demonstration and deployment phase. According to *[19]*, some commercial barriers to floating wind energy are related to costs, industrialisation, and mobilizing investments. Therefore, the CRI is introduced to give insight into the commercial state of a certain technology. The CRI is related to the TRL as depicted in Figure 2.5.

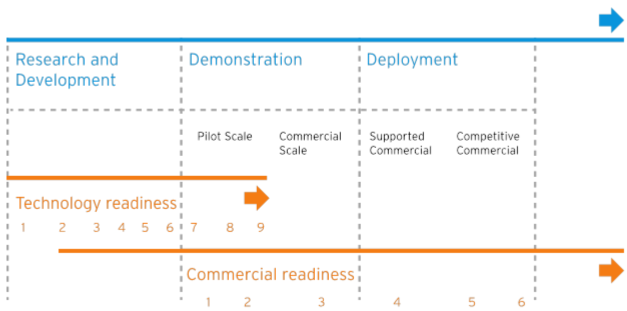


Figure 2.5: Technology Readiness Levels and Commercial Readiness Index on Technology Development Chain *[8]*

Technological and commercial maturity is essential for companies that are planning to enter a market. Especially the anticipated moment of the market entrance is important because a company immediately wants to begin production or construction when the assets and employees are available. Therefore, the technological and commercial maturity of the components involved in an operation should be sufficient at the time of deployment. Allseas is potentially planning to use the Pioneering Spirit for the installation of floating wind turbines within the coming 5 years. For this reason, the requirement has been formulated that all the different components of the concept design should be accessible and have been fitted on the Pioneering Spirit within the coming 5 years. This is not going to be assessed based on the TRL and CRI levels described above.

However, it is good to keep in mind that these measurement systems exist and could be important for design decisions.

2.2.4. Workability

Workability gives an estimation of the amount of time during a specific period that an operation can be conducted safely at a certain location. This estimation is based on the environmental conditions, vessel characteristics, equipment specifications, and type of operation. The environmental conditions at the project location are obtained by metocean data that is gathered during the past decades. Metocean data includes significant wave heights, wave directions, wave peak periods, wind speeds, and wind directions. According to *[14]*, the wind speed and sea states at a location have the biggest impact on the offshore wind turbine transportation and installation process. A sea state represents the combination of a specific significant wave height and wave period. The probability of different sea states is given in a wave scatter diagram (See Figure 2.6). However, the wind speed and the direction of wind and waves could also have an influence on workability. In Appendix C, the monthly wave scatter diagrams at the Rian Offshore Array (Phase 1) location can be found, which is used as the reference location for the installation of floating wind turbines with the Pioneering Spirit (see Section 3.2 and Appendix B).

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,30%	0,50%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	1%	1%
1 - 1.5	0%	0%	0%	0%	<0.1%	0,10%	0,40%	1,20%	2,50%	2,30%	1,30%	0,60%	0,30%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	9%	10%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,30%	0,60%	1,30%	2,90%	3,60%	2,70%	1,60%	0,70%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	14%	24%
2 - 2.5	0%	0%	0%	0%	0%	0,10%	0,60%	0,90%	2%	3,50%	3,10%	2,20%	1,20%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	14%	39%
2.5 - 3	0%	0%	0%	0%	0%	<0.1%	0,30%	0,80%	1,40%	2,50%	2,80%	2,20%	1,60%	0,80%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	13%	52%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,80%	1,60%	2,20%	2,10%	1,60%	1%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	10%	62%
3.5 - 4	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	0,90%	1,60%	1,90%	1,50%	1%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	8%	69%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,50%	1,20%	1,60%	1,50%	1,10%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	7%	76%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,70%	1,20%	1,30%	1%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	5%	81%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,30%	0,80%	1,20%	1%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	4%	86%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,50%	0,80%	0,80%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	3%	89%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,30%	0,70%	0,70%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	3%	91%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,40%	0,50%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	2%	93%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,40%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	1%	94%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,20%	0,30%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	1%	95%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,20%	0,20%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	1%	96%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,10%	0,10%	0,10%	<0.1%	<0.1%	0%	0%	96%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	96%
15.5 - 16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	96%
16 - 16.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	96%
16.5 - 17	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17 - 17.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17.5 - 18	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
18 - 18.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	2%	5%	11%	16%	16%	15%	13%	10%	5%	2%	1%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	2%	7%	18%	34%	50%	65%	78%	88%	93%	95%	96%	96%	96%	96%		

Figure 2.6: Annual wave scatter diagram of The Rian Offshore Array (Phase 1) location *[37]*

The response of a vessel to environmental loads influences the workability of a project. The response amplitude operator (RAO) describes the motion of a vessel in different sea states. The RAO is dependent on vessel characteristics such as the structural mass, added mass, damping, and restoring forces, but also on the hydrodynamic loads acting on it.

The workability can vary per type of operation. For example, the installation of offshore wind turbines consists of different steps such as loading the wind turbines from a feeder barge onto an installation vessel, the transportation of components over the vessel's deck, and the installation of the wind turbines or foundations. The overall workability of a project can be determined by evaluating the operational limits for different operations and compare these to the occurrence probabilities of the environmental conditions at the installation site. By developing an installation strategy, potential project delays due to weather constraints could be improved.

Significant wave height

The significant wave height (H_s) is an essential parameter for determining the workability of an operation. It represents the mean value of the highest one-third of the measured wave heights from trough to crest. Offshore operations are mostly executed during periods when the occurrence of large significant wave heights is low. In Figure 2.7, the annual and periodic cumulative occurrence of specific significant wave heights is plotted. This graph is based on measurements of wave heights at the Rian Offshore Array (Phase 1) location from 1979 till 2021. What can be seen is that large significant wave heights occur more often during the Autumn and Winter months compared to the Spring and Summer months. This chart gives a good indication of the probability of different significant wave height ranges and could potentially be used for the first estimations of the annual or periodic workability.

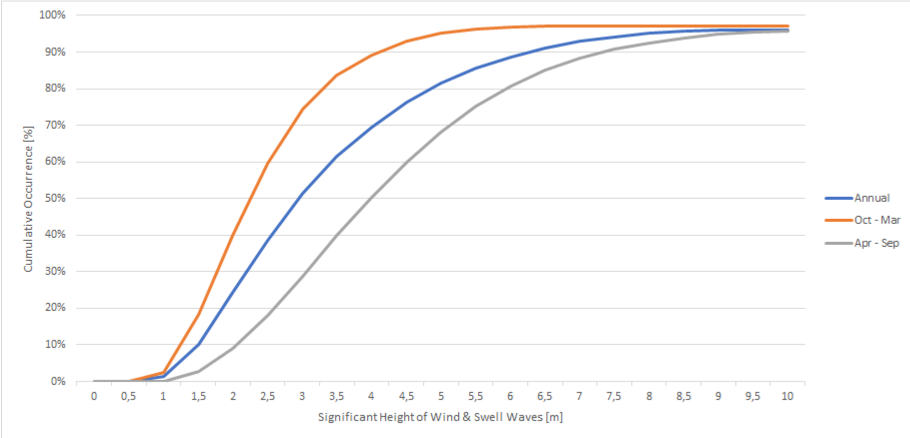


Figure 2.7: Significant wave height occurrence probability, based on data from *[37]*

Wave peak period

However, not only the significant wave height determines the response of a vessel. The combination of the significant wave height and the wave peak period (T_p), as depicted in the wave scatter diagram, gives a better estimation of the workability because this has an effect on the length and steepness of a wave. For large vessels, such as the Pioneering Spirit, steep waves (with large heights and short periods) have relatively less influence on the vessel's motion compared to waves with the same height and longer periods. This means that waves with relatively large significant wave heights and short periods may be allowed, while waves with relatively low significant wave heights and long periods may not be permissible during operations.

Wind speed

Offshore wind turbines are generally installed in areas with excellent wind resources to maximise energy production. Therefore, the installation procedure will most likely also have to cope with high wind speeds. Moreover, It can be expected that the wind conditions could have a significant impact on the installation of fully-assembled wind turbines compared to installation strategies with multiple lifts since the wind speed increases with height and the resulting drag force will increase with the structure's cross-sectional area. In Figure 2.8, the annual probability of different wind speeds at 10 meters above the mean sea level (MSL) is depicted.

Wind Speed W_s [m/s]	Wind Direction: N	NE	E	SE	S	SW	W	NW	Occurrence Probability W_s	Cummulative Occurrence Probability W_s
0 - 5	2,10%	2%	1,80%	1,70%	1,90%	2,30%	2,50%	2,30%	16,60%	16,60%
5 - 10	4,60%	3,90%	2,90%	3,40%	6,20%	8,50%	8,60%	6,20%	44,30%	60,90%
10 - 15	2,20%	1,20%	1,20%	2,20%	5,50%	7,10%	6,70%	3,70%	29,80%	90,70%
15 - 20	0,40%	0,20%	0,20%	0,60%	1,70%	1,90%	2,30%	1%	8,30%	99,00%
20 - 25	<0.1%	<0.1%	<0.1%	<0.1%	0,20%	0,20%	0,40%	0,10%	0,90%	99,90%
25 - 30	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0,00%	99,90%
30 - 35	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,00%	99,90%
35 - 40	0%	0%	0%	0%	0%	0%	<0.1%	0%	0,00%	99,90%

Figure 2.8: The annual wind speed and direction probability at The Rian Offshore Array (Phase 1) location *[37]*

Wave and wind direction

According to *[39]*, the optimal turbine spacing, when accounting for both wake losses and transmission costs, has been found to be between 6 and 10 times the rotor diameter. As a result, the spacing will range from approximately 1070 to 2520 meters for turbines with a capacity between 10- and 20-MW (See Table 2.3). This may allow the Pioneering Spirit to move freely around the designated wind turbine installation location.

Therefore, the position of the Pioneering Spirit relative to the wave or wind direction could potentially be adjusted. This will eliminate the influence of the wave and wind direction on the workability of an operation. However, in reality, it could be that the wind and waves come from different directions making it impossible to eliminate both. In this case, it is essential to determine the most critical condition for the operation.

2.2.5. Installation Time

When the environmental conditions are sufficient to allow for a safe operation, another essential characteristic of the concept design is the amount of time that is needed for an operation to be executed. The operation could refer to the activities such as the transportation, (un)loading or installation of the floating wind turbine components. The required amount of time for each operation can is influenced by technical or logistical factors and is closely related to the cost. Hence, the total installation time is an essential parameter for the concept design.

The technical factors relate to the vessel capabilities, equipment specifications, and other tools such as guiding beams or double slip joint connections for the integration of a foundation and wind turbine. The double slip joint is a connection piece without bolts, making it a faster and safer option. It can be used for the integration of different tower segments of a wind turbine or for the integration of wind turbines and foundations *[22]*. Guiding beams can be used to align two segments before mating *[49]*.

The logistical factors primarily comprise the installation strategy and deck layout. The efficiency of the deck load configuration for different concepts can be compared by dividing the number of loaded components by the available deck space. This is an important parameter because it influences the maximum loading capacity of a vessel which could potentially reduce the number of shuttle operations *[87]*.

2.3. Floating Wind Foundations

The dominant floating foundations for offshore wind turbines can be distinguished by their restoring mechanisms to obtain hydrostatic stability. The three main restoring mechanisms are buoyancy-stabilised, ballast-stabilised and mooring-stabilised. Figure 2.9 represents the hydrostatic stability triangle for floating structures. It can be observed that dominant foundation types such as spar, semi-submersible and tension leg platform (TLP) are ballast-stabilized, buoyancy-stabilized and mooring-stabilized respectively. The barge foundation is relatively new compared to the other floater types and is primarily buoyancy-stabilised. These four dominant foundation designs are shown in Figure 2.10. However, the hydrostatic stability of a substructure is actually obtained by a combination of the restoring mechanisms. For some floating structures, called hybrid structures, the attribution of the different restoring mechanisms is more equally distributed. In total there exist more than 50 different substructure designs having different manufacturing, assembly and installation procedures. Also, variations of the technology readiness levels and commercial readiness indices can be observed. The motion of floating wind turbines is restricted due to the connected mooring systems that provide station keeping (See Appendix A). The generated energy is transferred through dynamic electricity cables. In the next sub-chapters, a short description will be given of the dominant floating foundations. This information is widely known and thus is obtained by a single source *[26]*.

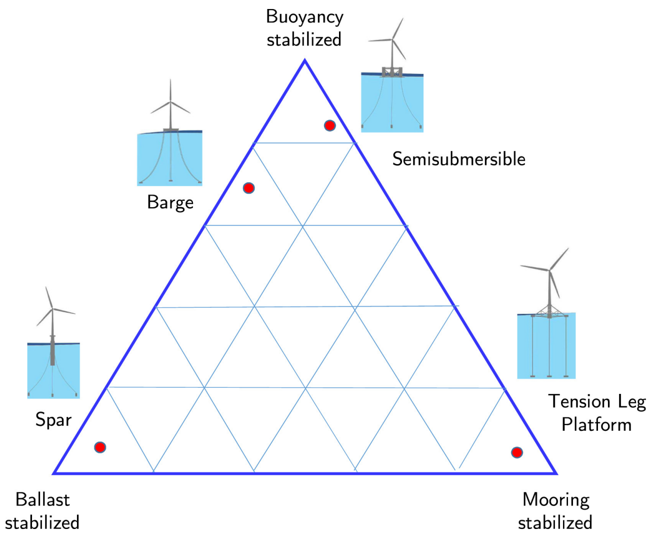


Figure 2.9: Hydrostatic stability triangle for floating structures *[76]*

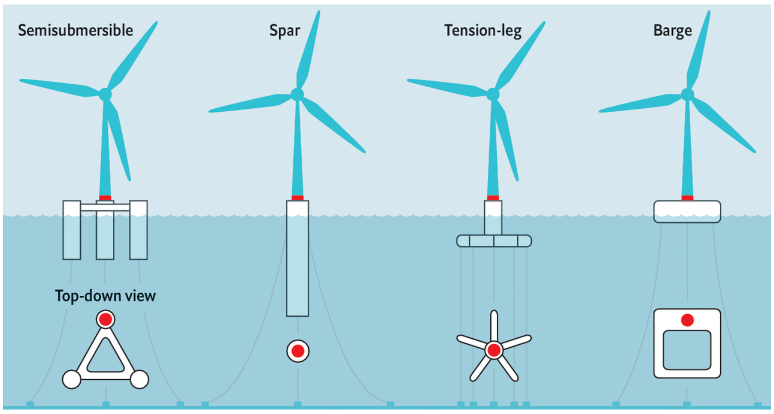


Figure 2.10: Dominant floating foundation concepts *[79]*

2.3.1. Spar

Spar foundations generally have the following characteristics:

- Hollow cylindrical design
- Steel and concrete structures
- Large draught of up to 100 meters
- Stability obtained by ballasting

The limitation of the spar foundation can be related to the structure's large draught. Therefore, spar-type wind turbines are normally suitable for areas with water depths exceeding 100 metres and cannot be fully assembled at harbours with shallow water depths. As a result, maintenance has to be done offshore and heavy-lift vessels are needed for offshore assembly which is generally more expensive. The conventional installation procedure for this type of structure will be elaborated in Section 2.4.2. In comparison to other floating offshore wind foundations, spar structures are less sensitive to hydrodynamic loading due to their small water plane area, and cylindrical shape. The cylindrical shape also makes it easier to fabricate.

2.3.2. Semi-Submersible

Typical characteristics of semi-submersible foundations are listed below:

- Multiple (3 to 4) buoyancy modules
- Horizontal heave plates below the modules
- draught between 10 and 20 metres
- Steel and concrete structures
- Stability obtained by large moment of inertia

Semi-submersible wind turbines are self-stabilised structures due to their restoring mechanism and shape. Furthermore, the dimensions of semi-submersible foundations allow for full assembly in a dry dock (see Figure 2.11). Therefore, only towing tugs are needed for the installation, making the need for heavy-lift vessels obsolete. As a consequence, this type of floating wind turbine shall be disregarded for installation with the Pioneering Spirit. However, the installation costs can be significantly reduced because less expensive vessels are required and offshore operation time can be minimised.

Apart from the lower installation cost, other advantages of semi-submersibles are that they can be installed in water depths between 50 and 100 metres and can be towed back to a port for maintenance. On the other hand, the complexity and mass of the structure could result in higher manufacturing costs and material requirements. Also, the structure has a larger cross-sectional area at the waterline, making it more sensitive to hydrodynamic loading and corrosion.

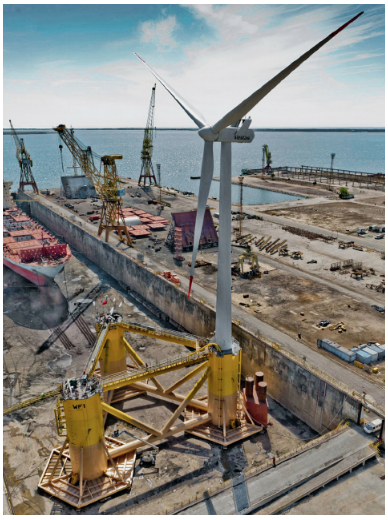


Figure 2.11: Semi-submersible wind turbine fully-assembled in a dry-dock *[7]*

2.3.3. Barge

Barge wind turbines are also self-stabilised structures and suitable for full assembly in a dry dock. Therefore, the installation procedure is similar to that of semi-submersible wind turbines. For this reason, barge wind turbines are not considered for installation with the Pioneering Spirit. Some ordinary particulars of barge foundations are formulated below:

- Damping pool in the middle of the foundation
- Hull consists of multiple buoyancy compartments
- draught of approximately 10 metres
- Steel and concrete structures
- Stability obtained by large moment of inertia

The (dis)advantages of barge foundations are comparable to that of semi-submersible structures. However, barge foundations are easier to manufacture but more sensitive to hydrodynamic loads and corrosion due to a larger waterplane area. Also, the mass of a barge structure is generally larger to obtain the same amount of buoyancy.

2.3.4. Tension Leg Platform

Commonly observed characteristics of TLP substructures are the following:

- Central column with several pontoons
- Relatively small structure
- Highly buoyant and initially unstable
- Stability obtained by tension in mooring lines
- Steel structure

The tension in the tendons is created due to the structure's buoyancy after it has been connected to the mooring system when it is submerged to a specific depth. Due to this restoring mechanism, the motion of TLP wind turbines is restricted in roll, pitch, yaw, and sway direction resulting in superior stability in comparison to the other foundations. Furthermore, the small water plane area makes TLPs less sensitive to hydrodynamic loads. Other advantages of TLP structures are the relatively small dimensions of the platform and the reduction of the mooring footprint. However, the disadvantages are the expensive mooring systems which have to withstand higher and continuous stresses, making them more sensitive to failure and more susceptible to severe storms, wave heights, or seismic activity. Another disadvantage is that TLPs are not self-stabilised structures, making towing tugs unable to install TLPs unless a specific buoyancy frame is used (See Section 2.4.2).

A summary of the advantages and disadvantages of the previously described dominant floating foundation types can be seen in Figure 2.12.

	Spar	Semi-submersible	Barge	TLP
Advantages	• Low sensitivity to wave motions. • Simpler design reduces cost and complexity of manufacturing.	• Smaller draft offers flexibility regarding wind farm water depth. • Shallow water quayside assembly and tow-to-port operations are supported by small draft and natural stability.	• Smaller draft offers flexibility regarding wind farm water depth. • Shallow water quayside assembly and tow-to-port operations are supported by small draft and natural stability. • Simpler design for manufacture and assembly (compared to semi-submersible).	• Excellent stability, once installed. • Small mooring footprint. • Smaller draft offers greater flexibility for wind farm depth and assembly facility.
Disadvantages	• Limited to deeper wind farm locations (+100 meters) due to large draft. Tow-to-port also challenging. • Assembly process requires deep water facility and expensive offshore heavy lift vessels.	• Heavier, more complex design can increase the cost of fabrication. • Greater sensitivity to wave loading.	• Greater sensitivity to wave loading. • Predominantly concrete designs require higher structural mass to achieve buoyancy.	• Reliance on mooring system for stability increases cost and complexity of assembly and towing processes. • Mooring system subject to higher stresses throughout project lifecycle. • Currently the least commercially advanced design.

Figure 2.12: Advantages and disadvantages of dominant foundations *[26]*

2.4. Installation

The installation procedure of floating offshore wind turbines consists of different operations. These operations can be executed onshore at a port side or offshore. In general, it is preferable to maximise the onshore operations because it does not require expensive installation vessels and can reduce downtime due to weather constraints. According to *[45]*, the distribution of onshore and offshore operations depends partly on the floating foundation as can be seen in Figure 2.13. What can be observed is that spar structures are mostly assembled offshore and TLP structures have the largest onshore assembly percentage. This can be attributed to the large draught of Spar structures and the relatively small dimensions of TLP foundations *[13]* *[26]*. When looking at the assembly of different floating wind turbine components it can be observed that the tower, nacelle, and blades can mostly be assembled onshore as can be seen in Figure 2.14.

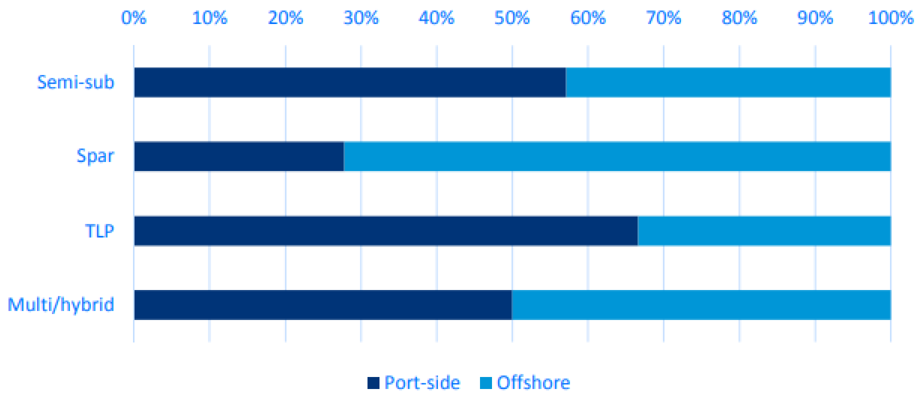


Figure 2.13: Distribution of on- and offshore assembly for the installation of floating wind turbine types *[45]*

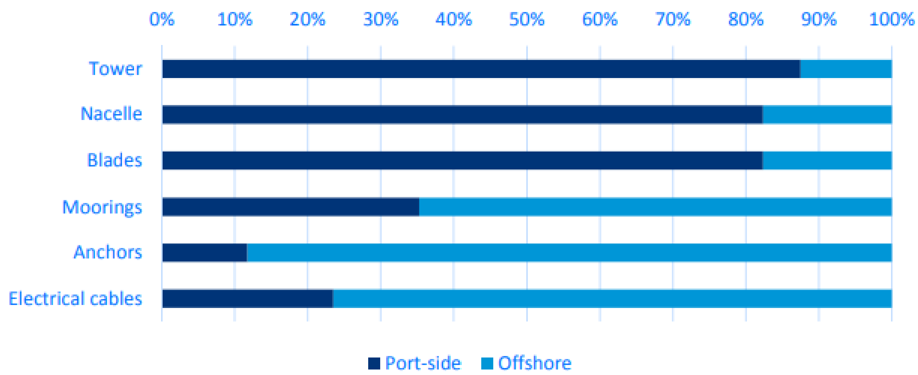


Figure 2.14: Distribution of on- and offshore assembly for the installation of floating wind turbine components *[45]*

After the onshore operations are finished, the different components of the FOWT are integrated if possible. Thereafter, it can be loaded out by using a dry-dock, slipway, or heavy lift vessel. Simultaneously, the anchors and moorings are installed by the appropriate vessels (e.g. Anchor Handling Tug (AHT), underwater Remotely Operated Vehicle (ROV)). Subsequently, the electrical cables are installed by a cable lay vessel. As soon as the mooring system and electrical cables are installed, the foundation or fully-assembled floating wind turbine can be coupled to the mooring systems. For some floating wind turbines, additional operations could be needed such as ballasting of the substructure or offshore integration of the wind turbine and floating foundation (See Section B). For TLP wind turbines, the foundation has to be stabilised until the mooring lines are connected and tensioned followed by the mating process of the wind turbine and substructure. However, the aforementioned installation process can differ depending on the installation method (e.g. type of vessel, strategy, port facilities and floating wind turbine design) *[45]*.

During the assembly, transportation and installation phases of different FOWTs concepts, variations in the draught requirement exist (see Figure 2.15). The transit of spar structures in the graph below refers transportation of the foundation before it has been upended. It can be observed that spar- and TLP-type wind turbines have lower draught requirements in comparison to the semi-submersible. This can be explained by the use of barges for spars and TLPs which can operate in shallower water. For this thesis, only the transit and installation draught requirements are of interest because it is assumed that all the necessary port facilities are available.

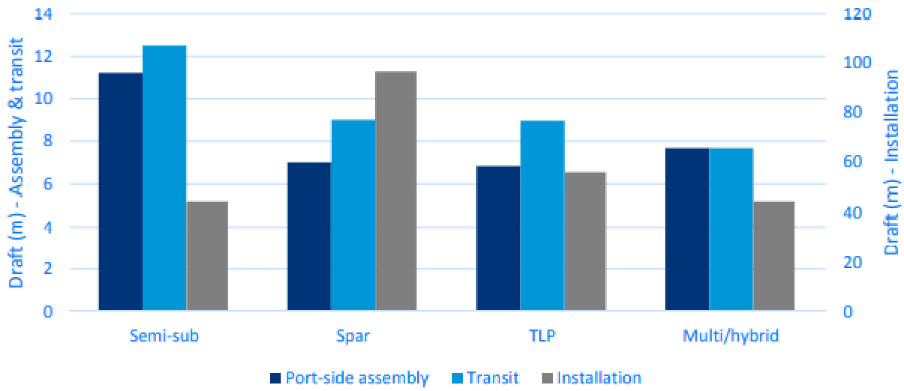


Figure 2.15: draught requirements of different floating wind turbine concepts *[45]*

As mentioned in Section 2.2.4, Another limitation during the assembly, transit, and installation phase is related to the metocean conditions. Especially the significant wave height is an important parameter that can influence the downtime of a project. An overview of the significant wave height limits for the various operations and different FOWT concepts can be seen in Figure 2.16. The concept for the installation of spar- and TLP-type wind turbines with the Pioneering Spirit may positively influence these operational limits due to its unique capabilities.

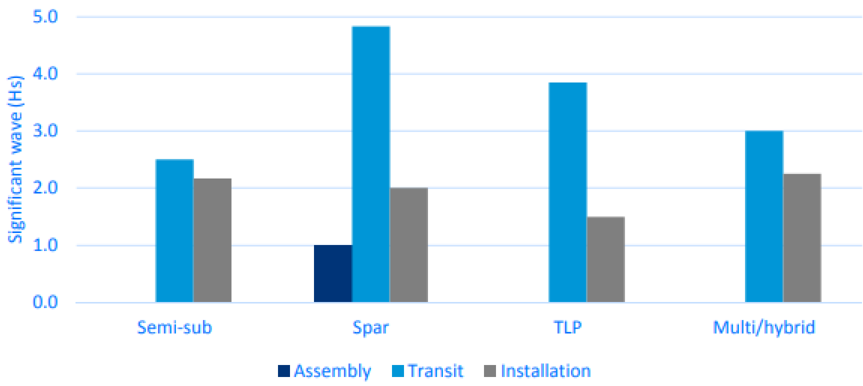


Figure 2.16: Significant wave height limitations for different FOWT concepts during assembly, transit and installation *[45]*

All of the above-mentioned requirements and limitations can affect the installation time and cost. A comparison between the installation time of different FOWT concepts is depicted in Figure 2.17. It is expected that the installation time will approximately be halved when the technology will be commercialised *[45]*.

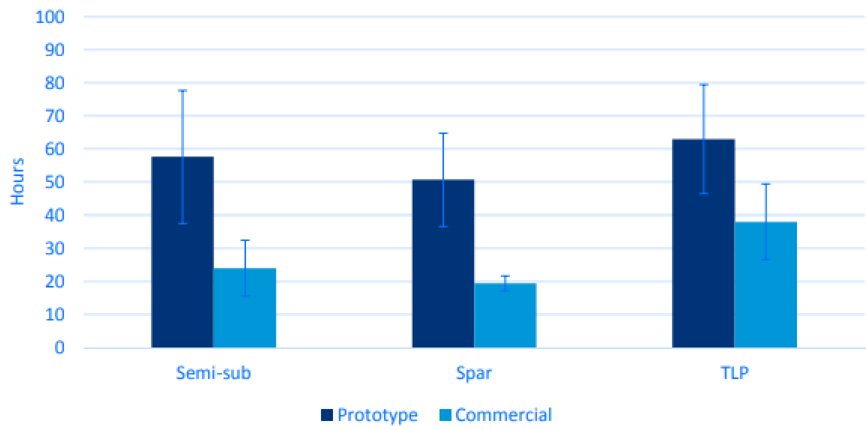


Figure 2.17: Installation time comparison between different FOWT concepts *[45]*

2.4.1. Installation Vessels

For the installation of different FOWT concepts, various vessel types are required (see Figure 2.18). As mentioned before, besides tugs and cable lay vessels, spar- and TLP-type wind turbines often need additional vessels due to the offshore integration of the wind turbine and foundation, and the instability in open water without additional assistance. Therefore, in Figure 2.18 it can be observed that barges, dynamic positioning (DP) and bespoke vessels may be required for the installation of spar and TLP wind turbines. However, variations of the required vessels are possible when using other installation methods.

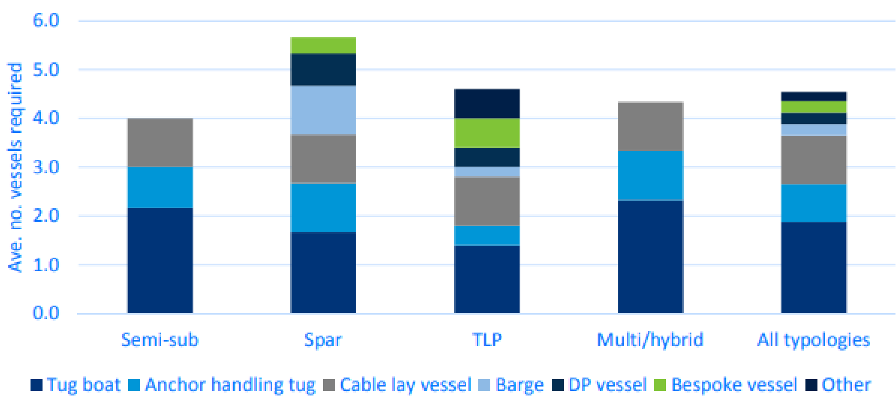


Figure 2.18: Vessel requirements for the installation of different floating wind turbine concepts *[45]*

Several companies are responding to the expected OWT installation vessel shortage by designing and building additional vessels. Some operational and conceptual FOWT installation vessels are depicted in Figure 2.19 and Figure 2.20 respectively.

Figure 2.19: FOWT installation vessels: Tug (left), Heavy-Lift Vessel (middle), and Semi-Submersible Crane Vessel (right) *[57] [46] [74]*

Figure 2.20: Conceptual FOWT installation vessels *[47] [40] [51]*

To increase the operational efficiency and safety during the transportation and installation of FOWTs, FIVs or WTIVs can be integrated with advanced equipment such as dynamic positioning systems, and motion compensating lifting equipment *[48]*. Typical values of operational limits for tugs and heavy-lift vessels are given in Table 2.1.

Vessel type	Max. Significant Wave Height [m]	Max. Wind Speed [m/s]
Tug	1 - 1.65	14
Heavy-lift vessel	1.8	15

Table 2.1: Operational characteristics of typical FOW installation vessels *[15]*

Apart from the FOWT concept and operational limits, the day rate of vessels is also an important factor in the decision-making of the installation method. The day rates of ordinary FOWT installation vessels are stated in Table 2.2. It can be observed that tugs are significantly cheaper than the other vessels. However, the operational limitations for towing tugs are inferior to that of heavy-lift vessels as can be seen in Table 2.1. Furthermore, the transportation procedure of a single fully-assembled floating wind turbine generally needs a large towing vessel for sufficient pulling force together with two to three smaller tugs that stabilize the structure's motion *[15]*. Therefore, in some cases it could be beneficial to use more advanced installation vessels.

Vessel type	Approximate Typical Day rate [EUR]
Tug boat	1000 - 4500
AHT	20000 - 50000
Cable Lay Vessel	70000 - 115000
Barge	80000 - 180000
DP vessel	50000 - 200000
Bespoke vessel	200000
Semi-submersible crane vessel	200000 - 360000

Table 2.2: Day rates of typical FOW installation vessels *[15]*

The mooring systems and electrical infrastructure can always be pre-installed by AHTs and cable lay vessels respectively. Since the day rate of these vessels is much lower in comparison to heavy-lift vessels, the

Pioneering Spirit will not be used for this purpose. Hence, installation of the mooring system and electrical infrastructure is left out of this analysis. Keep in mind that Figure 2.18 and Tables 2.1 and 2.2 are indicative and thus can be different in reality due to technological development and economic factors.

2.4.2. Installation Methods

The installation of semi-submersible and barge wind turbines is disregarded in this research. Therefore, only the installation methods of spar- and TLP-type FOWTs are described below.

Spar

Spar floating wind turbines were first installed in 2009 for the Hywind Demo project. The installation was performed in the following steps *[15]*:

1. Towing of the spar foundation to sheltered water with sufficient depth.
2. Upending the spar foundation by pumping water into the structure's hull.
3. Solid ballasting and de-ballasting of water.
4. Installation of the wind turbine tower and rotor.
5. Towing of the fully-assembled wind turbine to the installation location.
6. Connecting the structure to the pre-installed mooring system.
7. Final ballast modifications.

A couple of years later the Hywind Scotland floating wind farm was constructed using a similar installation strategy. The only difference was that a semi-submersible crane vessel installed a fully-assembled wind turbine onto the foundation with a single lift (see Figure 2.21).

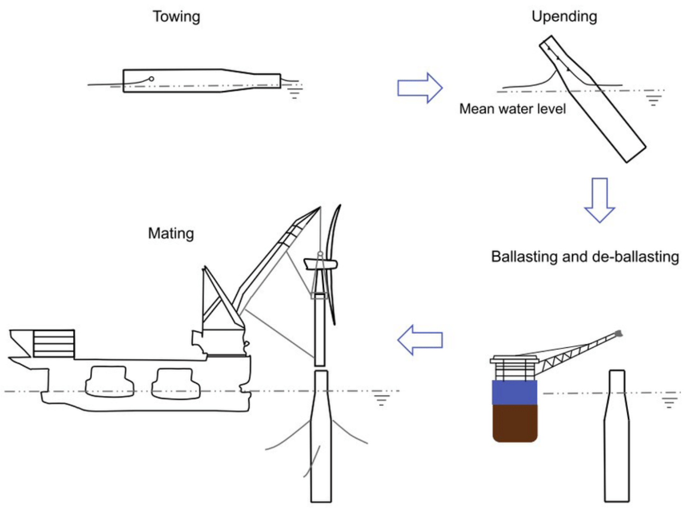


Figure 2.21: Conventional installation method for spar wind turbines *[15]*

However, if a location near shore has sufficient water depth, as was the case for the installation of the Hywind Tampen wind farm, it is possible to fully assemble the spar-type wind turbines at this facility before towing them out to the installation location with tugs. The assembly for the Hywind Tampen project was done at the Wergeland Base in Gulen, a municipality in Norway *[25]* (see Figure 2.22).

Figure 2.22: Fully assembled spar wind turbine at Wergeland Base, Photo by Jan Arne Wold/Woldcam/Equinor

Furthermore, some other innovative vessels are designed for the installation of spar-type wind turbines. A company called WindFlip has developed an installation barge named the WindFlip AS (see Figure 2.23). The turbine can be loaded almost horizontally on top of the WindFlip and towed to the installation location by a tug. The barge with the wind turbine will be flipped to a vertical position by ballasting both structures. Subsequently, the barge can be disconnected and the structure can be coupled to the pre-installed mooring system *[15]*.

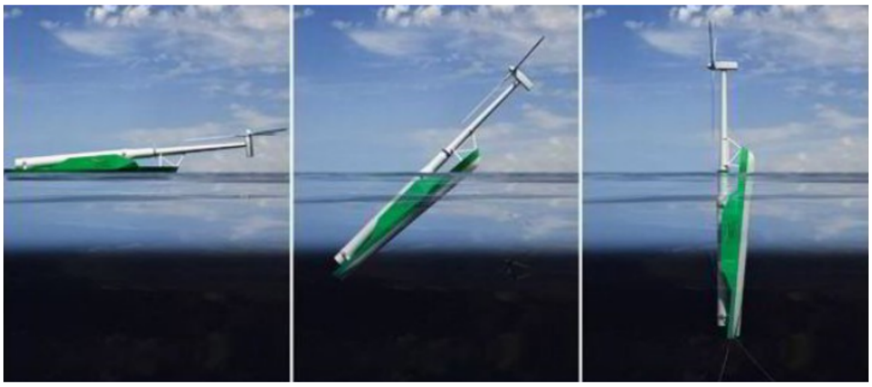


Figure 2.23: Installation procedure with the WindFlip AS *[15]*

Finally, a catamaran installation vessel has been suggested by the SFI MOVE project with the objective to avoid lifting operations that are highly sensitive to environmental conditions *[49]*. The catamaran vessel is used for the mating of a pre-installed spar foundation with a fully-assembled wind turbine by a single lift operation. The vessel and the installation process can be seen in Figure 2.24. The sliding grippers constrain the relative motion between the vessel and the foundation. The lifting grippers should be able to lift the fully assembled wind turbine and compensate for the relative heave motion of the spar foundation to minimise the forces of impact during mating.

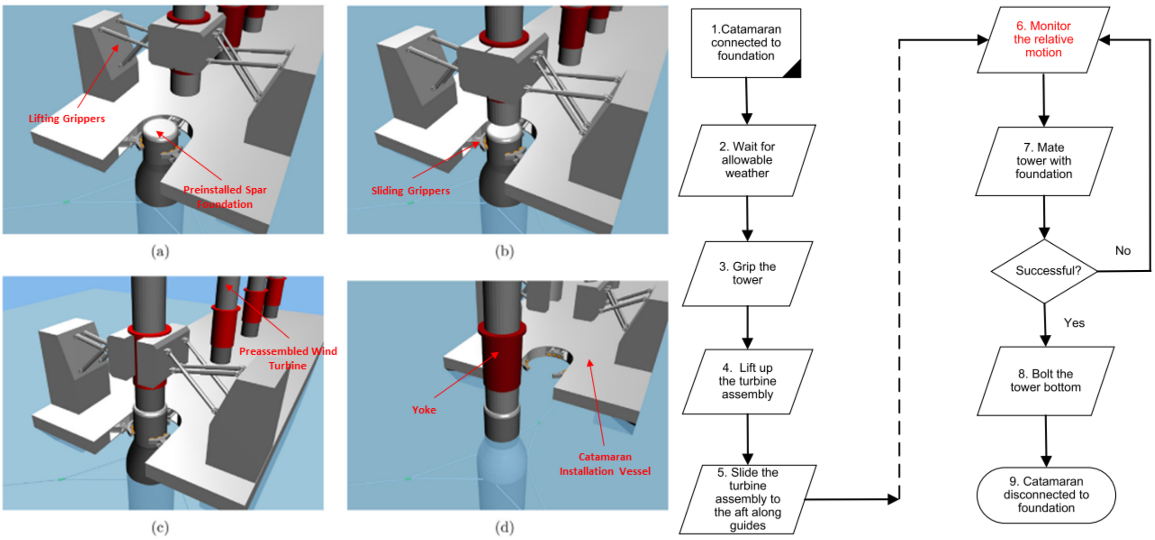


Figure 2.24: Installation steps for catamaran concept *[49]*

Tension Leg Platform

The TLP concept for wind turbines comes mainly from the expertise gained in the offshore oil and gas industry *[15]*. However, during the literature study, it was found that only a single small-scale TLP wind turbine has been installed in the past, having a capacity of 80 kilowatts *[11]*. This installation was performed by towing tugs. According to *[16]*, non-hybrid TLP wind turbines can be installed by making use of temporary buoyancy modules and towing tugs (see Figure 2.25), or DP crane vessels. An extremely important aspect of TLP installation is to create enough tension in the mooring lines so that the structure is stable. This could either be done by mechanically tensioning the mooring lines or submerging the TLP structure to a specific depth so that tension is created when released.

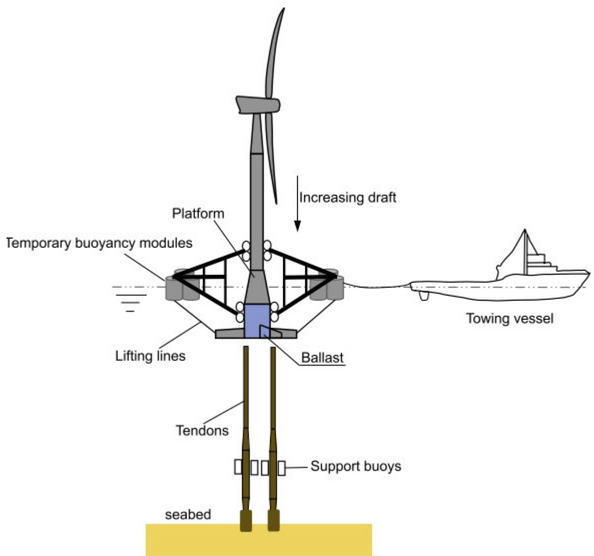


Figure 2.25: TLP wind turbine installation with buoyancy modules *[15]*

Another research developed a semi-submersible barge for the installation of fully-assembled TLP wind turbines. The transportation and installation procedure is depicted in Figure 2.26 *[6]*.

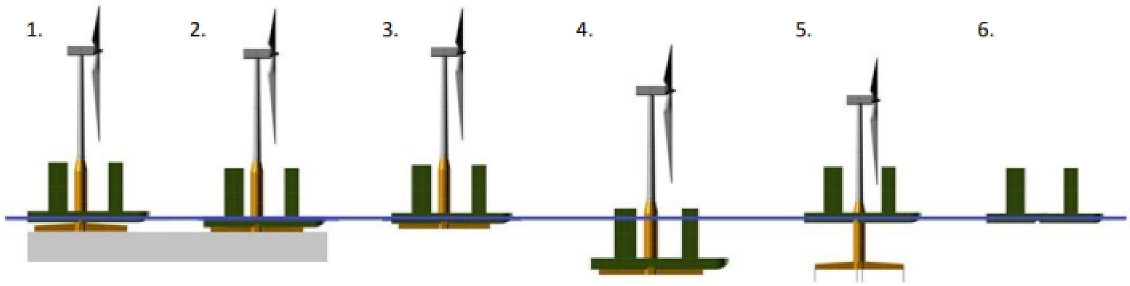


Figure 2.26: Transportation and installation procedure for TLP wind turbine with Semi-submersible barge *[6]*

Moreover, Heerema Marine Contractors have designed a lifting frame for TLP installation with a crane that can submerge the TLP to the required depth due to the frame's weight (see Figure 2.27) *[33]*.

Figure 2.27: TLP foundation installation frame *[6]*

2.5. Wind Turbines

The capacity and size of wind turbines have significantly increased in the past decades. This trend is most likely going to continue in the future, with the 15- to 20-MW wind turbines expected to enter the market between 2025 and 2030 *[43]*. As mentioned in Section 1.1, constructing a wind farm with higher capacity turbines will lower the LCOE significantly *[71]*. Therefore, bigger wind turbines will be the preferred option for both bottom-founded and floating wind farm construction projects, making it crucial for installation vessels to cope with the upcoming wind turbine sizes. Currently, the Haliade-X 14-MW is the largest available wind turbine suitable for offshore applications. The Haliade-X 12 MW prototype has been tested for two years at its location near the port of Rotterdam (Figure 2.28) *[94]*.

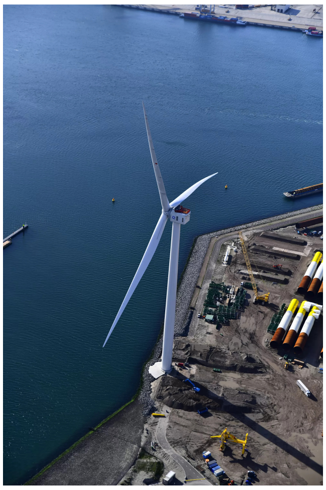


Figure 2.28: The GE Haliade-X offshore wind turbine prototype at the port of Rotterdam *[94]*

In order to increase the energy capacity of a wind turbine, improvements have to be made to the different components. One improvement is to increase the length of the blades resulting in a greater rotor diameter so that more wind can be captured due to the larger area and therefore produce more electricity. Another upgrade is to increase the height of the tower because the wind resources become stronger at higher altitudes, making it able to capture more energy *[90]*. But also improvements of the other components, such as the nacelle, are necessary for better capacities. All of the previously described aspects influence the parameters of the wind turbine. In Table 2.3, an overview of the parameters for wind turbines of 10-MW to 20-MW is given. Some advantages of bigger wind turbines is that fewer turbines have to be installed to reach a certain total capacity and that more turbines can be installed per area size. However, the installation of bigger wind turbines will be more challenging.

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

Table 2.3: Wind turbine parameters *[38][67][61][69]*

Different strategies exist for the installation of offshore wind turbines and depend on different factors. For example, the use of available deck space could be less efficient when installing fully-assembled wind turbines compared to a multiple-lift strategy. However, the installation time reduces for strategies having a lower number of lifts. Efficient deck space usage and installation time are closely related to cost. Therefore, a balance must be found between these two factors. In Figure 2.29, the possible installation methods are shown.

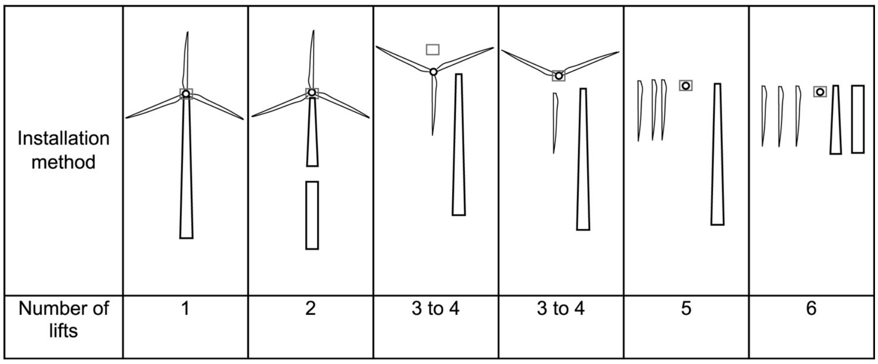


Figure 2.29: Installation of different pre-assembled wind turbine options *[48]*

According to *[48]*, the number of lifts depends on wind turbine design, lifting equipment, environmental conditions, and capacities of transport and installation vessels. Compared to other wind turbine installation vessels, the Pioneering Spirit presumably has superior lifting equipment, loading capacity, and sea-keeping capabilities. Therefore, it has been set as a requirement that the Pioneering Spirit should be able to install fully-assembled wind turbines.

In this research, vertical-axis wind turbines are left out of the analysis even though this type is considered promising for floating purposes due to the lower centre of gravity, greater cut-out wind speed, less spacing between turbines, and improved scalability *[12]*. However, because the development of vertical-axis wind turbines is lagging behind horizontal-axis wind turbines, mainly due to fatigue issues and low efficiencies that were discovered in the late 20th century *[12]*, and due to the criteria that the concept should consist of components that are available within the next 5 years, this type is left out of the analysis.

2.6. Concluding Remarks

In this Section, A summary of the most relevant findings from Chapter 2 is given and the operational requirements are formulated.

2.6.1. Offshore Wind Farm Development

The offshore wind farm development life cycle consists of five successive phases. The concept design is related to the *Transportation*, *Unloading*, and *Installation* procedures that are performed during the *Substructure Installation* and *Installation and Commissioning* phases of the development life cycle. Essential factors that ensure the safety and lower the costs of the aforementioned procedures are the vessel characteristics, installation strategy and logistics, and sea fastening and lifting equipment.

2.6.2. Economic Analysis

One of the objectives of the concept design is to reduce the LCOE of floating wind energy by focusing on the installation phase of offshore wind farm development. However, the LCOE is also influenced by, for example, the operational and maintenance cost and the energy production during the full life cycle of an offshore wind farm. Therefore, the economic feasibility of the concepts will be evaluated by determining the total installation cost resulting from the total project duration, vessel requirement, and fuel consumption for a reference floating wind farm project.

2.6.3. Technology and Commercial Readiness

Technology Readiness Levels and Commercial Readiness Indices are useful measurement systems for assessing the technological and commercial maturity of certain developments to evaluate the risk of investment decisions. However, in this research, the readiness of components is not assessed with respect to their TRLs and CRIs, because this would be highly time-consuming. Instead, the different components included in the concept design should be technically and commercially ready at the moment of implementation and market entrance.

2.6.4. Workability

Workability gives an estimation of the amount of time during a specific project period that an operation can be conducted safely at a certain location and depends on factors such as environmental conditions, vessel characteristics, equipment particulars, and type of operation. The environmental conditions that have the greatest impact on workability are the significant wave height, wave peak period, wind speed, and wind and wave direction. However, depending on the most critical condition, either the wind or the wave direction may be eliminated because the Pioneering Spirit could potentially adjust its heading before an operation due to the large spacing between the wind turbines. Furthermore, a first estimation of the workability for the concept design could be based on the cumulative annual significant wave height probability. The workability can be evaluated more precisely in a later phase of this research, taking more conditions into account and potentially evaluating it for different operations in order to compare the performance of the selected concept designs.

2.6.5. Installation Time

The installation time is closely related to the installation cost and depends on technical and logistical factors. The most relevant technical factors are the vessel's capabilities, specifications of the available equipment, and other promising tools. The logistical factors are mainly related to the installation strategy and deck layout.

2.6.6. Foundation

The FOWTs that are most relevant for installation with the Pioneering Spirit are the spar- and TLP-type because barge and semi-submersible wind turbines can be fully assembled in a dry-dock and installed by towing tugs which have lower day rates compared to floating heavy-lift vessels.

2.6.7. Installation Vessels and Methods

Due to the large draught of spar foundations and the instability of TLP structures, specialised vessels are generally required for the installation procedure. However, if the port has access to deep water or with the use of buoyancy modules both floating wind turbine types could be fully assembled onshore and installed by towing tugs. Still, one large towing vessel and 2-3 smaller towing tugs are needed for the installation of a single floating wind turbine. Also, specialised vessels normally have superior operational limits which could potentially improve the overall workability of a project. On the other hand, the day rates of specialised vessels are higher, making it an expensive option. Nevertheless, in some cases, it may be the preferred option. The Pioneering Spirit will not be used for the installation of the mooring systems or electrical infrastructure because these could always be installed by AHTs and cable lay vessels which are economically beneficial. Furthermore, there exist multiple conventional and conceptual installation vessels and methods which can be valuable for the development of the concept design.

2.6.8. Wind Turbine

Vertical axis wind turbines are expected to be a promising technology for floating offshore wind turbines. However, the maturity of this technology is lacking behind horizontal axis wind turbines. For this reason, only horizontal-axis wind turbines are considered in this research. Furthermore, because the LCOE has been identified as one of the main drivers for floating offshore wind development together with the fact that offshore operations are costly, the objective has been set that the concept should be able to install fully-assembled wind turbines with a single lift operation. Furthermore, the LCOE is dependent on the wind turbine capacity. Therefore, wind turbines with a capacity of 10 megawatt or higher are considered in this research.

2.6.9. Operational Requirements

Based on the analysis above, the following set of requirements have been created for the concept design of the Pioneering Spirit:

1. The concept must consist of components that are technically and commercially ready within the coming 5 years. - **OR1**

2. The concept must be able to safely install fully-assembled horizontal axis wind turbines with a capacity of 10 megawatt or higher on spar or TLP foundations. - **OR2**

3. The concept must be able to safely install the spar or TLP foundations with the necessary dimensions to support wind turbines with a capacity of 10 megawatt or higher. - **OR3**

4. The concept must be able to transport the fully assembled wind turbines and floating foundations safely between different lifting equipment. - **OR4**

5. The concept has to transport the components safely between the port and installation location. - **OR5**

6. The concept design must be able to unload the turbines from a feeder vessel. - **OR6**

7. The concept should have sufficient loading capacity. - **OR7**

8. The concept design for the installation of fully assembled wind turbines or foundations should have a workability within an acceptable range. - **OR8**

9. The concept design for the installation of fully assembled wind turbines or foundations should be able to install FOWTs within an acceptable time frame. - **OR9**

3 Case Study

The goal of this chapter is to provide the required information about the particulars of the Pioneering Spirit and the relevant lifting equipment. Since some of the particulars are confidential, this Section will be partly covered in Appendix E. Furthermore, a suitable installation location is selected based on requirements related to the main drivers and the floating structures. Together with Chapter 2, it will serve as a starting point for the concept exploration phase.

3.1. Pioneering Spirit Characteristics

The particulars of the Pioneering Spirit are stated in Table 3.1 and the Confidential Appendix E.

Vessel particulars	Dimensions
Length overall (incl. tilting lift beams and stinger)	477 [m]
Length overall (excl. tilting lift beams and stinger)	382 [m]
Length between perpendiculars	370 [m]
Breadth	124 [m]
Depth to main deck	30 [m]
Slot length	122 [m]
Slot breadth	59 [m]
Draught, operational	12-27 [m]
Vessel cruise speed	14 [kts] (= 25.93 km/h)

Table 3.1: Pioneering Spirit dimensions *[64]*

For offshore operations, the vessel can eliminate the relative motion between a bottom-fixed platform and itself in the x- and y-direction by enabling the active motion compensation system. This dynamic positioning system has the highest-rated redundancy named DP3. Also, the draught can be adjusted by an active ballast system. Moreover, the vessel's deck is equipped with different lifting equipment such as a Topside Lift System (TLS), Jacket Lift System (JLS), and multiple cranes (Figure 3.1). In Table 3.2, the maximum lifting capacity of the different lifting equipment is shown.

Lifting equipment	Lifting capacity [tonnes]
Topside Lift System	48000
Jacket Lift System	20000
5000t Special Purpose Crane	5000
Special Purpose Crane 2	600
Pipe Transfer Crane 1	50
Pipe Transfer Crane 2	50
Pipe Transfer Crane 3	50

Table 3.2: Lifting equipment characteristics of Pioneering Spirit *[64]*

The Pioneering Spirit is able to transport a topside and a jacket at the same time. Therefore, the vessel's stability during the transportation of multiple wind turbines or foundations is not considered problematic, because the weight of a topside could be tenfold or more compared to a fully-assembled wind turbine or foundation. Furthermore, the day rate of the Pioneering Spirit is assumed to be approximately the same as semi-submersible crane vessels (see Table 2.2). Finally, as a first estimation of the available deck space it has been assumed that 50% of the deck area between the aft and the beginning of the slot can be used for the storage of components. This is equal to 15376 square meters. This could be increased by removing equipment from the vessel's deck. However, this would result in additional costs and construction time. Below a more detailed description can be found of the different lifting equipment on the Pioneering Spirit.

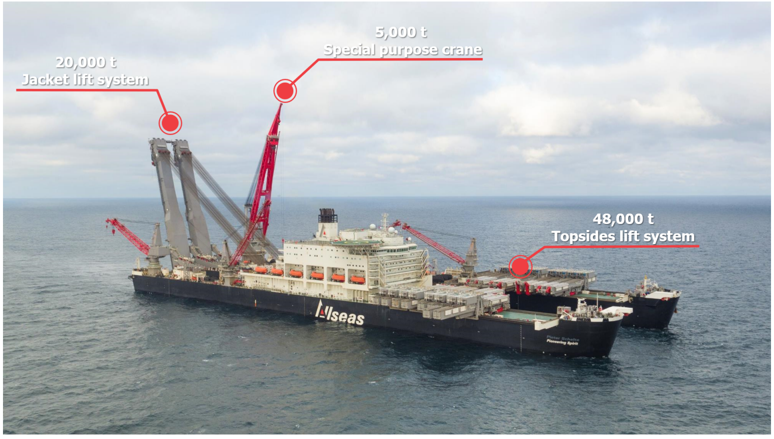


Figure 3.1: Topsides Lift System, Jacket Lift System, 5000t special purpose crane, courtesy of Allseas

3.1.1. Topside Lift System

For removing or installing offshore oil and gas platforms or substations with a single lift, the TLS can be used (See Figure 3.1). It consists of 16 parallel horizontal lifting beams, 8 on both the port side and starboard bow of the Pioneering Spirit, with a maximum lifting capacity of 3000 tonnes each resulting in a maximum lifting capacity of 48000 tonnes. The relative motion between the structure and the vessel can be compensated in the x-, y-, and z-direction. Furthermore, 12 out of the 16 beams have a length of 65 meters, and the remaining four beams have a length of 70 meters (See Figure 3.2) *[64]*. Further descriptions of the TLS will be provided in Section E.1.2 the confidential Appendix E.

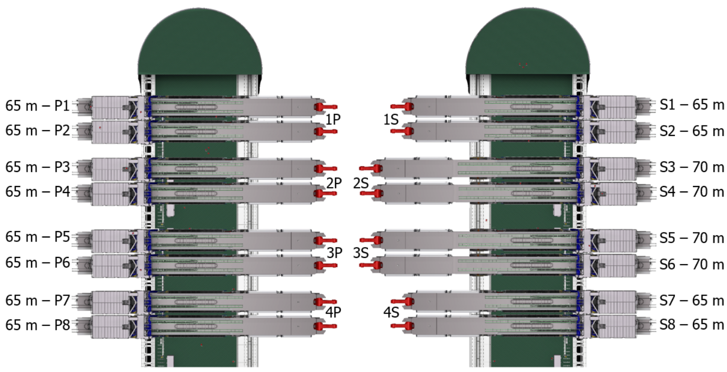


Figure 3.2: Lengths and names of lifting beams and forklift units, courtesy of Allseas

3.1.2. Jacket Lift System

Jackets can be removed or installed by the JLS (See Figure 3.3). The JLS consists of two parallel beams with a length of 170 metres containing three lifting blocks each. The relative distance between the centrelines of the beams varies per jacket lift operation and is adjustable by transverse skidding. By rotating the JLS beams the lifting blocks can be positioned above the jacket and the lifting operation can be performed. As previously mentioned, the JLS is capable of lifting structures of up to 20000 tonnes *[1]*. A more detailed description of the working principle and components is included in Section E.1.3 of Appendix E.

Figure 3.3: Jacket Lift System during operation *[84]*

3.1.3. 5000t Special Purpose Crane

The special purpose crane (Figure 3.1) can be used for multiple lifting operations with a maximum lifting capacity of 5000 tonnes. The crane can be equipped with a main, whip, auxiliary, and trolley hoist with different safe working loads (SWLs) and can rotate its base 360 degrees around the z-axis. All hoists are designed for both inboard and outboard lifts. The ranges for the lifting radius and height of the 5000t crane are provided in Section E.1.4 of Appendix E.

3.2. Installation Location

The interesting floating wind turbine concepts for installation with the Pioneering Spirit are with TLP or spar foundations. Below a list of requirements is given for the installation location to account for the limitations of the selected floating structures and the main drivers of floating offshore wind development:

- The water depth must exceed 100 meters
- The average wind speed should be greater than 9 m/s
- The earthquake risk should be low
- The installation location should be within 100 km reach from the shore
- The seabed conditions must be suitable for TLP and spar mooring systems

Based on the above characteristics, a potential installation site has been determined. However, Allseas may choose another installation location since there exist multiple locations globally that would satisfy the aforementioned requirements (see Appendix B). Also, the depth requirement only relates to the spar-type wind turbine and the earthquake risk only for the TLP-type. The Rian Offshore Array (Phase 1) location with an area of approximately 710 square meters could potentially serve as a floating wind farm development location (Figure 3.4). In Appendix B, the required information such as the average wind speed at 100 meters hub height, the water depth, the earthquake risk map, and the seabed conditions can be found. The port of Moneypoint is the closest to the installation location and thus will be considered as the port where the wind turbines will be assembled and consequently loaded onto the Pioneering Spirit or a feeder vessel. In Ireland, offshore operations are governed by the "2005 Safety, Health and Welfare at Work Act" and especially by the "Safety, Health and Welfare(Offshore Installations) Act, 1987". However, since the regulations and standards for offshore operations are different for various countries, it is not included in the design considerations of the concept.

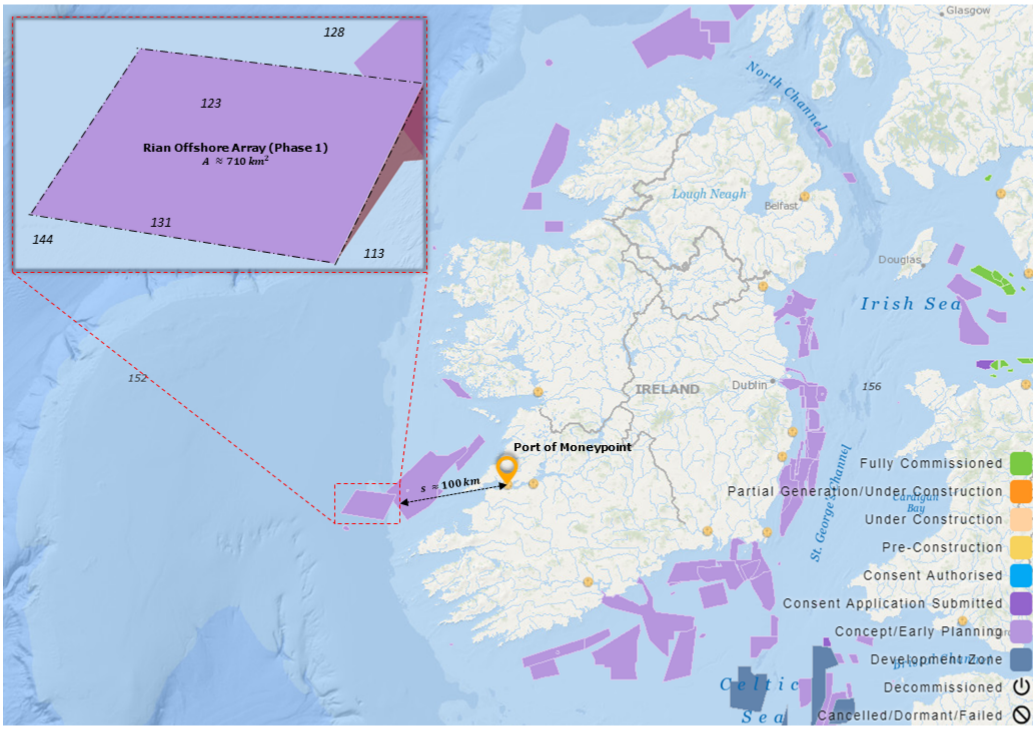


Figure 3.4: Potential installation location, *[3]*

3.3. Assumptions

Based on the information of Chapter 2 & 3, some assumptions have been made for the following stages of the research and are listed below:

- The mooring systems and electrical infrastructure are pre-installed at the installation location.
- It is possible to modify the Pioneering Spirit's deck (e.g. new equipment, modifications, removals).
- The Pioneering Spirit will not be obstructed during installation by the pre-installed mooring systems or electrical infrastructure.
- The feeder barge can only transport the wind turbines or foundations but is not capable of unloading itself.
- 50% of the deck space from aft to the beginning of the slot can be used for the storage of wind turbines or foundations.
- Only horizontal axis wind turbines will be installed by the Pioneering Spirit.
- Only spar or TLP wind turbines will be installed by the Pioneering Spirit.
- The Pioneering Spirit has a similar or slightly higher day rate compared to a semi-submersible crane vessel.
- The stability of the Pioneering Spirit is sufficient during all the stages of the installation process
- The distance between the Port of Moneypoint and the Rian Offshore Array (Phase 1) locations is approximately 100 kilometers.
- There are no standards or regulations regarding the installation of FOWTs at the Rian Offshore Array (Phase 1).

4 Concept Exploration

This chapter will answer the second research question *"What are alternative feasible concept designs that comply with the operational requirements, how can the performance of these concepts be evaluated and compared, and which concepts are the most promising?"*. It describes the development and provides sketches of the different concept designs. Thereafter, a method will be explained that is used to evaluate and compare the concepts followed by the results.

4.1. Concept Design Options

As described in Chapter 3, the Pioneering Spirit contains three alternative lifting systems that are in essence capable of handling the pre-assembled wind turbines or floating foundations with a relatively low amount of modifications needed. Considering the economics and logistics, it seems advantageous for the concept design to utilise the already available lifting equipment. Therefore, the concepts that will be explored will be using either the TLS, JLS, or 5000t Crane for the unloading and installation operations. This resulted in a Design Option Tree that is depicted in Figure 4.1. In this Figure, the different possibilities for *shuttling, unloading, installation, and strategies* are given. In the case that identical equipment is used for the unloading and installation procedures, the wind turbines and foundations can optionally be installed directly or indirectly. *Directly* refers to the operation in which either the wind turbine or foundation is immediately installed after it has been lifted from the feeder vessel, or when the components are transferred from a port to the lifting equipment and installed without placing them on deck. *Indirectly* relates to the operation in which all the wind turbines or foundations are first retrieved from the feeder vessel or a port and placed on deck before installation. Note that concepts 15 and 16 are only used for an indirect installation strategy. For the reason that these concepts are expected not to be economically viable for a direct installation strategy since the 5000t Crane and JLS can most likely lift a maximum of one or two components at a time.

It can be observed that a total of 16 possible alternative installation procedures exist when making use of different equipment or strategies. These procedures influence the design choices, resulting in a list of alternative concepts (see Table 4.2). Subsequently, the number of concepts has to be reduced by evaluating and comparing their performance with respect to certain factors. Due to the time limitations related to this thesis, it is not efficient to look into all the possible concepts in great detail. Therefore, it is preferable to identify the most promising concepts before starting with the concept definition phase. This will be described in Section 4.2. Some of the characteristics of the concept designs are not clearly depicted in Table 4.2. Therefore, a list of additional equipment per scenario is given in Table 4.1.

Scenario	Additional Equipment
TLS and Indirect Installation	• TLS-deck interface to transfer the components
Indirect Installation	• Deck transportation system
Indirect Installation and Feeder Vessel Transportation	• Sea fastening for both the Pioneering Spirit and the Feeder Vessels
Direct Installation and Feeder Vessel Transportation	• Sea fastening only for the Feeder Vessels
Indirect Installation and Pioneering Spirit Transport	• Sea fastening only for the Pioneering Spirit
TLS Operations	• Specially designed tool for lifting the components
JLS Operations	• Specially designed hoist and rigging to lift the components
5000t Crane Operations	• Specially designed hoist and rigging to lift the components

Table 4.1: Additional equipment requirement per scenario

Additionally, the following assumptions are formulated in order to give a more detailed description of the features regarding the different equipment that is included in the concept designs:

- The TLS can lift between 2-4 pre-assembled wind turbines or foundations simultaneously.
- The JLS can lift between 1-2 pre-assembled wind turbines or foundations simultaneously.
- The 5000t Crane can only lift a single pre-assembled wind turbine or foundation at a time.
- The feeder vessels have a loading capacity of between 2-4 pre-assembled wind turbines or foundations.
- There are enough Feeder Vessels available to allow for continuous installation.
- The fatigue life of all the utilised equipment is sufficient for multiple wind farm installation projects.
- The Pioneering Spirit and the Feeder Vessels have adequate stability during all offshore operations.
- All concept designs meet the required safety standards and are thus assumed to be equally safe.

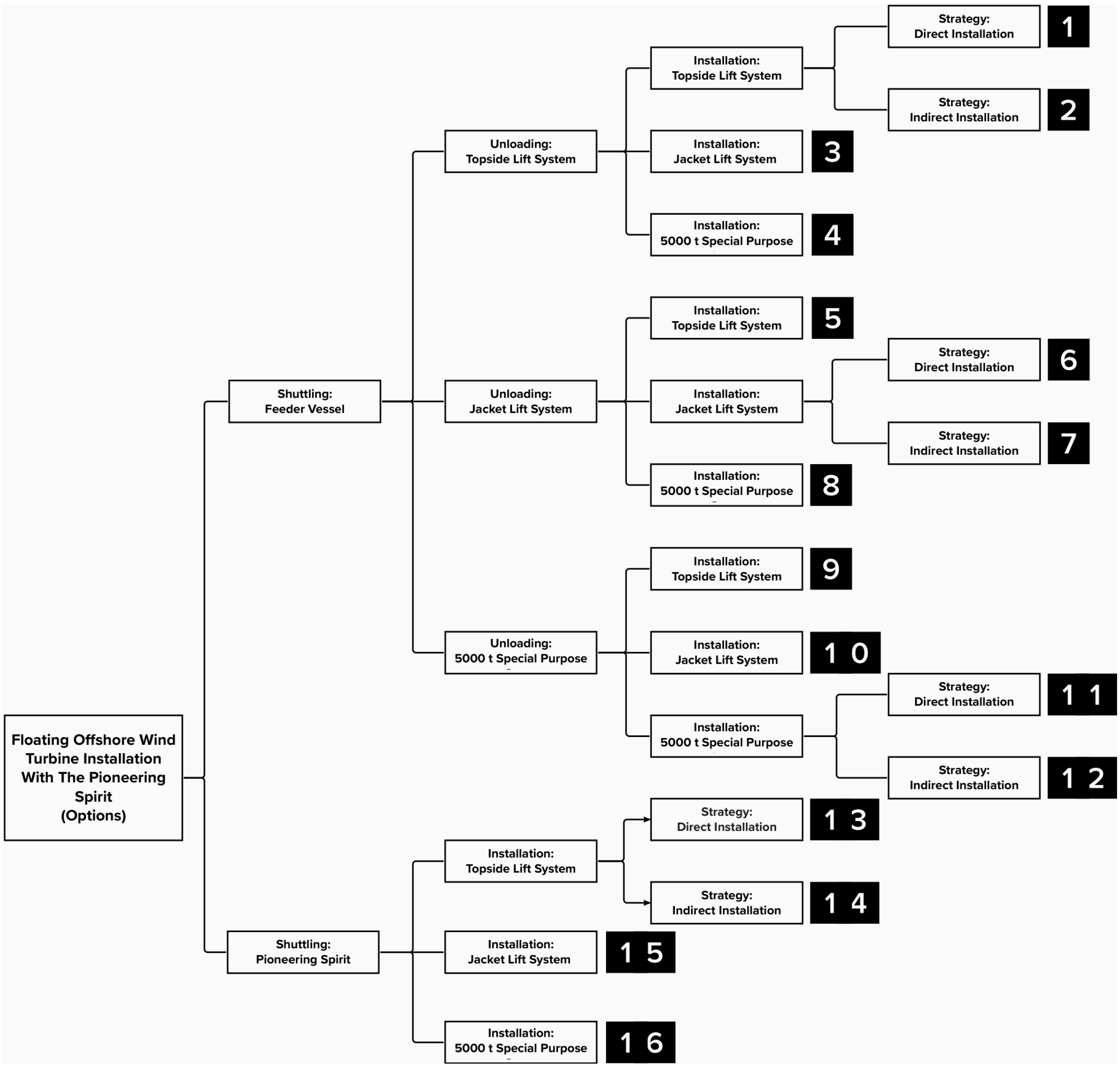
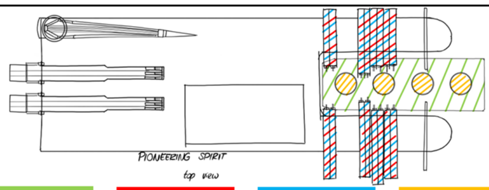
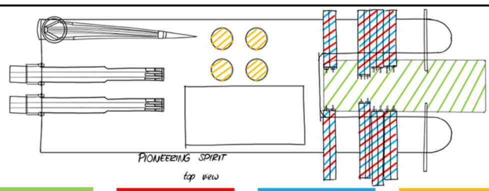
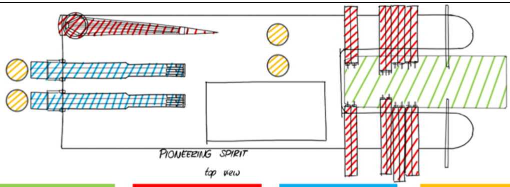
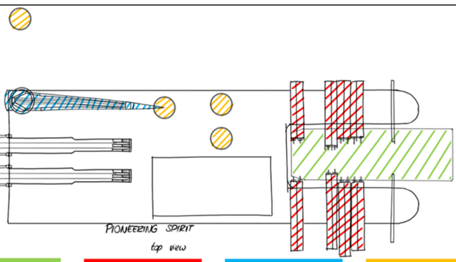
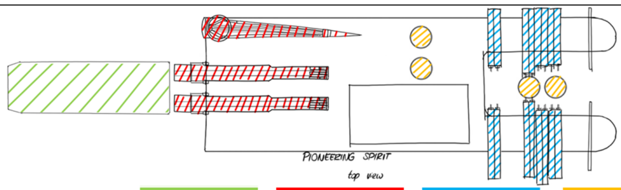
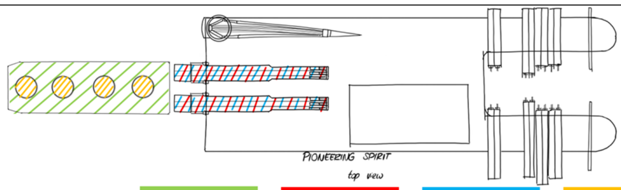
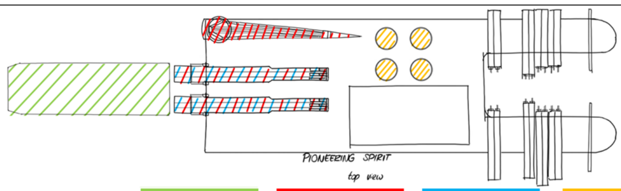


Figure 4.1: Design options tree

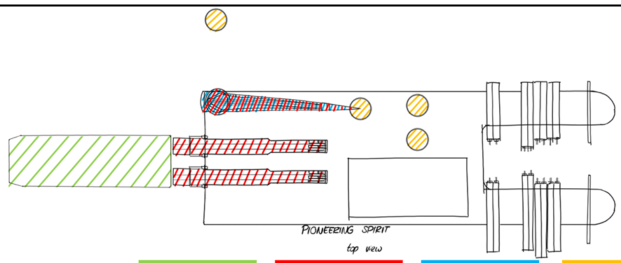
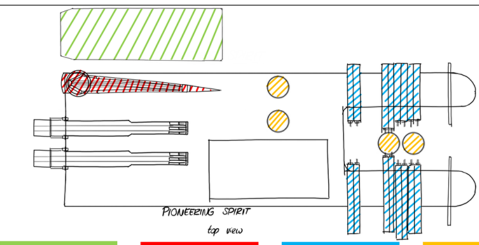
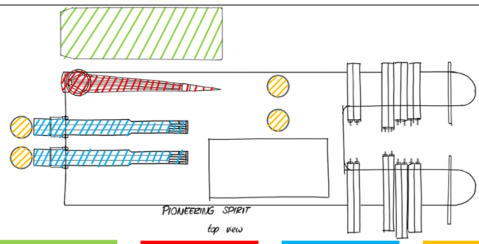
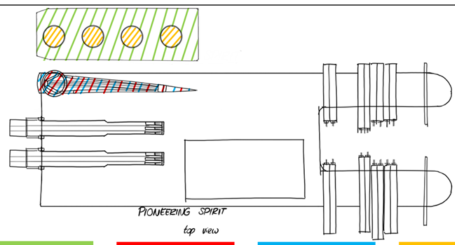
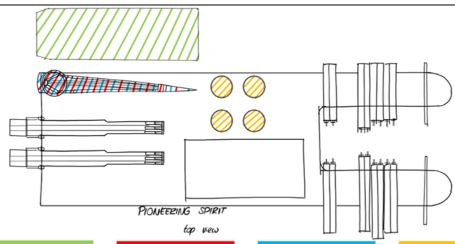
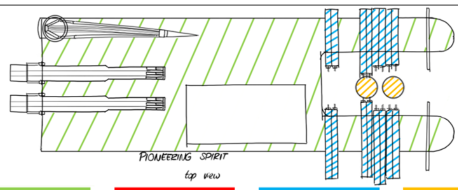
Table 4.2: Visual representation of the different concept design options.

Begin of Table	
Concept Design	Shuttling / Unloading / Installation / Method
1	 Feeder Vessel / TLS / TLS / Direct

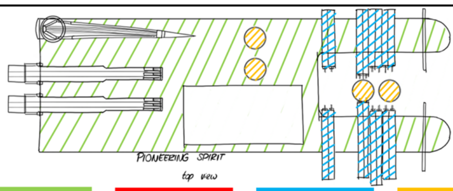
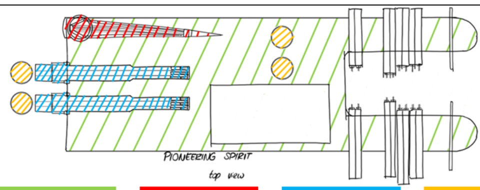
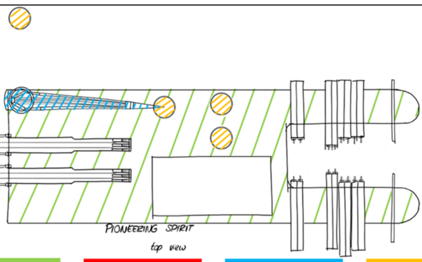
Continuation of Table 4.2

Concept Design	Shuttling / Unloading / Installation / Method
2	 Feeder Vessel / TLS / TLS / Indirect
3	 Feeder Vessel / TLS & 5000t Crane / JLS / Indirect
4	 Feeder Vessel / TLS / 5000t Crane / Indirect
5	 Feeder Vessel / JLS & 5000t Crane / TLS / Indirect
6	 Feeder Vessel / JLS / JLS / Direct
7	 Feeder Vessel / JLS & 5000t Crane / JLS / Indirect

Continuation of Table 4.2

Concept Design	Shuttling / Unloading / Installation / Method
8	 Feeder Vessel / JLS & 5000t Crane / 5000t Crane / Indirect
9	 Feeder Vessel / 5000t Crane / TLS / Indirect
10	 Feeder Vessel / 5000t Crane / JLS / Indirect
11	 Feeder Vessel / 5000t Crane / 5000t Crane / Direct
12	 Feeder Vessel / 5000t Crane / 5000t Crane / Indirect
13	 Pioneering Spirit / - / TLS / Direct

Continuation of Table 4.2

Concept Design		Shuttling	Unloading	Installation	Method
14		Pioneering Spirit	-	TLS	Indirect
15		Pioneering Spirit	5000t Crane	JLS	Indirect
16		Pioneering Spirit	-	5000t Crane	Indirect

End of Table

4.2. Trade-Off Analysis

In this Section, the Trade-Off analysis will be described followed by a further elaboration of the different steps that it comprises. Eventually, the concept design will be evaluated and the best-performing concept designs will be selected for further analysis.

4.2.1. General

In order to focus on the most promising concepts, the different design options from Table 4.2 will not be analysed in depth. Therefore, a decision-making tool is required that could reduce the number of concept designs before a more detailed analysis and comparison is performed. The Trade-Off Analysis is a tool that analyses, evaluates, and compares alternatives in order to make a decision and can be used during different stages in the SE method. However, uncertainty is an inevitable factor when making decisions due to the complexity of systems, incomplete information or missing requirements which could significantly impact the concept design selection *[77]*. Still, it is unavoidable to make decisions when developing a new system. Hence, it is essential that the judgements are as substantiated as possible which can be realised by improving the objectivity and quality of the decision-making process. Therefore, the Trade-Off Analysis of the various concept designs will be performed in collaboration with multiple employees of Allseas Engineering B.V., who are recognised experts on this topic. According to *[77]*, the Formal Trade-Off Analysis consists of seven steps that are listed below.

1. Definition of the Objectives.
2. Identification of Viable Alternatives.
3. Definition of Selection Criteria.
4. Assignment of Weighting Factors to Selection Criteria.

5. Assignment of Value Ratings for Alternatives.
6. Calculating Comparative Scores
7. Analysing the Results.

The first two steps of the Trade-Off Analysis have already been executed in an earlier stage of this thesis, with the operational requirements (see Section 2.6.9.) serving as the outcome of the first step and the concept designs from Table 4.2 of Section 4.1. resulting from the second step. Therefore, only steps 3 to 7 will be described in the following Sections.

4.2.2. Definition of Selection Criteria

In order to compare the concept designs, several criteria must be composed that are related to one or more of the operational requirements (see Section 2.6.9.). These criteria must consist of crucial aspects that can be used for the estimation of the performance of a system for achieving the objective and operational requirements that it is devoted to accomplishing. However, at this early stage of concept development, it is extremely challenging to measure the criteria performance of the concept designs with sufficient reliability which has an influence on the outcome of the Trade-Off Analysis. The criteria used in this Trade-Off Analysis are described below.

Modification Scope

The modification scope refers to the amount and complexity of the preparation work that is needed for the development of the concept design before it can be put into operation. This criterion is mainly linked to the *OR1* of Section 2.6.9. The modification scope has an impact on the lead time and the investment cost. Some examples that are covered by the modification scope are:

- New equipment (e.g. sea fastening, skidding system, TLS-deck interface or feeder vessel)
- Modifications to available equipment (e.g. equipment upgrades)
- Removals (e.g. pipelay or lifting equipment)

Downtime

Downtime refers to the period during which certain operations can not be executed. For the analysis, it has been separated into mechanical and operational downtime. This criterion is primarily related to *OR8* of Section 2.6.9. Downtime results in project delays which significantly increases the cost and therefore it has been included in the Trade-Off Analysis. Factors that influence the downtime are:

- Lifting Equipment Specifications (e.g. operational limits)
- Number of Offshore Operations (e.g. installation procedure)
- Type of Offshore Operations (e.g. transportation, unloading, skidding, installation)

Precision and Accuracy

Equipment with sufficient precision and accuracy is required during offshore operations to complete a project and to ensure safety. If the precision and accuracy is substandard, guiding beams could be necessary to increase the tolerance of the mating process *[49]*. However, this would result in higher costs. The criterion is mainly related to *OR2*, *OR3* and *OR6* of Section 2.6.9 and impacted by:

- Equipment Characteristics (e.g. motion compensation system, working principle or dynamic positioning system)

Transportation Time

The total project cost rise with greater port-to-site distances due to increasing transportation time. However, transportation time can be minimised by optimising different variables or using alternative strategies. For this reason, it has been taken into consideration for the evaluation of the concept designs. This criterion is mostly related to *OR5* and *OR9* of Section 2.6.9 and influenced by:

- Transportation Vessel Specifications (e.g. maximum sailing speed)
- Wind Farm Location (e.g. port-to-farm site distance)
- Transportation Logistics (e.g. number of feeder vessels)

Installation Time

Apart from the downtime and transportation time, the operational cost is also affected by the installation time. It represents the average amount of time that is needed to install a single floating wind turbine excluding the downtime and transportation time contributions. This criterion is primarily linked to *OR2*, *OR3*, *OR4*, *OR6* and *OR9* of Section 2.6.9 and depends on:

- Installation Procedure (e.g. number of offshore operations or (in)direct installation)
- Equipment Specifications (e.g. lifting speed or preparation time)

Loading Capacity

For installation sites located further offshore, the loading capacity becomes an important parameter because it determines the number of shuttle operations. Hence, for vessels with larger loading capacities, the total transportation duration reduces *[87]*. Since the distance to shore is a variable parameter, this criterion has been added to the Trade-Off Analysis. It is especially related to *OR7* of Section 2.6.9 and is affected by the following factors:

- Equipment Characteristics (e.g. loading capacity of lifting equipment and vessels)
- Installation Strategy (e.g. (in)direct installation, feeder vessel transportation)
- Deck Modifications (e.g. equipment removal, deck layout adjustment)

Scalability

As described in Section 1.1 and 2.5, it is expected that the dimensions of future wind turbines will increase. In order to respond to this development, it is advantageous to have a concept design with promising scalability features. For this reason, scalability has been incorporated as a criterion in the Trade-Off Analysis. It is mostly correlated to *OR2* and *OR3* of Section 2.6.9 and is depending on:

- Equipment Specifications (e.g. maximum lifting capacity, height, or radius)
- Upgrade Complexity (e.g. improving lifting capacity, height, or radius)

Final Remarks

Supplementary to the previously described selection criteria, there are other important factors which have not been separately incorporated into the Trade-Off Analysis. These factors and the reasoning for exclusion will be described below:

1. *Safety:* All the operations must comply with the safety regulations resulting in equally safe concept designs and thus can not be distinguished among.
2. *Investment Cost:* The modification scope comprises the investment cost of the concept designs.
3. *Stability:* Stability of both the Pioneering Spirit and the Feeder Vessels are assumed to be sufficient.
4. *Flexibility:* The concept performance regarding flexibility is difficult to assess at this stage of development and should be investigated in the concept definition phase.
5. *Reliability:* The reliability is partly incorporated in the downtime and precision and accuracy criteria.
6. *Fatigue Life:* It is assumed that the fatigue life of all the utilised equipment is sufficient for multiple wind farm installation projects.

Furthermore, it could be that some valuable selection criteria have not been identified during the concept exploration phase. However, due to time limitations, iterations as a result of newly identified criteria will not be performed.

Criteria Summary

An overview of the criteria together with the influencing factors and examples is shown in Table 4.3.

Criterion	Influencing Factor	Examples
Modification Scope	• New Equipment • Modifications • Removals	• Sea fastening, skidding system, TLS-deck interface, feeder vessel • Equipment upgrades • Pipelay or lifting equipment removal
Downtime	• Lifting Equipment Specifications • Number of Offshore Operations • Type of Offshore Operations	• Operational limits • Installation procedure • Unloading, skidding, component transfer
Precision and Accuracy	• Equipment Characteristics	• Motion compensation system, working principle, dynamic positioning system
Transportation Time	• Transportation Vessel Specifications • Wind Farm Location • Transportation Logistics	• Maximum sailing speed • Port-to-farm site distance • Number of feeder vessels
Installation Time	• Installation Procedure • Equipment Specifications	• number of offshore operations, (in)direct installation • Lifting speed, preparation time
Loading Capacity	• Equipment Characteristics • Installation Strategy • Deck Modifications	• Loading capacity of lifting equipment or vessels • (In)Direct installation, feeder vessel transportation • Equipment removal, deck layout adjustment
Scalability	• Equipment Specifications • Upgrade Complexity	• Maximum lifting capacity, height, or radius • Improving lifting capacity, height, or radius

Table 4.3: Overview of the influencing factors with examples for each criterion

4.2.3. Assignment of Weighting Factors

The previously formulated criteria have different levels of importance. Therefore, to be able to differentiate between the significance of the various criteria, weighting factors can be assigned to them so that the total score for the overall performance of the concept designs becomes more sensitive to the most crucial criteria and vice versa. However, there are some limitations that are related to weighting factors. For instance, the weighting factors indicate that the criteria are comparable, while in most cases they are not. Furthermore, the determination of the relative importance of the criteria is a rather subjective process.

The value of the weighting factors can be determined through the use of several alternative schemes. According to *[77]*, to avoid grouping the weighting factors around the median and to improve the objectivity, the following weighting scheme can be applied.

$$MaxSum = \frac{MaxWeight - MinWeight}{2} \cdot n \tag{4.1}$$

In this equation, the MaxSum refers to the total amount of weighting points that can be assigned to the criteria. The MaxWeight and MinWeight are the highest and lowest allowed weighting factors respectively. Lastly, The number of criteria that are included in the Trade-Off Analysis is represented by n.

This scheme makes the assignment of the weighting factors to the criteria a decision-making process in itself. Since trade-offs have to be made when certain criteria are weighted higher or lower because of the maximum amount of weighting points that can be allocated. The weighting factors for the criteria have been determined during a meeting[1]with multiple employees from Allseas, which are experts on this topic. The results are depicted in Table 4.4.

Criterion	Weighting Factor	Explanation
Modification Scope	6	• Modifications are closely linked to the cost and lead time resulting in a certain business risk that ultimately determines the realisation of the concept.
Downtime	5	• Mechanical downtime and workability cause project delays resulting in significantly higher installation costs.
Precision and Accuracy	2	• All the equipment must meet certain precision and accuracy requirements to be able to install components safely, over-designing these specifications is thus unnecessary.
Transportation Time	3	• The transportation time is less important as long as components arrive on time and it can almost be eliminated by using feeder vessels.
Installation Time	6	• The installation time largely determines the project duration and therefore has a major impact on installation costs.
Loading Capacity	3	• The loading capacity can reduce the number of shuttle operations, but it is less crucial when feeder vessels are used or for short-distance locations.
Scalability	3	• A scalable concept design is advantageous since turbine sizes are expected to increase but it is not an essential factor.

Table 4.4: Weighting factors for the various criteria

4.2.4. Assignment of Value Ratings

In order to determine the overall performance of the alternative concept designs, the criteria scores have to be summed up. However, in reality, the criteria can have different units and value ranges. Therefore, it is necessary to incorporate the criteria into a unified value system. According to *[77]*, there are multiple methods to determine the values for the criteria. For this Trade-Off Analysis, the subjective value method is used because the criteria are difficult to quantify at this early stage of development as was mentioned earlier. The working principle of the subjective value method is depicted in Figure 4.2.

For each alternative ...			
Selection criteria	Weights	Value	Score = weight × value
1	w_1	v_1	$w_1 v_1$
2	w_2	v_2	$w_2 v_2$
3	w_3	v_3	$w_3 v_3$
4	w_4	v_4	$w_4 v_4$

Figure 4.2: Working principle of the subjective value method *[77]*

This method involves a subjective evaluation of the concept design's performance with respect to each criterion. The criteria will be given a value ranging from 1 to 5 depending on the expected level of criteria achievement. The highest value will be assigned to excellent-performing and the lowest to the least-performing concept designs. Consequently, the score for each criterion can be calculated by multiplying the weight factor with the assigned value. The criteria evaluation of the concept designs is shown in Table 4.5.

[1] The Trade-Off Analysis Meeting was organised on the 8th of March 2023 from 14:00 until 16:30 in a conference room of Allseas Engineering B.V. which is located at the Poortweg 12 in Delft. To improve the objectivity of the thesis and the quality of the Trade-Off Analysis, three employees from Allseas named André Steenhuis, Vera Terlouw and Jeroen Breukels were joining the meeting. The goal of the meeting was to determine the weighting factors for the selection criteria and to evaluate the alternative concept designs based on these criteria. First, a presentation was given to provide the guests with the necessary information for the Trade-Off analysis. Subsequently, the weighting factors were assigned to the selection criteria after looking at the influencing factors, the consequences, and their relative importance. Eventually, the concept design options were described and evaluated separately by argumentation and discussion.

Criteria	Concept Design Option															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Modification Scope	5	1	1	1	1	5	2	2	1	2	4	3	5	1	2	3
Downtime	4	2	1	2	1	3	2	2	2	2	3	3	4	2	3	3
Precision and Accuracy	5	4	1	2	1	2	2	2	3	2	2	2	5	4	2	2
Transportation Time	4	4	4	4	4	3	4	4	4	4	3	4	1	1	1	1
Installation Time	5	3	1	3	1	3	2	2	4	2	3	3	5	4	2	3
Loading Capacity	3	5	5	5	5	2	4	4	5	4	1	3	3	5	4	3
Scalability	5	4	1	3	1	4	2	2	3	2	3	3	5	4	4	3

Table 4.5: Criteria evaluation of the concept design options

Modification Scope

The concept designs that require an interface between the Pioneering Spirit's deck and the TLS will most likely need another crane capable of transferring the components. This crane would be designed for future dimensions of wind turbines resulting in extremely high investment costs. Furthermore, a large part of the pipelay equipment below the deck must be removed in this case. Therefore, these concept design options score the lowest for this criterion. The highest-rated concept designs only utilise the TLS or JLS, since it is expected that these will need the least amount of modification work.

Downtime

The lowest-rated concept designs with respect to the downtime criterion utilise all the available lifting equipment together with a skidding system and the deck-TLS interface. This increases the probability of equipment downtime and reduces overall workability due to more operations. The concept designs that only use the TLS have the highest values for the reason that the TLS has beneficial operational limits in comparison to the other lifting equipment.

Precision and Accuracy

Since the TLS has the most advanced motion compensation system and movement accuracy, the concepts that only use the TLS have the highest values for this criterion. As for the previous criterion, the concepts that require all the lifting equipment together with a skidding system and TLS-Deck interface are scored the lowest because it involves precision and accuracy of all the equipment.

Transportation Time

For the concept designs that use the Pioneering Spirit for transportation scored the lowest because continuous installation is not possible. The rating differences between the concepts with feeder vessels are caused by the fact that the feeder vessel has to stay at the installation site in the case of direct installation with the JLS or the crane. This would increase the total transportation time.

Installation Time

The installation time is largely influenced by the number of offshore operations and the type of equipment that is required. Therefore, the concept designs with the most offshore operations that need all the equipment are scored the lowest. Furthermore, the installation speed with the TLS is most likely faster in comparison to the other lifting equipment and thus the concepts that only utilise the TLS have the highest value for this criterion.

Loading Capacity

For the concept designs, it has been assumed that four pre-assembled wind turbines or foundations can be stored on the TLS. Therefore, the concepts that use the TLS either for the unloading or installation procedure together with an indirect installation strategy scored the highest for this criterion. However, it could be questioned whether this will also be possible for TLP foundations since these generally cover a larger area.

Direct installation with the 5000t crane scored the lowest because it can only lift a single wind turbine or foundation.

Scalability

When lifting the pre-assembled wind turbines or foundations, the TLS is performing far below its maximum capacity while the operational limits of the 5000t crane are potentially reached. Hence, concepts with only TLS operations are scoring the highest on this criteria and the lowest scores were assigned to the ones that require all the available and additional equipment.

4.2.5. Calculating Comparative Scores

From Table 4.4 and 4.5, the overall performance of the alternative concept designs can be computed by summing up all of the criteria scores. The results are depicted in Table 4.6. To account for the uncertainties as a result of the subjective assignment of the weighting factors and evaluation of the concept designs, a 20% deviation from the total score has been assumed. Subsequently, the concept designs are ranked based on their scores and plotted in Figure 4.3.

Criteria	Concept Design Option															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Modification Scope	30	6	6	6	6	30	12	12	6	12	24	18	30	6	12	18
Downtime	20	10	5	10	5	15	10	10	10	10	15	15	20	10	15	15
Precision and Accuracy	10	8	2	4	2	4	4	4	6	4	4	4	10	8	4	4
Transportation Time	12	12	12	12	12	9	12	12	12	12	9	12	3	3	3	3
Installation Time	30	18	6	18	6	18	12	12	24	12	18	18	30	24	12	18
Loading Capacity	9	15	15	15	15	6	12	12	15	12	3	9	9	15	12	9
Scalability	15	12	3	9	3	12	6	6	9	6	9	9	15	12	12	9
Total Score	126	81	49	74	49	94	68	68	82	68	82	85	117	78	70	76

Table 4.6: Criteria evaluation of the concept design options

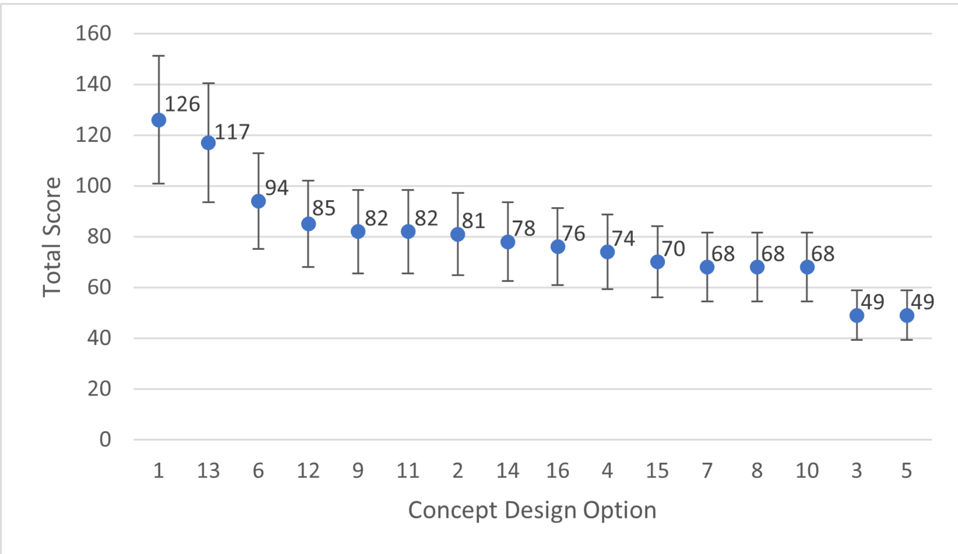


Figure 4.3: Total scores overview of the concept design options with 20% error bars

4.2.6. Analysing the Results

The results from the Formal Trade-Off Analysis indicate that Concept 1 is the best-performing design with respect to the overall criteria scoring. However, to check whether Concept 1 is also the superior concept regarding the performance on the highest weighted criteria, it is essential to compare it with other concept designs by means of a criteria profile. This criteria profile has been plotted in Figure 4.4. Only Concepts 1, 6 and 13 are included in the criteria profile graph because it can be seen from Figure 4.3 that even with a 20% total score variation it is almost impossible for Concept 12 to outperform the winning concept design.

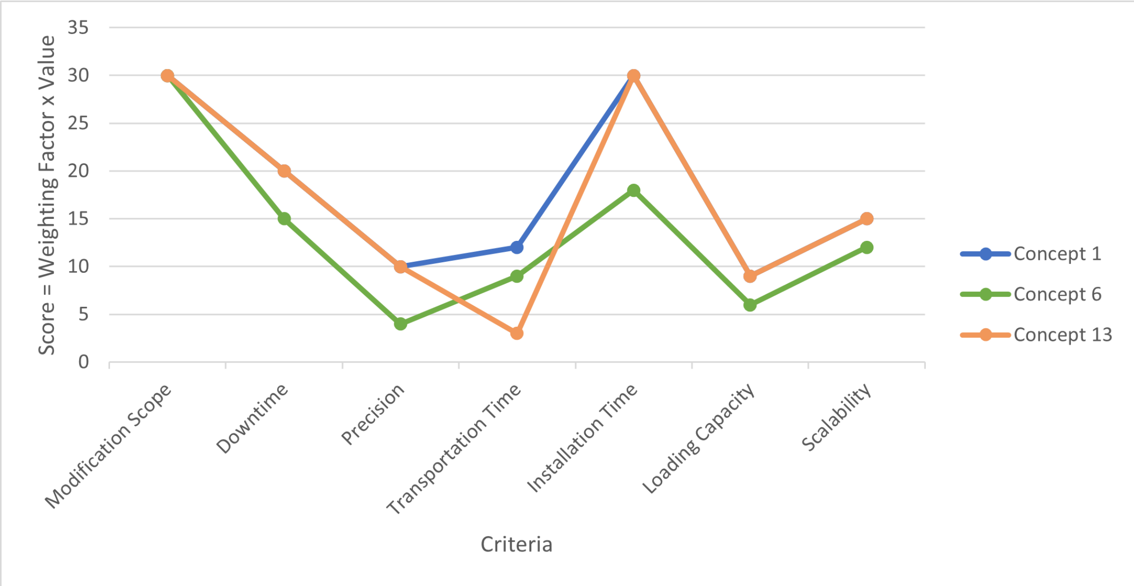


Figure 4.4: Criteria profile of the top three best-performing concept designs

This Figure shows that Concept 1 scores equivalent or higher on all the criteria in comparison to the other concept designs. However, Concept 13 is almost scoring the same as concept 1 except for the Transportation Time criterion because the Pioneering Spirit is used for shuttling. As mentioned in Section 4.2.3, the modification scope, installation time and downtime were identified as the most important criteria. Hence, Concepts 1 and 14 are scoring equally on the highest weighted criteria. Moreover, concept 6 is scoring the lowest on all but two criteria. It has an advantage regarding the transportation time in comparison to Concept 13 due to the use of feeder vessels that could allow for continuous installation when a sufficient number of these vessels is available. Still, the JLS can most likely lift a maximum of one pre-assembled wind turbine or TLP foundation and two spar foundations. As a consequence, the feeder vessel must remain at the installation location for as long as all the components are unloaded and installed by the Pioneering Spirit. This results in the need for more feeder vessels to allow for continuous installation.

To conclude, Concepts 1 and 13 (See Figure 4.5 and 4.6) will be included in the concept definition phase. Not only because their total scores are almost similar, but also because both concepts score equally on the most important criteria. Therefore, it will be interesting to analyse if Concept 13 could be the best-performing concept design by changing certain variables (e.g. distance, loading capacity, or feeder vessel availability). Furthermore, since these concepts are almost similar except for the method of transportation and unloading, an additional concept design will be included in the concept definition phase for comparison. This concept design should have a completely different installation procedure meaning that either the JLS or the 5000t Crane should be used. From a personal point of view, Concept 11 (See Figure 4.7) is an interesting concept because it uses a traditional crane together with a direct installation strategy and a feeder vessel for transportation. This concept will also be included in the concept definition phase.

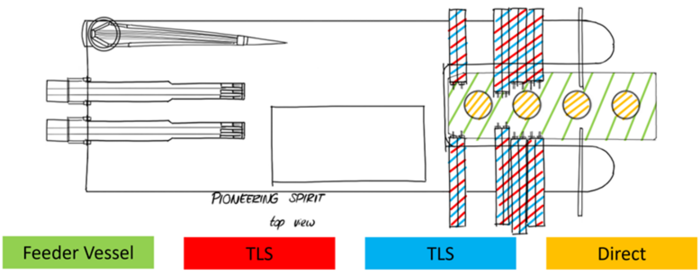


Figure 4.5: Concept Design Option 1

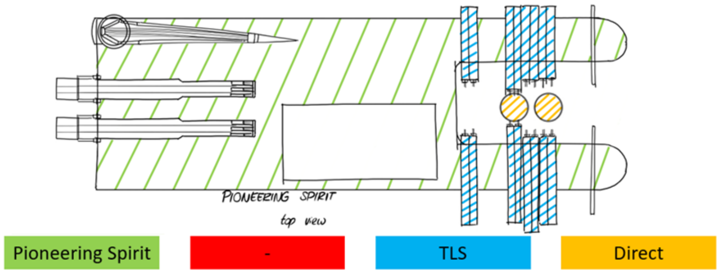


Figure 4.6: Concept Design Option 13

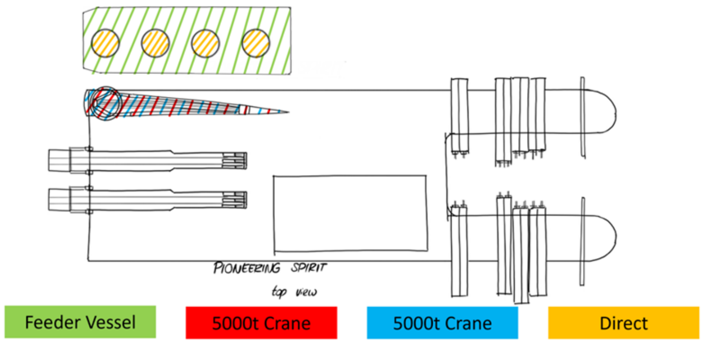


Figure 4.7: Concept Design Option 11

5
Concept Definition

This chapter will answer the third research question *"How do the installation procedures of the selected concept designs look like and what are their technical feasibility, workability, and economic feasibility?".* First, the technical feasibility of Concepts 1, 11 and 13 will be evaluated. Subsequently, the workability will be assessed for different operations that are executed in the various installation procedures with the concept designs. Eventually, the outcome of the technical feasibility analysis and the the workability assessment can be used to compare the economic feasibility of these concepts based on the total installation cost for a reference wind farm.

5.1. Technical Feasibility

The technical feasibility of the concepts will be assessed by first developing storyboards for the different installation procedures. Thereafter, the stability of the feeder vessel will be analysed for the considered load cases. Finally, technical descriptions are provided for specific operations and potentially required equipment or tools. These topics will be covered in Sections 5.1.1, 5.1.2 and 5.1.3.

5.1.1. Storyboards

The storyboards will be created for the installation of the proportional 15-MW wind turbine (indicated by 15-MW* in Table 2.3) along with the associated floaters, because these types are already used in future planned offshore wind farm projects *[68].* It provides illustrations with corresponding descriptions of the various operations that are performed in the different installation procedures. However, before the storyboards are presented, it is useful to get an overview of the relevant assumptions, parameters, and limitations. These will be described in the following Sections. For information, all the schematic representations of the limitations and storyboards are drawn to scale and the indicated dimensions are presented in metres. Furthermore, the crane boom has been extended in the storyboards. Also, for the installation procedures of the spar-type floating wind turbine and the wind turbine integration on top of a TLP foundation with Concept 11, the base of the 5000t crane has been over-dimensioned, since the operational limit for the lifting height is exceeded (See limitation 5 of Section 5.1.1.3.

5.1.1.1. Assumptions

For the development of the storyboards, a set of reasonable assumptions have been made in order to get an idea of the possibilities regarding each installation procedure. These assumptions are listed below.

1. The Pioneering Spirit is capable of lifting the components while having the minimum operational draught of 12 metres.
2. The load can be rotated 360 degrees around the vertical axis during the lifting operation with the 5000t crane.
3. A height of 2.5 metres for the grillages, that are used for the sea fastening, is sufficient to safely transport the pre-assembled wind turbine generators (WTGs) and spars.

4. A vertical clearance of 4 metres between the load and other structures has to be achieved during all the lifting operations.
5. A clearance of 3.6 metres is sufficient when the Iron Lady is moored to the port side of the Pioneering Spirit.
6. To account for the rigging between the main hoist of the 5000t crane and the load, a distance of 10 metres has been assumed.
7. Two towing tugs are required for the transportation and mooring operations of the Iron Lady.
8. The transition pieces have already been integrated into the spar and TLP floaters.
9. The mooring lines are connected to the floating structures at a certain water depth so there is no obstruction during wind turbine installation with the PS.
10. The PS can be used for lifting and ballasting operations simultaneously.
11. The PS and tugs can travel over a distance of 1000 kilometres with a full tank of fuel.
12. Specially designed lifting tools for both the 5000t crane and TLS are used that are capable of performing the described lifting operations.

5.1.1.2. Particulars

In Section 3, the specifications for the Pioneering Spirit, the reference installation location, and the different lifting equipment were provided. Furthermore, the characteristics of the wind turbines with different capacities are listed in Table 2.3 of Section 2.5. In addition, it will be necessary to determine the parameters of the substructures and feeder vessel, since the concept design should be able to transport and install spar and TLP foundations that support wind turbines with a capacity of 10 MW or higher (See 2.6.9).

The particulars for the spar foundations are found in the literature and are listed in Table 5.1. However, for the freeboard, diameter upper part, SWL to taper top, and SWL to taper bottom of the 15-MW spar foundation together with the wall thickness of the 20-MW spar foundation, a realistic value has been assumed.

Parameter	10-MW	15-MW	20-MW
Total length [m]	100	100	100
Freeboard [m]	10	10	10
draught [m]	90	90	90
SWL to taper top [m]	4	4	6
SWL to taper bottom [m]	12	12	13.71
Diameter upper part [m]	8.3	10.5	15.2
Diameter lower part [m]	15	18	24.10
Wall thickness [m]	0.06	0.06	0.06
Density Steel [kg/m^3]	7850	7850	7850
Steel mass [kg]	$2.13 \cdot 10^6$	$2.59 \cdot 10^6$	$3.53 \cdot 10^6$
Reference	*[36]*	*[66]*	*[18]*

Table 5.1: Spar foundation dimensions for 10-, 15- and 20-MW wind turbines

The characteristics of the TLP foundation supporting a 10-MW wind turbine were also found in the literature. However, this was not the case for TLPs supporting 15- or 20-MW wind turbines. Consequently, the parameters for the 15-MW TLP have been based on an estimation[1]. However, the dimensions of the 20-MW TLP will not be estimated since the storyboards will be based on the installation of 15-MW floating wind turbines together with the uncertainty of a 20-MW TLP design. The particulars of the different TLPs are presented in Table 5.2.

[1] The parameters for the TLP platform supporting the 15-MW wind turbine are estimated and provided by André Steenhuis, supervisor of this thesis from Allseas Engineering B.V.

Parameter	10-MW	15-MW
Total length [m]	45.3	40
Freeboard [m]	10	18
draught [m]	35.3	22
Diameter cylinder [m]	19.8	10.5
Number of pontoons	3	3
Pontoon radius [m]	39.6	50
Diameter of pontoons [m]	–	10
Height of pontoons [m]	8.5	–
Width of pontoons [m]	8.5	–
Steel mass [kg]	$3.667 \cdot 10^6$	$3 \cdot 10^6$
Displacement [kg]	$17.74 \cdot 10^6$	$9 \cdot 10^6$
Reference	*[81]*	–

Table 5.2: TLP foundation dimensions for 10- and 15-MW wind turbines

The Iron Lady will be used as the reference feeder vessel for the transportation of the components between the port and the installation site. The parameters of the Iron Lady are provided in Table 5.3.

Particular	Value
Length [m]	200.7
Breadth [m]	57.6
Height [m]	13
Dry Weight [t]	23337
Average Sailing Speed [kn]	8.3

Table 5.3: Specifications of the Iron Lady, adopted from *[30]* and Allseas

5.1.1.3. Concept Limitations

During the development of the storyboards for the installation procedures with the different concept designs, multiple concept limitations were encountered. These limitations are listed below.

1. The TLP does not fit into the slot of the PS.
2. No clearance can be realised between the pre-installed TLP and PS during wind turbine installation with the TLS.
3. The Iron Lady has to be extended from the stern of the PS when moored.
4. The clearance between the wind turbine blades during unloading and installation with the 5000t crane is limited.
5. The 5000t crane is not capable of lifting the pre-assembled spars and WTGs from the Iron Lady.
6. The Iron Lady loaded with TLPs has to be moored to the Pioneering Spirit with a large gap space.
7. The Pioneering Spirit can not adjust its heading for the installation of TLP-type floating wind turbines.

For all of the previously mentioned limitations, solutions have to be found in order to mitigate the effects. In some cases, this will result in changes of the installation procedure. In others, the equipment may require an upgrade or new solutions have to be found. The limitations will be described and mitigated separately below.

Limitation 1 - Insufficient slot breadth

The TLP consists of pontoons with a length of 50 metres. As a consequence, even with the best possible configuration and without taking any clearance into account, the centre of the TLP will only reach into the slot for a length of 18.80 metres (See Figure 5.1). The maximum position of the FLU that is located closest to the bow of the PS, is 344 metres measured from the aft of the PS. Hence, the tip of this FLU can can be located at a minimum distance of 38 metres, measured from the front of the PS. Therefore, the TLP foundations can not be installed with the TLS. This limitation could be mitigated by installing the TLPs with the 5000t crane.

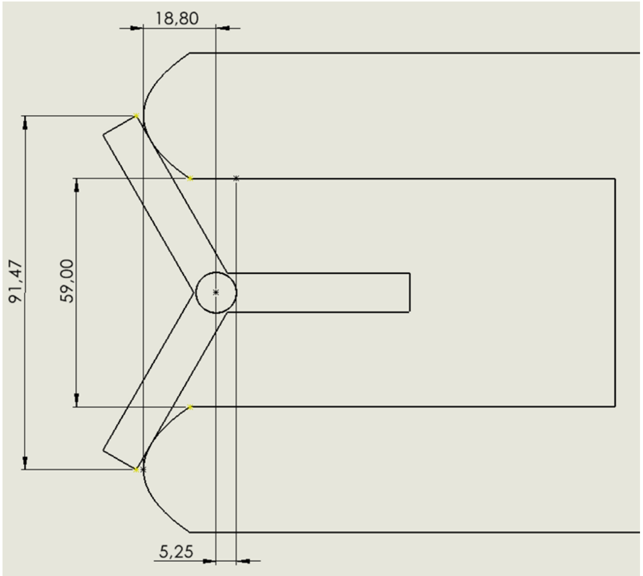


Figure 5.1: Schematic of limitation 1

Limitation 2 - Absence of vertical clearance

The TLP has a freeboard of 18 metres after it has been installed (See Table 5.2), resulting in a draught of 12 metres for the upper part of the pontoons. This is equivalent to the minimum draught of the PS. Therefore, no clearance can be realised between the PS and the TLP platform during the mating procedure of the WTG and TLP with the TLS (See Figure 5.2). Hence, this procedure has to be executed by the 5000t crane.

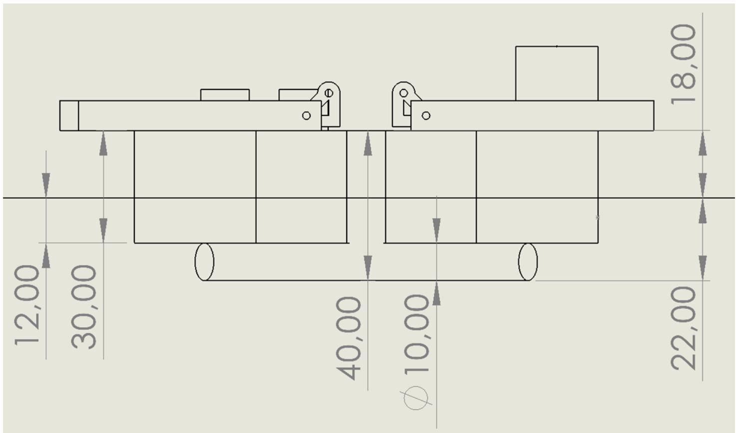


Figure 5.2: Schematic of limitation 2

Limitation 3 - Barge extension

The Iron Lady has to be moored to the port side of the PS for the installation procedures with the 5000t crane. Normally, the Iron Lady is moored with sufficient contact area to the port side of the PS so that the environmental loads acting on the barge are reduced due to shielding effects and because it enables the design of a suitable mooring arrangement that can evenly distribute the environmental loads *[73]*. However, in Concept 11 the Iron Lady will be extended from the Pioneering Spirit's stern to reduce the lifting radius of the 5000t crane. According to *[73]*, there are multiple mooring solutions that could in principle be used for an extending barge configuration (See Section 5.1.3). In the storyboards, an extension piece of 20 metres is mounted on the stern of the Pioneering Spirit as an illustration (See Figure 5.3). However, the development of a feasible design is beyond the scope of this paper.

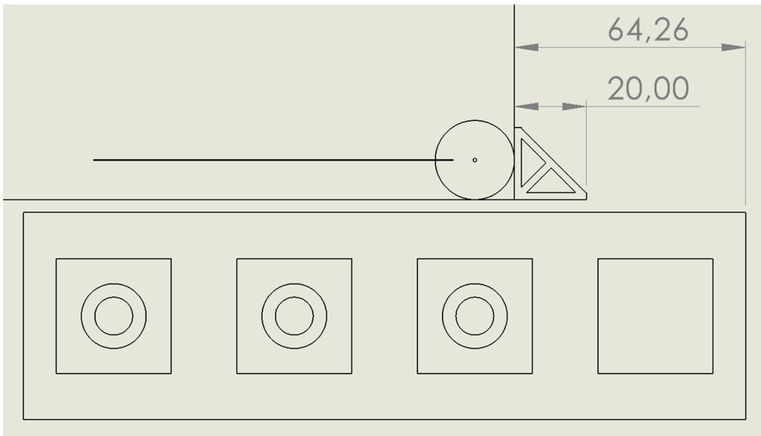


Figure 5.3: Schematic of limitation 3

Limitation 4 - Complex lifting operation

The wind turbines will be lifted by the 5000t crane from the Iron Lady with the rotor pointing away from the Pioneering Spirit. After the first two components have been unloaded, the Iron Lady has to be rotated 180 degrees before it can be moored to the Pioneering Spirit due to limitation 3. Therefore, the WTGs are placed on the Iron Lady in the configuration as depicted in Figure 5.4.

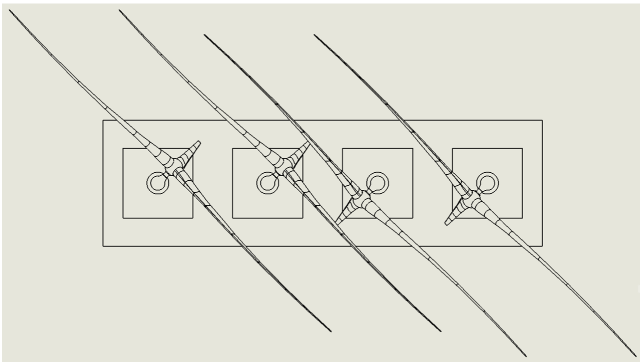


Figure 5.4: Loading configuration for WTGs on the Iron Lady for crane installations

It can be observed that there is little spacing left between the WTGs in the middle of the Iron Lady. Thus, a potential collision of the structures during the lifting operation has to be excluded for safety reasons. Different orientations of the lifting operation for the most critical lift are illustrated in Figure 5.5.

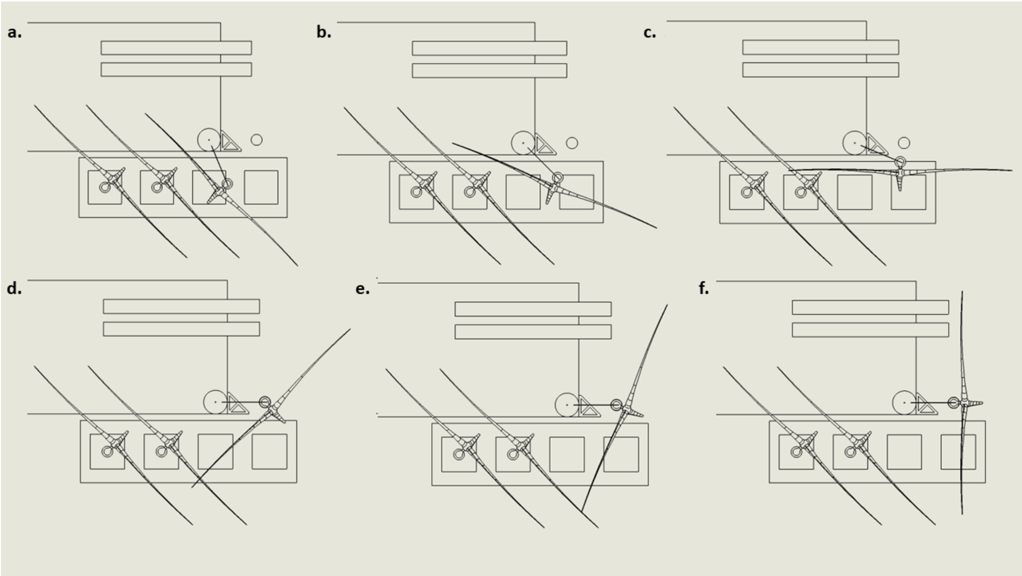


Figure 5.5: Various orientations during the lifting of a 15-MW WTG with the crane

Orientations c, d and e show that there is an overlap of the wind turbine blades. These overlapping parts do not coincide but are located above each other as shown in Figure 5.6.

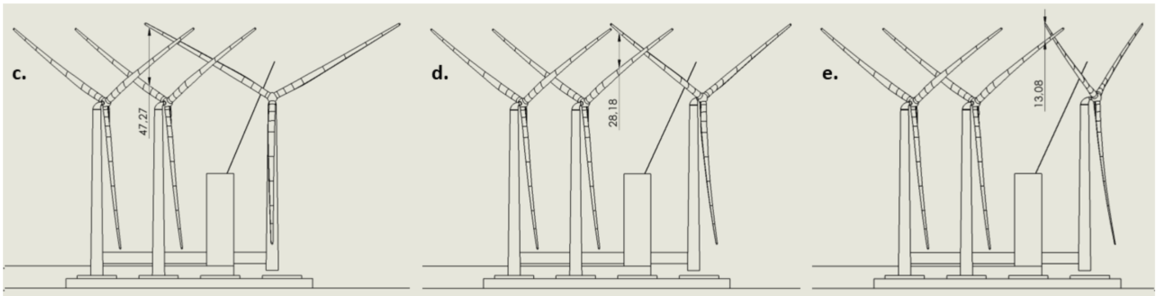


Figure 5.6: Vertical clearance between the overlapping parts during a lifting operation of a 15-MW WTG with the crane

From this Figure, it can be concluded there is sufficient clearance so that all WTGs can be lifted safely from the Iron Lady with the loading configuration shown in Figure 5.4. However, this lifting operation will be extremely complex with a low tolerance for the motion of the crane load or the vessels.

Limitation 5 - Operational limit of 5000t Crane

A gap space of 3.6 metres is left between the PS and IL for the installation procedures of the spars or wind turbines with the 5000t crane. This gap is reached by placing a single Yokohama (See Figure 5.7) in between them *[73]*. The spars and wind turbines are placed on the centreline of the barge and are positioned at the smallest distance from the crane boom's pivot point during every unloading operation. This results in a minimal required lifting radius of 37.4 metres. The maximum lifting height that corresponds to this radius for structures with a weight of 2000 tonnes or more, together with the required upgrade for lifting 15-MW spar structures and wind turbines are provided in Section E.2.1.1 of the confidential Appendix E. The required lifting height has been estimated by accounting for the assumed height of the grillage, clearance, and rigging of 2.5, 4.0, and 10.0 metres respectively. To conclude, the original 5000t crane is not capable of lifting the 15-MW spar or wind turbine from the Iron Lady and thus an upgrade is needed.

Limitation 6 - Increasing gap space

As described in the previous limitation, a gap space of 3.6 metres can be achieved with a single Yokohama. However, for the installation procedure of the TLPs with the 5000t crane, this gap has to be increased because the pontoons are sticking out of the barge. It has been assumed that a clearance of 2 metres between any part of the TLP and the PS is sufficient, resulting in a gap of approximately 13.6 metres (See Figure 5.8). This can be realised by coupling multiple Yokohamas as can be seen in Figure 5.7. Whether 2 metres clearance is sufficient so that the structures will not collide has to be determined in another study.

Figure 5.7: Triangular Yokohama connection *[65]*

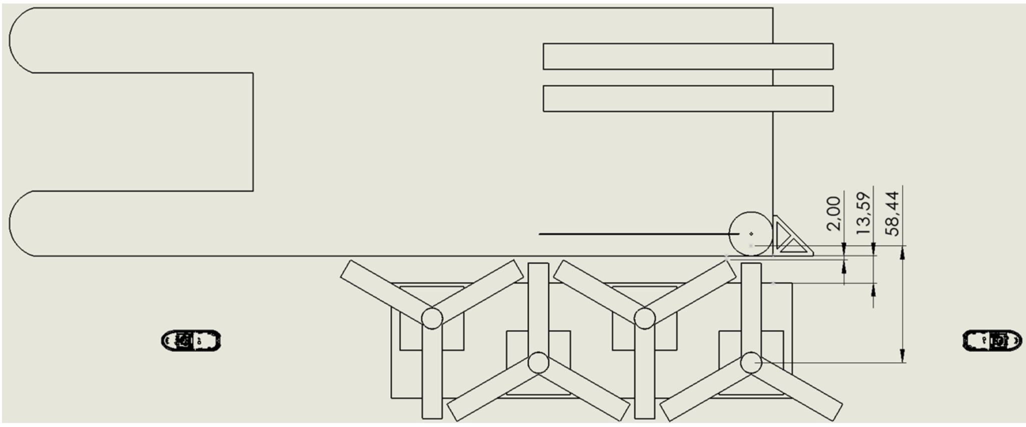


Figure 5.8: Schematic of limitation 6

Limitation 7 - Non-adjustable vessel heading

During the installation of the spar-type floating wind turbine, the PS can adjust its heading to eliminate the effect of the wave direction on the vessel motions. However, this is not possible for the installation of the TLP wind turbine due to limited clearance as a result of the large pontoon length. Therefore, the wind turbine and TLP foundation must be installed as depicted in Figure 5.9. With visualisation a. showing a side view of the wind turbine installation and b. the top view of the TLP floater installation. This limitation could be mitigated either by changes in characteristics of the TLP floater (e.g. design draught or pontoon length) or by upgrading the 5000t crane to increase the lifting radius. Nevertheless, the feasibility of these mitigations should be analysed in another study and are thus not considered in the development of the storyboards.

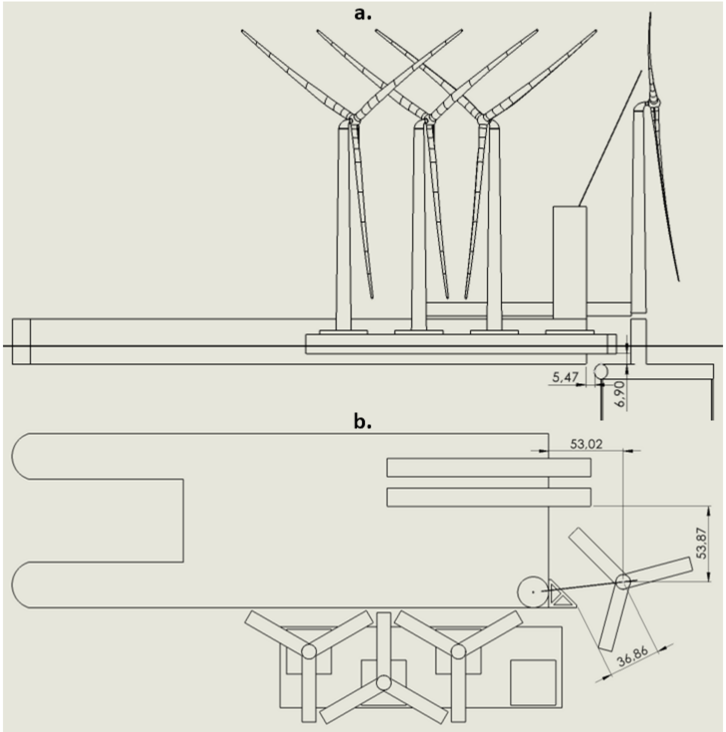


Figure 5.9: Schematics of limitation 7

5.1.1.4. Storyboard Concept 1

Installing floating wind turbines with TLP foundations will not be possible with the TLS due to limitations 1 and 2. Therefore, Concept 1 can only be used for the installation of spar-type floating wind turbines. The storyboards for the installation procedures are depicted in the following order:

- Installation of spar foundations - Figures 5.10 and 5.11
- Installation of WTGs onto spar foundations - Figures 5.12 and 5.13.

A description of the steps performed in the first storyboard (installation of spar foundations) is given below.

1. Four spar foundations are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation site by two tugs (located behind each other in Figure 5.10).
3. The IL is moved into the slot of the PS and the mooring system is connected.
4. The spar foundations are lifted sequentially. First, the sea fastening is disconnected from the spar when the TLS (4 FLUs per spar) is connected to it. Thereafter, the spar is lifted over a height of 4 metres.
5. The IL is towed out of the slot after the mooring lines are uncoupled. Subsequently, the PS sails to the location where the first spar (located closest to the bow of the Pioneering Spirit) is installed by lowering and ballasting the spar simultaneously (See Section 5.1.3).
6. When the design draught is reached, the TLS can be uncoupled and the pre-installed mooring lines can be connected to the spar with underwater ROVs followed by a move-out and transit to the next location.
7. See Step 5.
8. See step 6.
9. By rotating the IL 180 degrees and repeating Step 3, the remaining two spars can be unloaded with the TLS. After unloading and unmooring the IL, it can be towed back to shore.

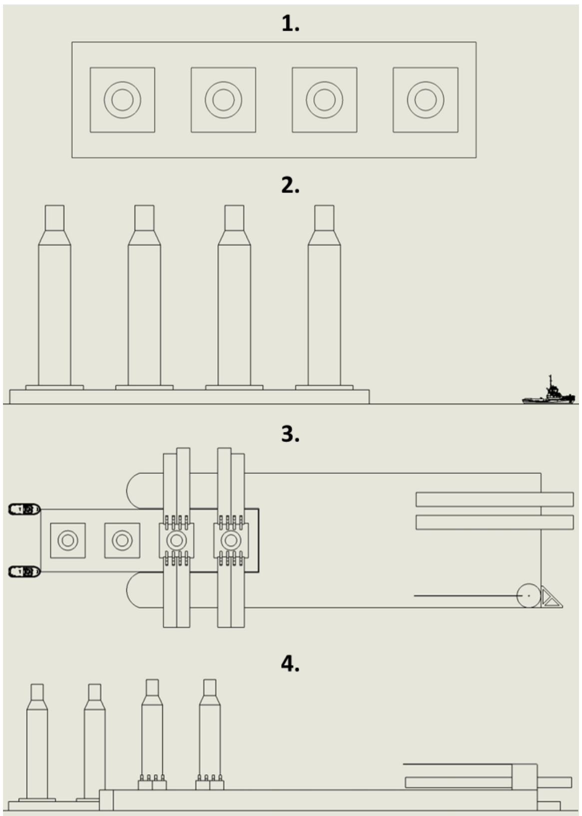


Figure 5.10: Storyboard visualising the first 4 steps for the installation of spar foundations with Concept 1

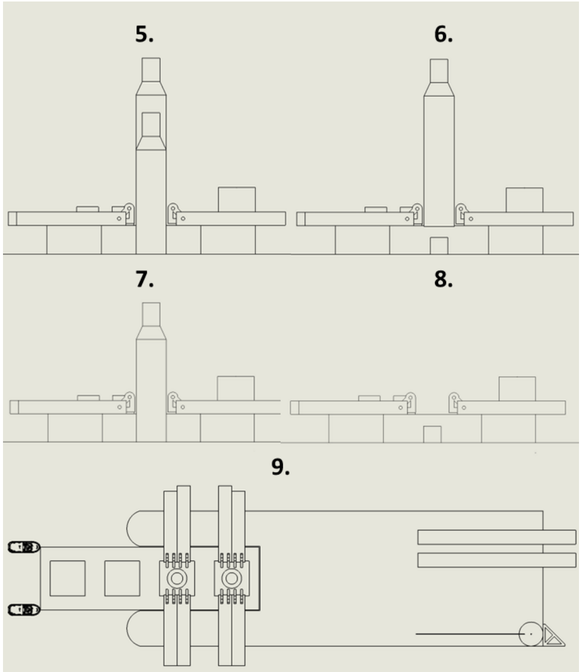


Figure 5.11: Storyboard visualising the last 5 steps for the installation of spar foundations with Concept 1

The steps for the second storyboard (installation of WTGs onto spar foundations) include the following:

1. Four WTGs are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation location by two tugs (located behind each other in Figure 5.12).
3. The IL is moved into the slot of the PS and the mooring system is connected.
4. The WTGs are lifted sequentially. First, the sea fastening is detached from the WTG when the TLS (4 FLUs per spar) is connected to it. After that, the WTG is lifted over a height of 4 metres.
5. The IL is towed out of the slot after the mooring lines are uncoupled. Subsequently, the PS sails to the location where the first WTG (located closest to the bow of the Pioneering Spirit) has to be installed.
6. The WTG is lowered onto the spar while de-ballasting the structure to maintain its design draught (See Section 5.1.3). When the installation is completed successfully, the TLS can be uncoupled followed by a move-out and transit to the next location.
7. See step 5.
8. See step 6.
9. By rotating the IL 180 degrees and repeating Step 3, the remaining two WTGs can be unloaded with the TLS. After unloading and unmooring the IL, it can be towed back to shore.

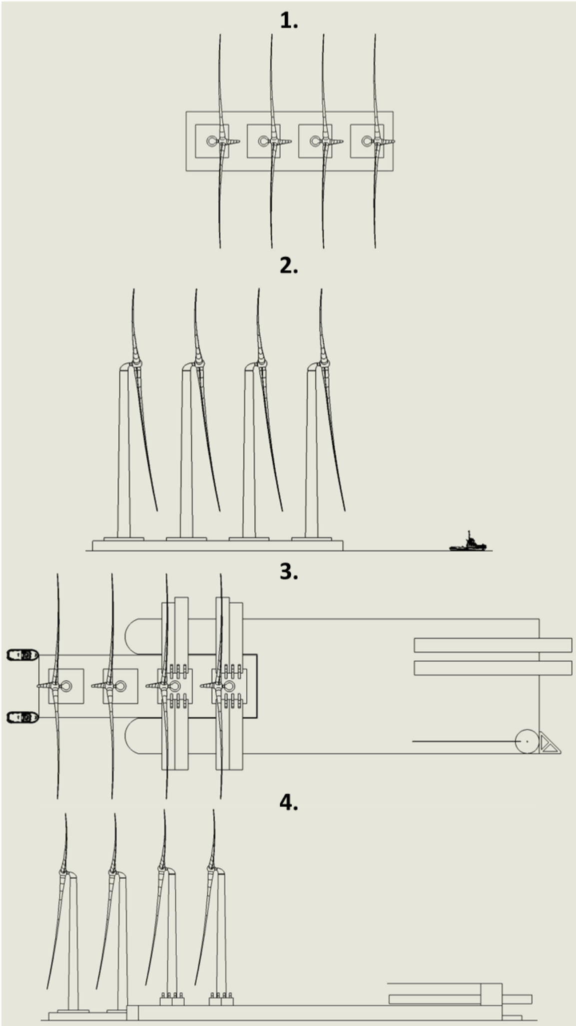


Figure 5.12: Storyboard visualising the first 4 steps for the installation of WTGs on spar foundations with Concept 1

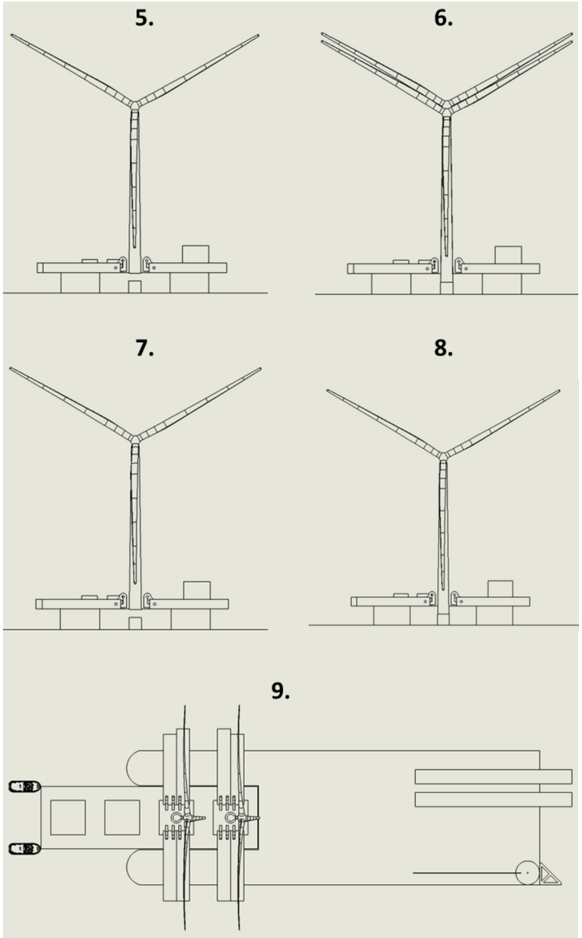


Figure 5.13: Storyboard visualising the last 5 steps for the installation of WTGs on spar foundations with Concept 1

5.1.1.5. Storyboard Concept 11

Concept 11 can be used for the installation of both the spar- and TLP-type floating wind turbines. The storyboards will be presented in the following order:

- Installation of spar foundation - Figures 5.14, 5.15 and 5.16.
- Installation of WTGs onto spar foundations - Figures 5.17, 5.18 and 5.19.
- Installation of TLP substructures - Figures 5.20, 5.21 and 5.22.
- Installation of WTGs onto TLP substructures - Figures 5.23, 5.24 and 5.25.

Only the full installation cycle of the first component is included in each storyboard since the installation steps for the consecutive components are almost identical to that of the first. However, the mooring positions of the barge are different. Therefore, the changes in the barge positions for the various storyboards are shown in Figures 5.16, 5.19, 5.25, 5.25. The radius between the lifting point and the crane boom's pivot point is kept constant for the different barge positions within each storyboards. Below the annotation for the different barge positions is explained.

- i - is the second mooring position in which the IL is shifted more to the stern of the PS.
- ii - refers to the third mooring position in which the IL has been rotated 180 degrees and connected with a similar mooring system as the first configuration.
- iii - represents the last mooring position where the Iron Lady is again shifted more to the aft of the Pioneering Spirit with a similar mooring system as in the second configuration.

Furthermore, the JLS beams are shifted as far to the starboard side of the PS as possible to increase clearance during the lifting operations and avoid potential obstructions or collisions.

An explanation of the steps performed in the first storyboard (installation of the spar foundations) is provided below.

1. Four spar foundations are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation site by two tugs (located behind each other in Figure 5.14).
3. The IL is moored to the port side of the PS.
4. When the rigging is connected to the spar, the sea fastening can be removed and the spar can be lifted from the IL until a clearance of 4 metres is reached.
5. The 5000t crane's base rotates while Keeping the lifting radius and height constant so that the spar is positioned above the seawater and near the pre-installed mooring lines.
6. The spar is lowered and ballasted simultaneously until the design draught is reached (See Section 5.1.3). Subsequently, the mooring lines can be connected by ROVs. Eventually, the IL and PS can sail to the next location after disconnection of the rigging from the structure and uncoupling of the mooring lines from the IL. Upon arrival, the steps can be repeated with the other mooring positions of the IL.

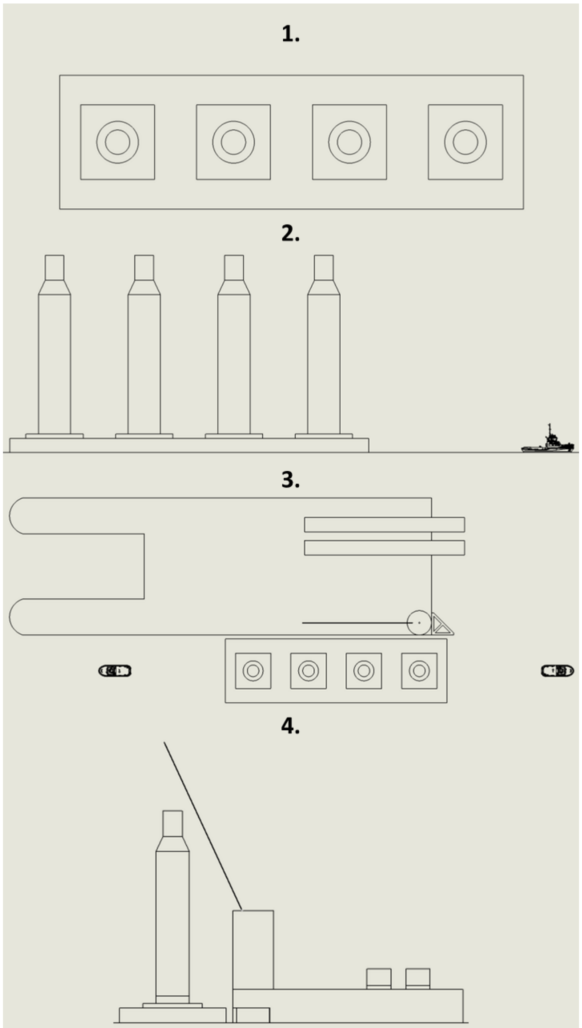


Figure 5.14: Storyboard visualising the first 4 steps for the installation of spar foundations with Concept 11

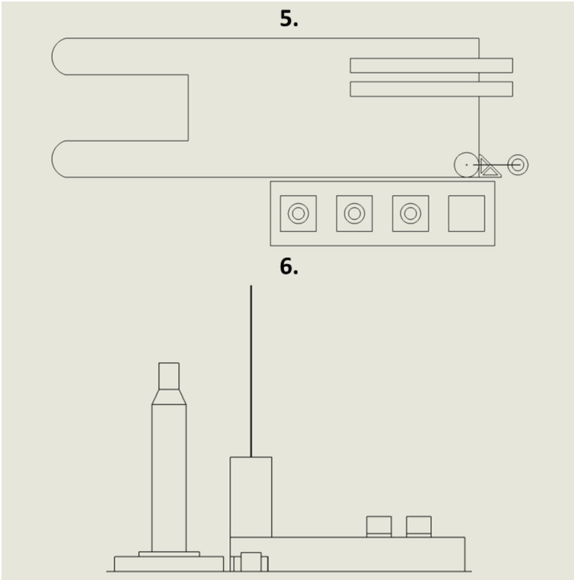


Figure 5.15: Storyboard visualising the last 2 steps for the installation of spar foundations with Concept 11

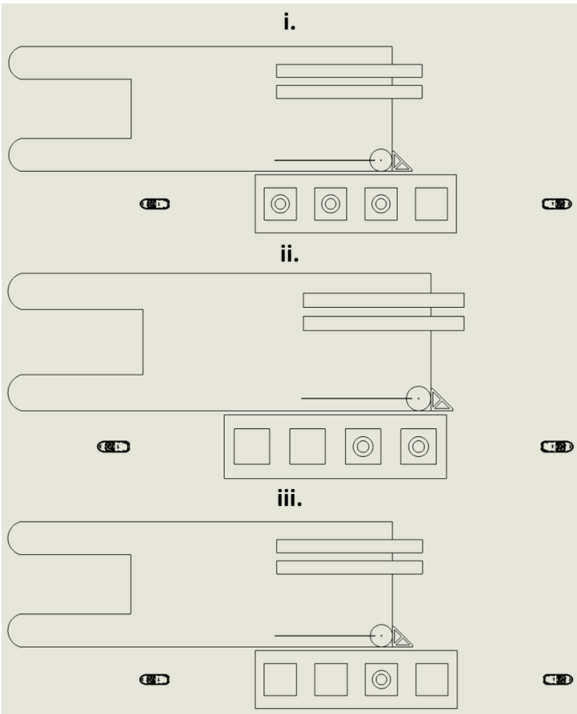


Figure 5.16: Different barge positions for the installation of spar foundations with Concept 11

The steps for the second storyboard (installation of WTGs onto spar foundations) are the following:

1. Four WTGs are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation location by two tugs (located behind each other in Figure 5.15).
3. The IL is moored to the port side of the PS.
4. When the rigging is connected to the WTG, the sea fastening can be removed and the WTG can be lifted from the IL until a clearance of 4 metres is reached.
5. Both the 5000t cranes base and the wind turbine rotate while keeping the lifting radius and height constant so that the WTG is positioned above the pre-installed spar as depicted in the Storyboard. Also

see Figures 5.5 and 5.6 for more visualisations related to this operation and the relevant clearances between the wind turbine components.

6. The WTG is lowered onto the spar while the structure is being de-ballasted to maintain its design draught (See Section 5.1.3). Eventually, when the operation is completed successfully, the IL and PS can sail to the next location after disconnection of the rigging from the structure and uncoupling of the mooring lines from the IL. Upon arrival, the steps can be repeated with the different mooring positions of the IL.

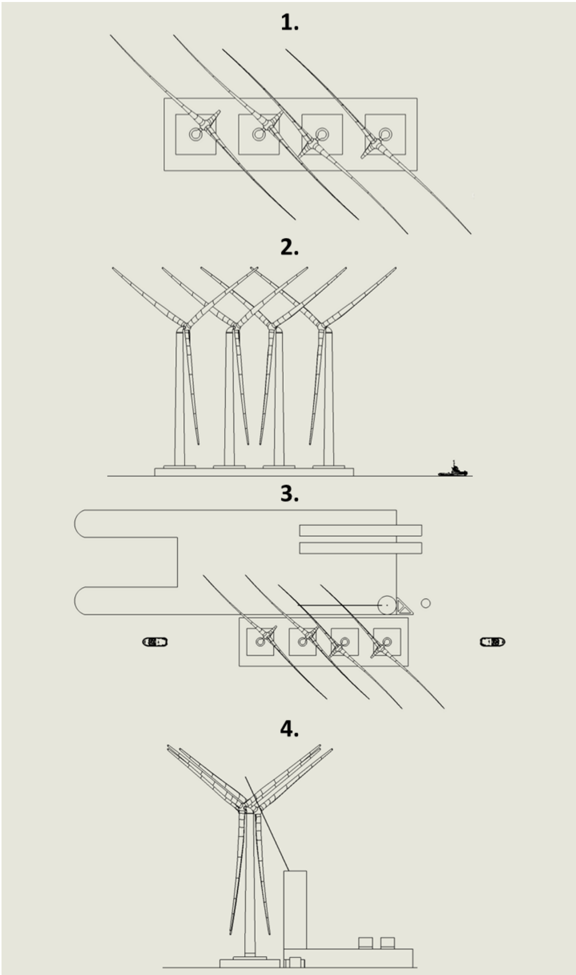


Figure 5.17: Storyboard visualising the first 4 steps for the installation of WTGs on spar foundations with Concept 11

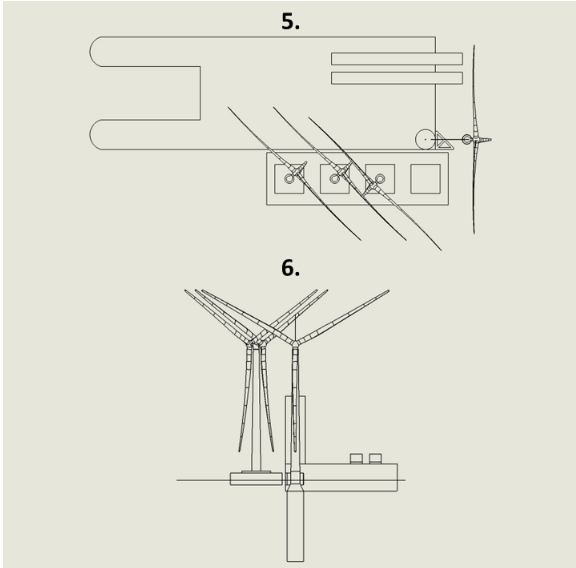


Figure 5.18: Storyboard visualising the last 2 steps for the installation of WTGs on spar foundations with Concept 11

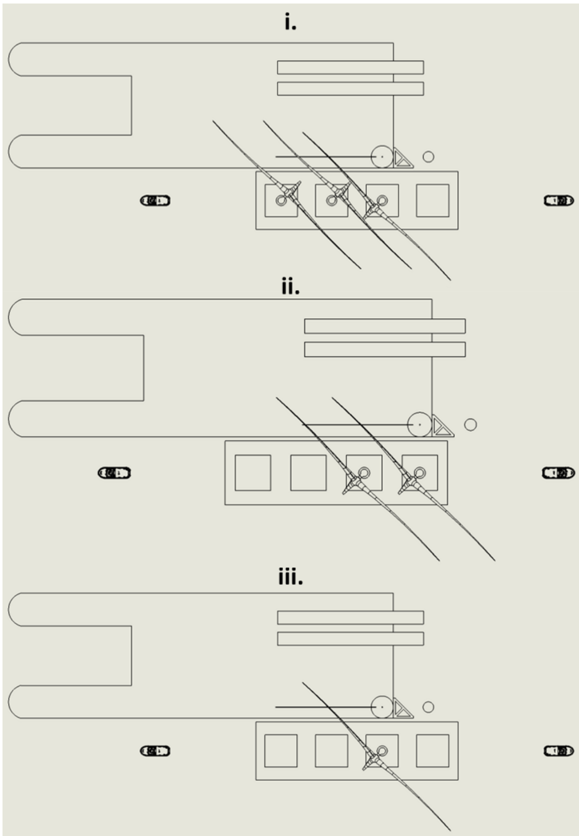


Figure 5.19: Different barge positions for the installation of WTGs on spar foundations with Concept 11

The procedure for the installation of TLP floaters with Concept 11 consists of the steps that are addressed below.

1. Four TLPs are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation site by two tugs (located behind each other in Figure 5.20).
3. The IL is moored to the port side of the PS.

4. After the rigging is connected, the sea fastening can be removed and the TLP can be lifted from the IL until a clearance of 4 metres is reached.
5. Keeping the lifting height and radius constant, the crane's base and TLP are rotated to the required position.
6. The TLP is lowered and excessively ballasted with seawater to increase the structure's draught (See Section 5.1.3).
7. The pre-installed mooring lines are connected by an underwater ROV.
8. The mooring lines are tensioned by de-ballasting the TLP until the design draught is reached and the structure is stable (See Section 5.1.3). Finally, the structure's rigging and mooring system of the IL can be disconnected followed by the transit to the next installation location. Here, the steps can be repeated with different mooring positions of the IL.

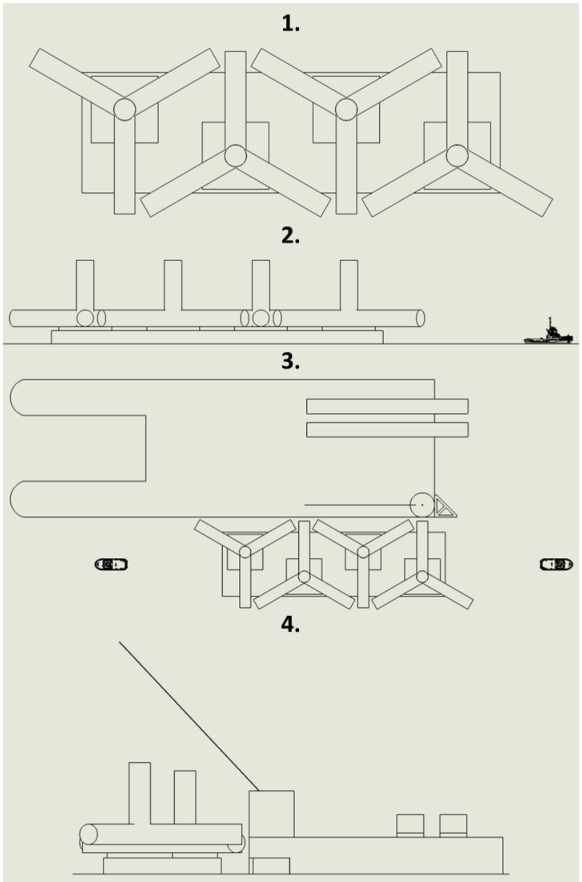


Figure 5.20: Storyboard visualising the first 4 steps for the installation of TLP foundations with Concept 11

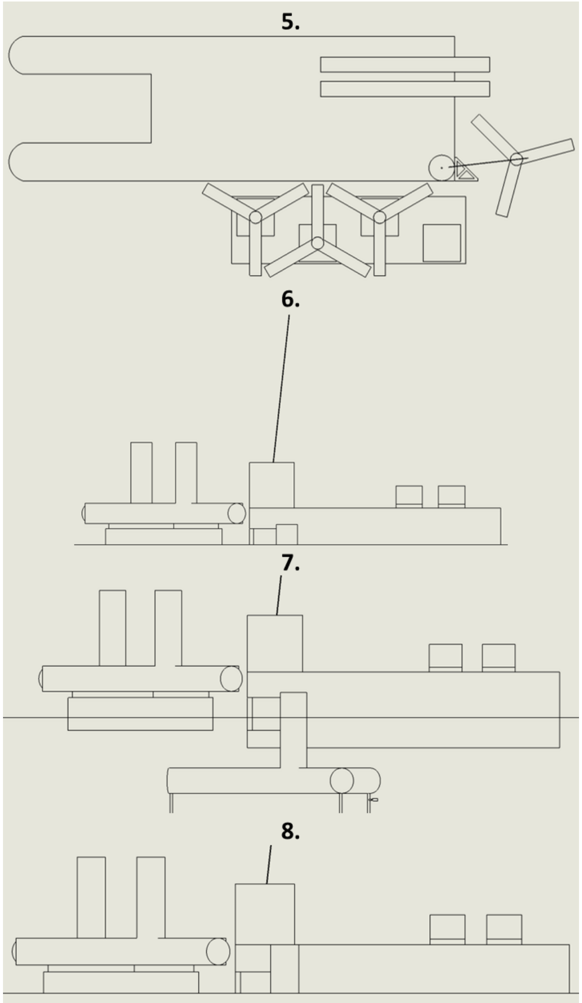


Figure 5.21: Storyboard visualising the last 4 steps for the installation of TLP foundations with Concept 11

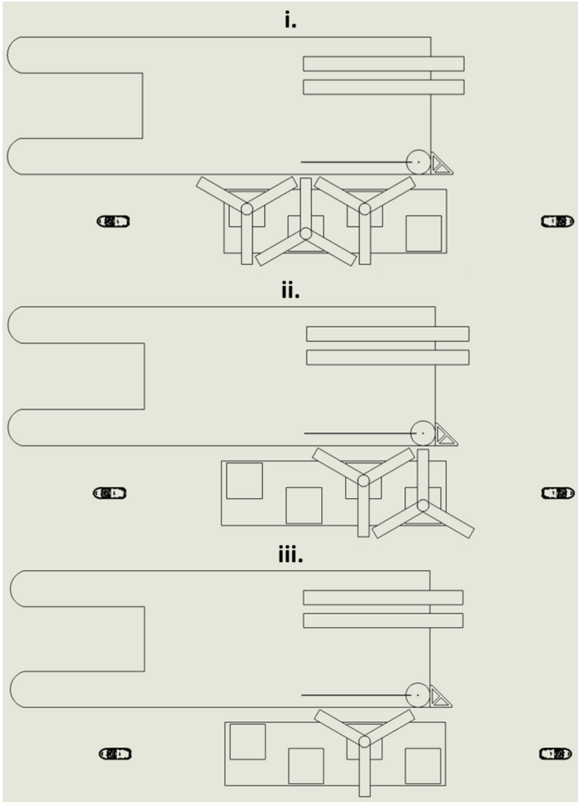


Figure 5.22: Different barge positions for the installation TLP foundations with Concept 11

1. Four WTGs are loaded onto the IL at a port and sea fastened.
2. The IL is towed to the installation site by two tugs (located behind each other in Figure 5.23).
3. The IL is moored to the port side of the PS.
4. When the rigging is connected, the sea fastening can be removed and the WTG can be lifted over a height of 4 metres from the IL.
5. Both the cranes base and the wind turbine rotate while keeping the lifting radius and height constant so that the WTG is positioned above the pre-installed TLP as depicted in the Storyboard. Also see Figures 5.5 and 5.6 for more visualisations related to this operation and the relevant clearances between the wind turbine components.
6. The WTG is lowered onto the TLP and fully de-ballasted afterwards so that the design draught is reached (See Section 5.1.3). Subsequently, the rigging can be disconnected from the structure and the mooring system can be uncoupled from the IL. Finally, the steps can be repeated for the different mooring positions of the IL after arriving at the next installation location.

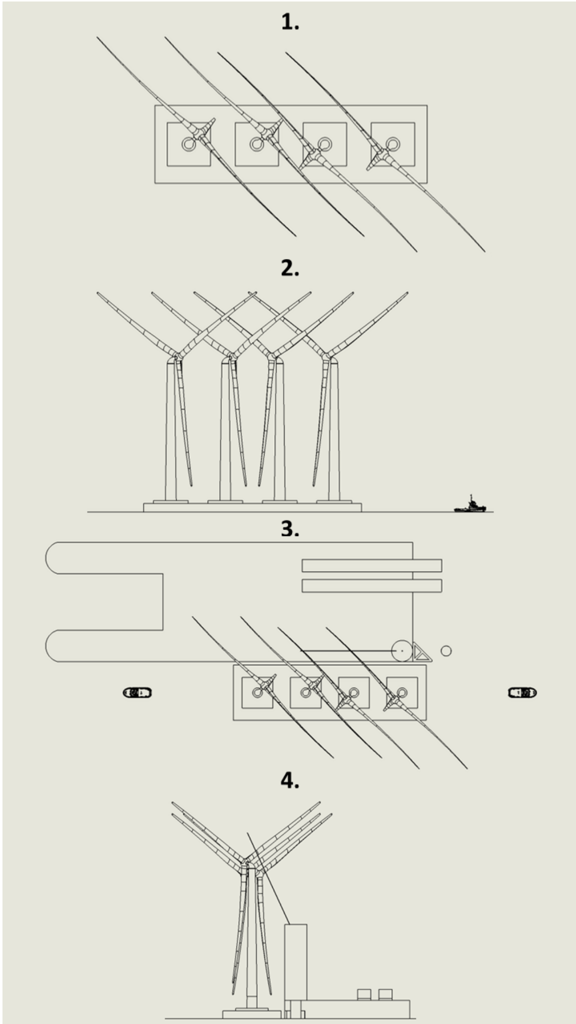


Figure 5.23: Storyboard visualising the first 4 steps for the installation of WTGs on TLP foundations with Concept 11

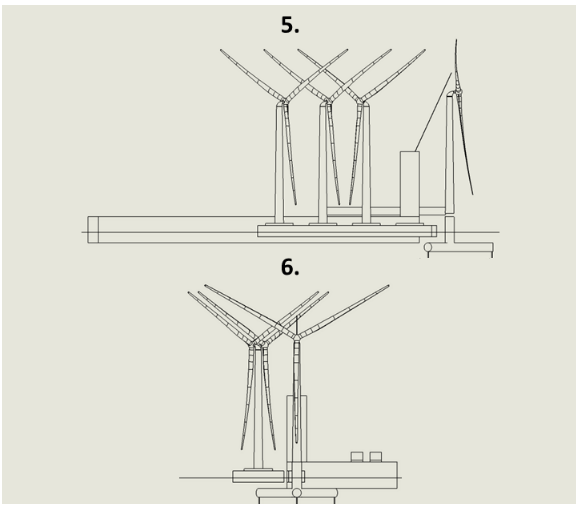


Figure 5.24: Storyboard visualising the last 2 steps for the installation of WTGs on TLP foundations with Concept 11

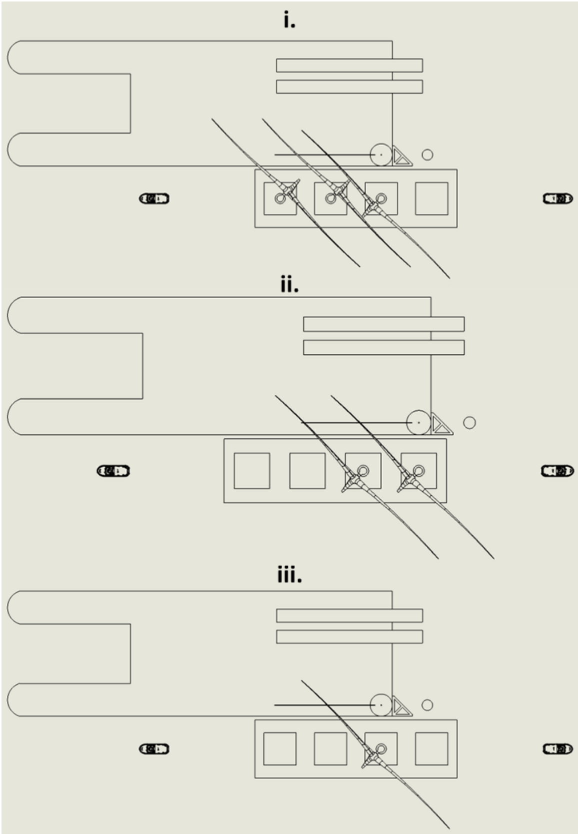


Figure 5.25: Different barge positions for the installation of WTGs on TLP foundations with Concept 11

5.1.1.6. Storyboard Concept 13

As previously described, the installation of the 15-MW TLP-type floating wind turbine will not be possible with this concept design due to the limitations described in Section 5.1.1.3. Therefore, this concept will only be used for the installation of the 15-MW spar-type floating wind turbines. The storyboards are provided in the following order:

- Installation of spar foundation - Figure 5.26
- Installation of WTG on top of the spar - Figure 5.27

The steps for the installation of the spar foundation with Concept 13 are as follows:

1. Two spars are transferred to the TLS of the PS at a port (4 FLUs per spar).
2. The PS sails to the offshore wind farm site.
3. When the PS has arrived at the correct location, the first spar (located closest to the bow of the Pioneering Spirit) can be installed by lowering and ballasting it simultaneously (See Section 5.1.3).
4. The TLS can be uncoupled after the spar is at its design draught and the pre-installed mooring lines are connected by underwater ROVs. Eventually, the PS sails to the next location to install the second spar. This procedure can be repeated after the PS has travelled back to the port.

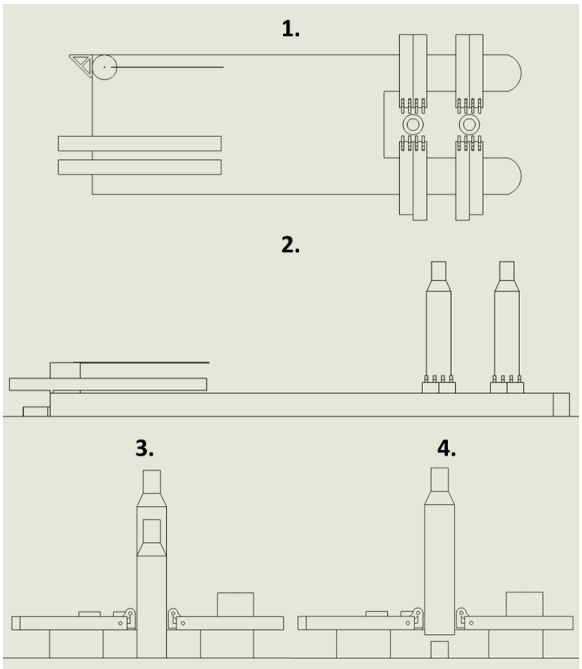


Figure 5.26: Storyboard visualising the 4 steps for the installation spar foundations with Concept 13

The steps for the installation of the WTG on top of the spar are described below.

1. Two WTGs are transferred to the TLS of the PS at a port (4 FLUs per spar).
2. The PS sails to the offshore wind farm site.
3. When the PS has arrived at the correct location and the first WTG (located closest to the bow of the Pioneering Spirit) is positioned above the pre-installed spar, it can be lowered on top of the structure which is simultaneously de-ballasted to maintain its draught (See Section 5.1.3).
4. The TLS can be uncoupled after the installation is completed. Eventually, the PS sails to the next location to install the second WTG. This procedure can be repeated after the PS has travelled back to the port.

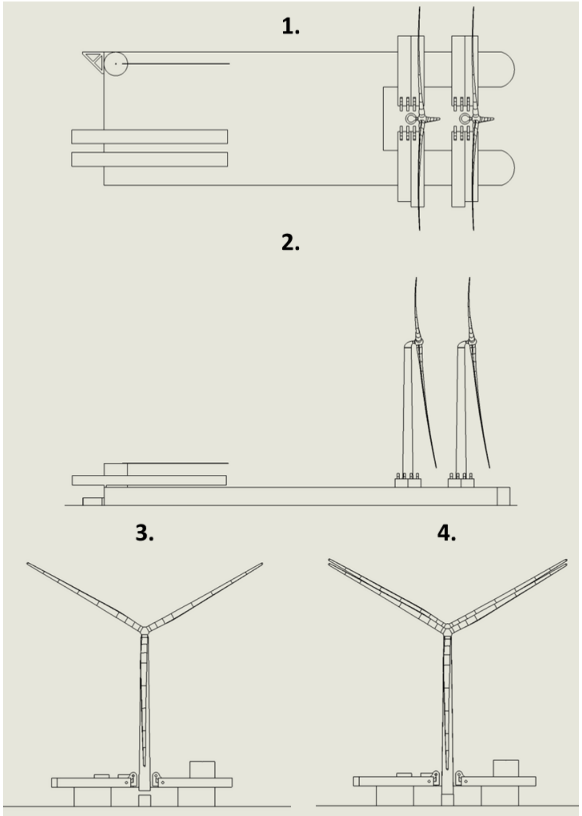


Figure 5.27: Storyboard visualising the 4 steps for the installation of WTGs on spar foundations with Concept 13

5.1.2. Stability Analysis

The stability will only be determined for the Iron Lady since it has been assumed that the Pioneering Spirit has sufficient stability during all offshore operations. As a first approach, the initial stability can be determined by looking at the barge in its upright position. When the centre of gravity (CoG) of a vessel with its load is lower than the metacentre, a vessel is considered initially stable resulting in a positive metacentric height. This relation can be expressed by the following Equation *[10]*.

$$GM = KB + BM - KG > 0 \tag{5.1}$$

GM refers to the metacentric height, KB is the vertical distance between the centre of buoyancy and the keel, BM is the metacentric radius, and KG is the centre of gravity measured from the keel. These components have to be determined for the different load cases of the Iron Lady.

Centre of Buoyancy

The draught of the Iron Lady for all the different load cases is assumed to be 5.1 metres. This value has been based on the draught of the Iron Lady during the transportation of a topside of 20000 tonnes which is approximate twice the weight of the different load cases (See Table 5.4). The buoyancy force is acting upward from the centreline of the Iron Lady at half the draught. Hence, KB is equal to 2.55 metres.

Centre of Gravity

There is a static equilibrium between the total gravitational and buoyancy force when the fully loaded Iron Lady has a draught of 5.1 metres. An expression for this equilibrium is given in the following equation.

$$\rho_w g \nabla = m_{tot} g \tag{5.2}$$

Where,

$$\nabla = L \cdot B \cdot D \tag{5.3}$$

And,

$$m_{tot} = m_{IronLady} + m_{load} + m_{Ballast} \tag{5.4}$$

In these Equations, ∇ refers to the water displacement which is obtained by multiplying the length ("L"), breadth ("B") and draught ("D") of the barge. Moreover, ρ_w is the density of seawater which is approximately 1025 kg/m^3 and g the gravitational acceleration of 9.81 m/s^2. Lastly, $m_{IronLady}$ is the dry weight of the Iron Lady, m_{load} is the total mass of the transported components and $m_{ballast}$ is the weight of the ballast in the tanks. The dry weight of the Iron Lady is determined by assuming that the Iron Lady is a hollow steel structure with a wall thickness of 0.1 metres and a density of 7850 kg/m^3. Furthermore, the total mass of the load can be calculated by multiplying the mass of the 15-MW structures (See Tables 2.3, 5.1 and 5.2) with the loading capacity of the Iron Lady. By substitution, the amount of ballast can be determined per load case. The results are shown in Table 5.4.

Load Case	Load Mass [t]	Iron Lady Mass [t]	Ballast Mass [t]
4 WTGs	9268	23337	27827
4 Spars	10360	23337	26735
4 TLPs	12000	23337	25095

Table 5.4: Mass contributions for different load cases

Subsequently, the vertical CoG of the different components has to be determined in order to compute their contributions to KG. For the Iron Lady and the spar foundation, it has been assumed that the CoG is in the middle of the structure. Moreover, the CoG of the WTG and TLP has been calculated with the following Equation.

$$y_{CoG} = \frac{\sum m_i \cdot y_{CoG,i}}{\sum m_i} \tag{5.5}$$

For the TLP it has been assumed that the mass of the centre column is equal to the mass of a single pontoon and that the CoG is located in the middle of each component as can be seen in Figure 5.28.

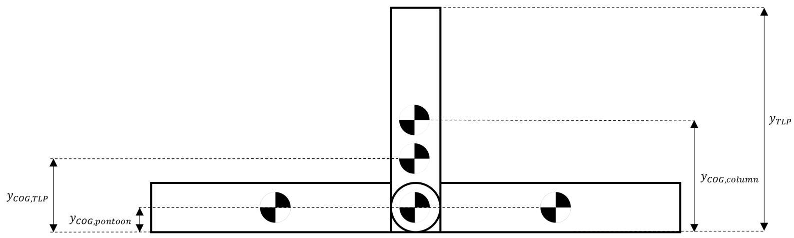


Figure 5.28: Schematic of the centre of gravity positions for a TLP

Furthermore, the CoG of the tower and blades have been assumed to be at 40% and 33% of their total lengths respectively. The nacelle and rotor are considered point masses. Eventually, the CoG location of each component for a fully-assembled wind turbine has to be specified (See Figure 5.29). The hub height of the 15-MW wind turbine has been taken to be 150 metres, but in reality it is smaller due to the freeboard of the floaters. This reduces the hub height to 140 and 132 metres for the spar and TLP wind turbines respectively.

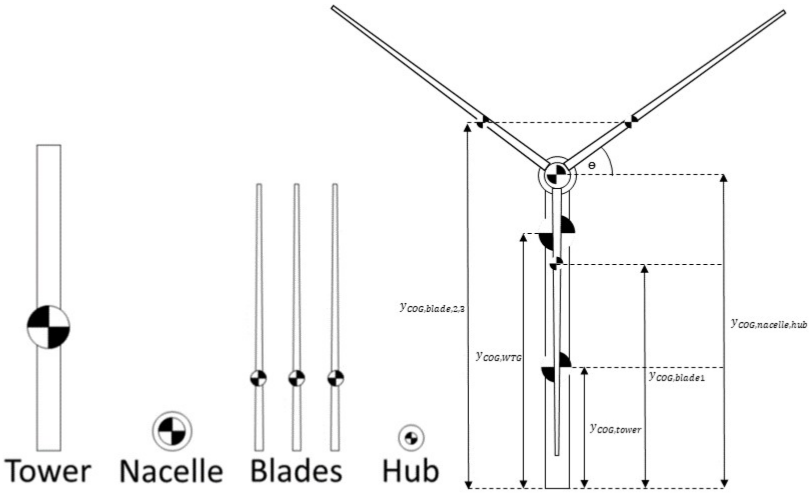


Figure 5.29: Schematic of the centre of gravity positions a wind turbine

The results for the different load cases are shown in Table 5.5, where the vertical CoG of the different components is measured from the Iron Lady's keel. The KG has been calculated with Equation 5.5. Note that the height and weight of the sea fastening has not been taken into account for the initial stability.

Load Case	CoG Iron Lady [m]	CoG Load [m]	CoG Ballast [m]	KG [m]
4 WTGs	6.5	112.5	1.17	20.3
4 Spars	6.5	63	1.12	13.8
4 TLPs	6.5	21.8	1.06	7.3

Table 5.5: Centres of gravity measured from the Iron Lady's keel for different load cases

Metacentric Radius

The metacentric radius is the ratio between the transverse moment of inertia of the waterplane (indicated as I_t in Equation 5.6) to the volume of displaced water. It can be determined with the following Equations.

$$BM = \frac{I_t}{\nabla} \tag{5.6}$$

Where,

$$I_t = \frac{L \cdot B^3}{12} \tag{5.7}$$

Results

Ultimately, the metacentric height GM can be determined by substituting the previously calculated values into Equation 5.1. The results are shown in Table 5.6. It can be seen that all the values for GM are positive, meaning that the Iron Lady is initially stable for the different load cases.

Load Case	KB [m]	BM [m]	KG [m]	GM [m]
4 WTGs	2.55	54.2	20.3	36.45
4 Spars	2.55	54.2	13.8	42.95
4 TLPs	2.55	54.2	7.3	49.45

Table 5.6: Metacentric height of the Iron Lady for different load cases

5.1.3. Technical Description

Ballasting

Spar Foundation - During the installation of the spar foundation, it has to be lowered and ballasted simultaneously by the Pioneering Spirit. First, the structure is ballasted with seawater to keep the spar in a vertical position when it is submerged. The structure's draught is increased to 90 metres by ballasting it with a higher-density material. This will also lower the centre of gravity which increases the structure's stability. Since the wind turbine has to be installed after the spar has been coupled to the mooring lines, the ballast composition consists of both seawater and a heavier material so that final adjustments can be made to the structure's draught by removing the seawater.

When placing the wind turbine on top of the pre-installed spar foundation, it would be fully submerged due to the extra weight. This has to be avoided by de-ballasting seawater out of the spar structure while slowly lowering the wind turbine on top of it. This is both done by the Pioneering Spirit. The ballasting process is finished when all the seawater is pumped out of the spar's hull and the wind turbine is connected to the structure.

Tension Leg Platform - Also for the installation of the TLP, both lifting and ballasting are performed simultaneously by the Pioneering Spirit. The pre-installed mooring system can be coupled to the TLP when the structure is excessively ballasted with seawater until the required draught is reached at which the ROVs are capable of connecting the tendons. Subsequently, it has to de-ballasted so that the design draught of 22 metres is achieved. As a consequence, tension is created in the mooring lines that stabilise the structure. Note that the TLP contains seawater ballast after the installation is completed.

The procedure for the installation of the wind turbine on top of a TLP is expected to be faster in comparison to that of the spar. Due to the highly buoyant structure and excessive tension in the mooring lines, the structure will experience fewer draught effects when the pre-assembled wind turbine is placed on top of it. However, the TLP still has to be fully de-ballasted by the Pioneering Spirit in order to reach the required tension in the mooring lines.

Sea Fastening

In research by Izzo *[44]*, 6 sea fastening concepts for a tower-nacelle assembly of the ALSTOM 6-MW wind turbine were analysed (See Figure 5.30). These solutions may potentially be suitable for the sea fastening of the pre-assembled 15-MW wind turbines. However, the feasibility and scalability of these sea-fastening concepts for 15-MW wind turbines should be assessed in another study.

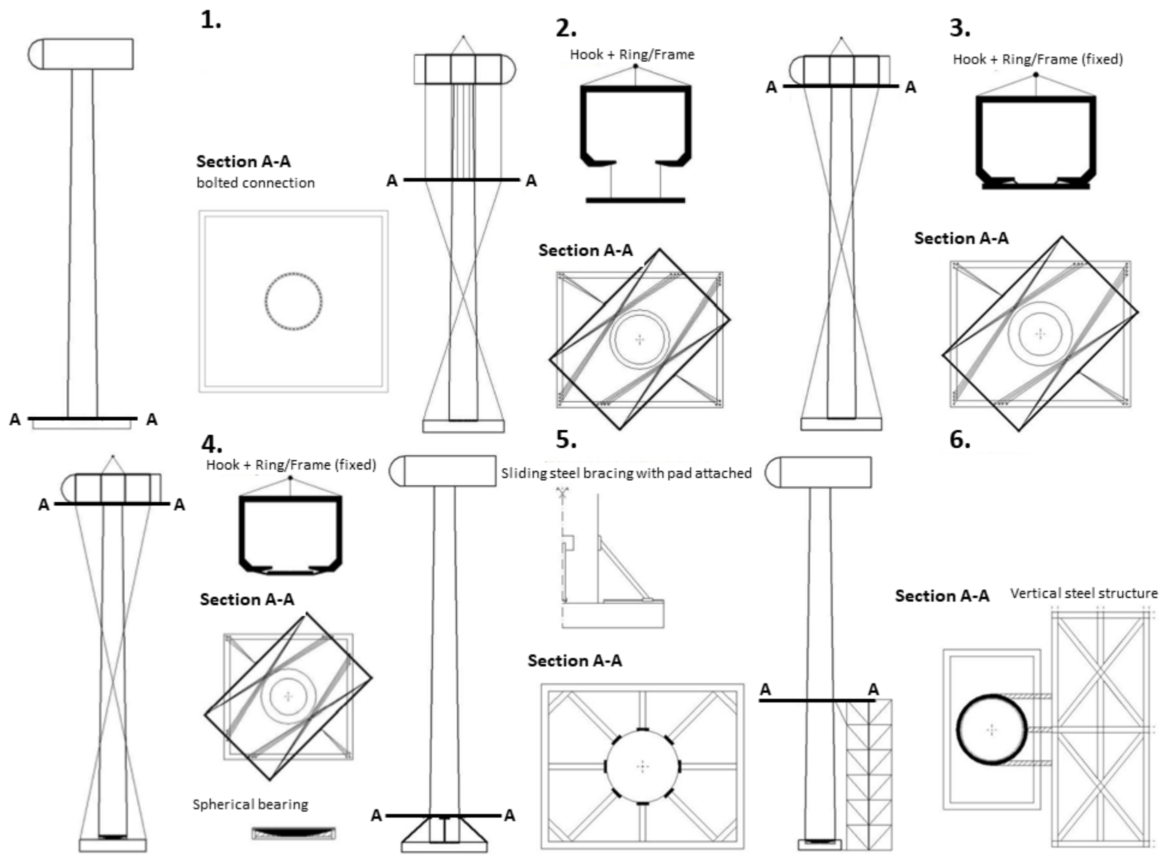


Figure 5.30: Potential sea fastening solutions for transportation of pre-assembled wind turbines *[44]*

Mooring System

In a study conducted by Sinke *[73]*, different mooring systems were analysed to secure the Iron Lady to the Pioneering Spirit. However, more details about this study have been included in Section E.2.2 of the confidential Appendix E since it was under embargo when consulting the source through Allseas' internal database.

Lifting Tools

Topside Lift System - It has been assumed that 8 TLS beams (forming 4 FLUs) are required for the lifting procedure of a single spar or wind turbine. Since lifting operations of single-piled structures with a significant height have never been performed with the TLS, special lifting tools have to be designed that can perform the lifting operations for the spar and WTG. However, the design of such lifting tools is beyond the scope of this research.

5000t Crane - Specially designed rigging has to be made for the lifting of the different structures. Ideally, the rigging reduces the motion of the load during the lifting operation, improving workability. However, the analysis of potential rigging designs for the floaters and wind turbines should be conducted in another study.

Connection

For the connection between the substructures and the wind turbines, a double slip joint may be used (See Figure 5.31). This solution is maintenance-free and requires no manual work which improves the safety of the installation procedure. Due to the weight of the wind turbine, two conical rings are aligned which provide instant stability without needing any bolting or grouting. Furthermore, it decreases the installation time and lowers the costs *[88]*. In this research, it is assumed that the double slip joint can be used for the connection of floating platforms and wind turbines.

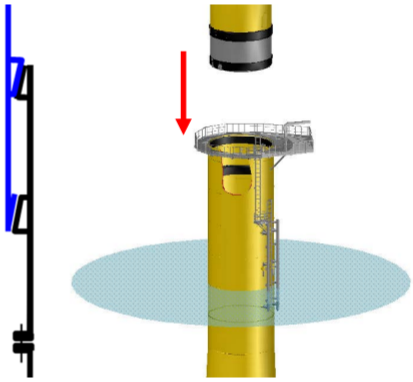


Figure 5.31: Working principle of the Double Slip Joint *[88]*

Additional Equipment

Jiang et al. *[49]* looked into the installation of pre-assembled wind turbines onto spar foundations with a catamaran vessel. This installation method has some similarities to that of the concepts using the TLS. In the research, additional equipment was described that may also be required for the installation procedures with the different concept designs. These different types of equipment are described below.

Gripper - The relative motion between the pre-installed spar and wind turbine should be limited during the mating procedure. Therefore, a gripper could be necessary to eliminate the motion in the x-y plane (See Figure 2.24). However, the structure can still move in the heave, roll, and pitch directions. The heave motion can be compensated by the TLS but not with the 5000t crane. Moreover, adding a second gripper could also limit the structure's pitch or roll motions.

Guiding Beams - The mating process of the wind turbine and foundation is considered a highly complex and accurate procedure. While a lot of motions can be eliminated with grippers, dynamic positioning, and motion compensation systems, it could still be necessary to include guiding beams to increase the tolerance during the mating process. (See Figure 5.32)

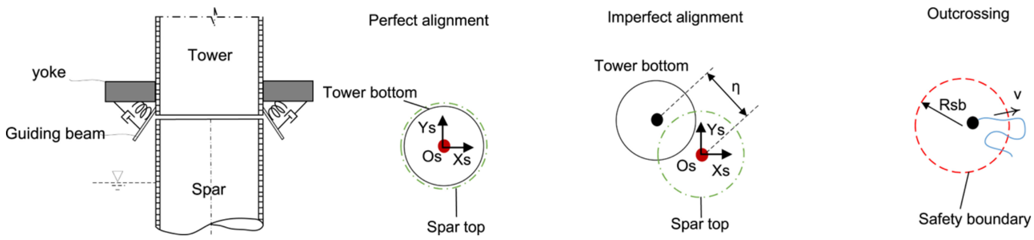


Figure 5.32: Schematic of a guiding beam and the allowable alignment deviation *[49]*

Lifting Yokes - Depending on the method to lift spars or wind turbines with the TLS, a yoke may potentially be placed on every structure. The lifting yoke should serve as an interface between the component and the specially designed lifting tool that is connected to each FLU. It must be capable of handling the forces that are applied during the lifting procedure and distributing these forces to the structure so that no fatigue can occur. Figure 2.24) shows an example of such a yoke.

5.1.4. Concluding Remarks

The technical feasibility analysis shows that the Pioneering Spirit is in principle capable of installing both spar- and TLP-type floating wind turbines with a capacity of 15-MW. Also, the Iron Lady is initially stable for the considered load cases indicating that transportation with a barge is possible. However, numerous studies have to be conducted relating to equipment design and dynamic analysis of structures during various operations in order to guarantee the technical feasibility. Still, the following conclusions can made regarding concepts 1, 11 and 13.

Concept 1

Since Concept 1 transports the components with the barge, it enables the possibility for continuous installation. The barge can be fully unloaded with two mooring operations because the TLS can carry two components simultaneously. Furthermore, the lifting points are within reach of the TLS beams and the four FLUs have a lifting capacity of 24000 tonnes making an upgrade unnecessary. However, installation of 15-MW TLPs is not possible due to the large pontoon length which makes it unable to fit into the slot of the Pioneering Spirit. Also, as a consequence of the design draught of the 15-MW TLP together with the minimum draught of the Pioneering Spirit, insufficient clearance can be obtained during the mating operation of the 15-MW wind turbine and TLP. Lastly, the Pioneering Spirit can adjust its heading prior to both spar and wind turbine installation due to sufficient clearance.

Concept 11

Concept 11 is capable of installing both 15-MW spar- and TLP-type floating wind turbines. Also for this concept continuous installation is possible as a result of transporting the components with a barge. However, four mooring operations are needed to fully unload the barge and an extension piece is required for a feasible mooring configuration. Unlike the TLS, the 5000t crane must be upgraded in order to reach the necessary lifting height for the installation of 15-MW spar foundations and wind turbines. Furthermore, the gap space between the Iron Lady and Pioneering Spirit has to be increased during the TLP installation procedure due to the large pontoon length. In contrast to the installation of spar-type wind turbines, the large pontoon length also makes it unable to adjust the vessel's heading prior to installation. Lastly, the lifting operation of the wind turbines is highly complex with a low tolerance for motions due to limited clearance.

Concept 13

Concept 13 uses the Pioneering Spirit for both transportation and installation of the components. As a consequence, continuous installation is not possible. However, since the components are transferred to the TLS at a port, fewer offshore operations are performed. Moreover, in all other respects the technical feasibility is similar to that of Concept 11.

5.2. Workability Assessment

The workability of the installation procedures with the concept designs will be estimated by first determining the environmental limits for the different operations. The environmental conditions that will be included in the analysis are related to waves and wind because it is expected that these will have the greatest impact on workability *[15]*. The current speed and direction are disregarded in this analysis. Furthermore, the operations that will be considered are transportation, barge (un-)mooring, unloading, and installation. Normally, different steps with corresponding environmental limits are performed during each operation. However, for this workability evaluation, only the environmental limits associated with the most critical step were taken for each operation.

The environmental limits for transportation and (un-)mooring are estimated based on data obtained from previous projects executed by Allseas and are listed in Section E.3 of Appendix E.

Here, no distinction was made between the transportation with the Pioneering Spirit or the Iron Lady and between the differences in the mooring locations of the Iron Lady to the Pioneering Spirit. Furthermore, it has been assumed that the significant wave height and wind speed limits associated with these operations hold for all wave and wind directions. Also, these limits are considered permissible regardless of the occurring wave periods.

The significant wave height and wave period limits for unloading and installation are determined based on the 3-hour most probable maximum single amplitude (MPMSA) heave motion of the lifting points in different sea states and for all wave directions. It has been assumed that this value should be lower or equal to 1 metre to ensure safety for both TLS and 5000t crane lifting operations. The 3-hour MPMSA heave motion is determined with a model that Allseas provided. The model translates specific input values such as a predetermined range of wave periods and wave directions together with a certain significant wave height into a wave spectrum. In this model, a water depth of 200 metres has been taken and a JONSWAP wave spectrum has been considered. However, there could be variations in both the water depth and wave spectrum depending on the offshore location. Subsequently, the motion response spectrum of the Pioneering Spirit can be obtained from this wave spectrum with the following Equation:

$$S_z(\omega,\theta,k) = |RAO(\omega,\theta,k)|^2 \cdot S_\zeta(\omega,\theta) \tag{5.8}$$

In this Equation, $RAO(\omega,\theta,k)$ refers to the response amplitude operator of the Pioneering Spirit. The RAO is a transfer function between the vessel motions and a certain wave characteristic for different degrees of freedom (DOFs). The RAOs were obtained by pre-calculating the first-order motion response of the Pioneering Spirit to different wave conditions (e.g. wave height, period and direction) with the hydrodynamic software package ANSYS AQWA. In this case, the RAO is the ratio between the vessel motion amplitude and the wave amplitude for different DOFs which is expressed in the Equation below.

$$RAO = \frac{z_a(\omega,\theta)}{\zeta_a(\omega,\theta)} \tag{5.9}$$

In which $z_a(\omega,\theta)$ is the motion amplitude and $\zeta_a(\omega,\theta)$ is the wave amplitude for different wave frequencies and directions. By inserting the coordinates of the lifting points into the model, a reliable prediction of the expected maximal motion of these lifting points in different sea states and for various wave directions can be made. The coordinates of the lifting points and the definition of the reference system are included in Table F.1 and Figure F.1 of Appendix F. The operational limits regarding the unloading and installation of components with Concepts 1 and 13 are based on the lifting point that is located closest to the vessel's bow. While in reality, these lifting points are different since the TLS can carry two components simultaneously. The 3-hour MPMSA heave motion of the lifting points has been determined for all wave directions, wave periods between 4.0 and 20.0 seconds with intervals of 0.5 seconds, and significant wave heights between 1 and 5 metres with intervals of 1 metre (See Appendix E). The resulting sea state limits for the different installation procedures are shown in Appendix E. Note that contributions of the other vessel motions to the 3-hour MPMSA heave motion have been included by the model.

It can be observed that the significant wave height and wave period limits are equal for the unloading and installation of spars and WTGs with Concepts 1 and 13. This can be explained by the position of the lifting points with respect to the vessel's CoG which is the same for both operations and structures. Also, the limits are higher for the unloading and installation operations of the spar-type floating wind turbine in comparison to that of the TLP-type. Since the PS can adjust its heading in all directions before unloading or installing the spar-type wind turbine, which is not possible for the TLP-type due to limited clearance as a result of the large pontoon lengths. Therefore, the sea state limits for the installation of TLP-type wind turbines apply to all wave directions and the limits for the spar-type wind turbine to a wave direction of 180 degrees (See Figure 5.33). Lastly, no limits are presented for the unloading operation with Concept 13 because the components are loaded onto the TLS at a port.

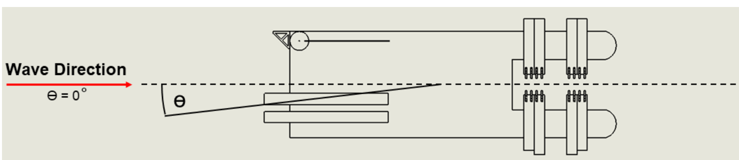


Figure 5.33: Reference system for the wave heading relative to the Pioneering Spirit's centreline

Still, this model does not take wind speed into account. Therefore, the wind speed limits are estimated based on values provided in the literature and past projects provided by Allseas (See Appendix E). In the literature, values between 7 and 20 m/s were found for the wind speed limits of blade or nacelle installation with jack-up vessels *[58] [78]*. In this analysis, the following wind speed limits are considered.

- $V_w \leq 15 m/s$ for the unloading and installation of the floaters.
- $V_w \leq 12 m/s$ for the installation of the WTGs.

These limits hold for all wind directions and the annual probability of wind speeds up to 12 m/s is linearly scaled with the data from Table 2.8.

Subsequently, when the relevant environmental limits are formulated, the workability can be determined by comparing these values to the statistical sea state and wind probabilities at the reference location (See Section 3). These probabilities are included in the scatter diagrams of Appendix C. The results for the workability values as a consequence of the wind speed and sea state limits are shown in Figure 5.7 and 5.8 respectively.

Operation	**Annual Workability**	
	Installation procedure floater	Installation procedure WTG
Transportation	99%	99%
(Un-)mooring	99%	99%
Unloading	91%	73%
Installation	91%	73%

Table 5.7: Annual workability as a result of the wind speed for floater and wind turbine installation procedures

Installation Procedure	Operation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
Concept 1 – Spar and WTG on Spar	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	6%	7%	11%	25%	41%	49%	52%	45%	28%	16%	10%	6%	24%
	Unloading	6%	8%	14%	33%	55%	66%	76%	70%	42%	26%	15%	9%	35%
	Installation	6%	8%	14%	33%	55%	66%	76%	70%	42%	26%	15%	9%	35%
Concept 11 – Spar	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	6%	7%	11%	25%	41%	49%	52%	45%	28%	16%	10%	6%	24%
	Unloading	12%	14%	23%	47%	69%	80%	87%	82%	57%	39%	25%	16%	46%
	Installation	11%	13%	21%	45%	68%	79%	86%	82%	56%	38%	24%	15%	45%
Concept 11 – WTG on Spar	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	6%	7%	11%	25%	41%	49%	52%	45%	28%	16%	10%	6%	24%
	Unloading	13%	15%	23%	47%	70%	80%	87%	83%	58%	40%	25%	16%	47%
	Installation	11%	13%	21%	45%	68%	79%	86%	82%	56%	38%	24%	15%	45%
Concept 11 – TLP	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	6%	7%	11%	25%	41%	49%	52%	45%	28%	16%	10%	6%	24%
	Unloading	1%	2%	3%	8%	21%	28%	35%	33%	14%	7%	3%	2%	13%
	Installation	1%	2%	3%	8%	21%	29%	35%	33%	14%	7%	3%	2%	13%
Concept 11 – WTG on TLP	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	6%	7%	11%	25%	41%	49%	52%	45%	28%	16%	10%	6%	24%
	Unloading	2%	2%	4%	9%	22%	29%	35%	33%	14%	8%	4%	2%	14%
	Installation	2%	3%	5%	13%	31%	41%	49%	44%	21%	11%	5%	3%	19%
Concept 13 – Spar and WTG on Spar	Transportation	38%	43%	56%	81%	89%	95%	95%	94%	83%	66%	54%	44%	69%
	(Un-)Mooring	–	–	–	–	–	–	–	–	–	–	–	–	–
	Unloading	–	–	–	–	–	–	–	–	–	–	–	–	–
	Installation	6%	8%	14%	33%	55%	66%	76%	70%	42%	26%	15%	9%	35%

Table 5.8: Monthly and annual workability resulting from sea state limits for the installation procedures with different Concepts

The overall annual workability can be calculated by taking the product of the sea state and wind workabilities (See Table 5.9).

Installation Procedure	Transportation	(Un-)Mooring	Unloading	Installation
Concept 1 – Spar	68%	24%	32%	32%
Concept 1 – WTG on Spar	68%	24%	26%	26%
Concept 11 – Spar	68%	24%	42%	41%
Concept 11 – WTG on Spar	68%	24%	34%	33%
Concept 11 – TLP	68%	24%	12%	12%
Concept 11 – WTG on TLP	68%	24%	10%	14%
Concept 13 – Spar	68%	–	–	32%
Concept 13 – WTG on Spar	68%	–	–	26%

Table 5.9: Annual workability resulting from wind and sea state limits for installation procedures with different Concepts

5.3. Economic Feasibility

The economic feasibility of the installation procedures with the concept designs will be approached by comparing the estimated installation cost for a reference wind farm construction project. The wind farm site is located at a variable distance from the nearest port where 180 floating wind turbines with a capacity of 15-MW should be installed, resulting in a total capacity of 2.7 gigawatts (GW). Since Concepts 1 and 13 are not capable of installing TLP-type floating wind turbines with a capacity of 15-MW, the spar-type will be considered in this analysis. Moreover, the various planned operational periods (referred to as "T" in Table 5.10) have been estimated based on data from Allseas' past projects in which similar equipment or installation methods were used (See Appendix E). Furthermore, the loading capacity, the possibility for continuous installation, the number of shuttle operations (indicated by "N" in Table 5.10), and the number of operations (denoted by "n" in Table 5.10) that are executed per installation cycle for the different concepts are based on the storyboards (See Sections 5.1.1.4, 5.1.1.5, and 5.1.1.6). All of the previously mentioned particulars are presented in Table 5.10.

Particulars	Concept 1	Concept 11	Concept 13
Loading Capacity [-]	4	4	2
Continuous Installation	✓	✓	✗
N [-]	45	45	90
$T_{loading}$ [h]	3	3	2
$n_{loading}$ [-]	4	4	2
$T_{mooring}$ [h]	2	2	–
$n_{mooring}$ [-]	2	4	–
$T_{unloading}$ [h]	4	11	–
$n_{unloading}$ [-]	4	4	–
$T_{installation}$ [h]	10	18	10
$n_{installation}$ [-]	4	4	2
$T_{unmooring}$ [h]	1	1	1
$n_{unmooring}$ [-]	2	4	–

Table 5.10: Particulars of the installation procedures with different Concepts

Note that this table does not distinguish between planned operational periods for spar or wind turbine structures and that the transportation time is not included since this is a variable. The transportation time will be determined for distances between 0 and 500 kilometres. For this, the average speed of the Pioneering Spirit has been assumed to be the highest economic cruise speed (See Appendix E). Furthermore, the average sailing speed of the Iron Lady has been based on an online database and taken as 8.3 knots *[29]*.

By using the formerly provided information, the total project duration can be calculated with the following Equation.

$$T_{total,(in-)cont.} = 2 \cdot T_{oper.,(in-)cont.} + 2 \cdot T_{trans.,(in-)cont.} \tag{5.10}$$

In this equation, $T_{oper.,(in-)cont.}$ refers to the total duration of all the offshore operations, except for the transportation, for the installation of 180 spar foundations or wind turbines with either continuous or in-continuous installation procedures. It can be determined with the Equations below.

$$T_{oper.,cont.} = T_{loading} \cdot n_{loading} + N \cdot \sum T_i \cdot n_i \tag{5.11}$$

And,

$$T_{oper.,in-cont.} = N \cdot (T_{loading} \cdot n_{loading} + \sum T_i \cdot n_i) \tag{5.12}$$

In which,

$$i = mooring, unloading, installation, unmooring \tag{5.13}$$

$T_{trans.,(in-)cont.}$ represents the contribution of the transportation time to the total project duration of continuous or in-continuous installation procedures. The transit time between installation locations within the wind farm has been disregarded. The following Equations are used for the computation of $T_{trans.,(in-)cont.}$.

$$T_{trans.,cont.} = \frac{2 \cdot s}{v_{sailing,IL}} \tag{5.14}$$

And,

$$T_{trans.,in-cont.} = N \cdot \frac{2 \cdot s}{v_{sailing,PS}} \tag{5.15}$$

The $v_{sailing,IL}$ and $v_{sailing,PS}$ represent the average sailing speed of the Iron Lady and Pioneering Spirit respectively. Furthermore, "s" refers to the distance from the shore to the wind farm site. Subsequently, the total project duration for the installation of the reference wind farm can be plotted as a function of the distance from shore (See Figure 5.34). The intermediate results related to this Figure are included in Figure D.1 of Appendix D.

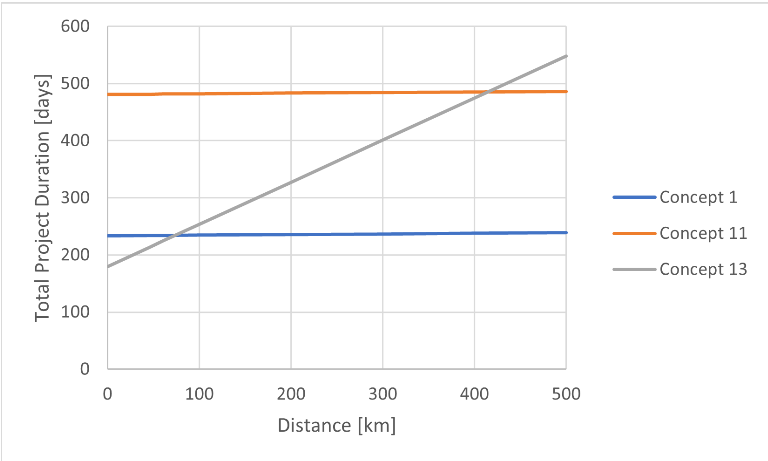


Figure 5.34: Total effective project duration as function of the wind farm location for installation with different Concepts

This Figure shows that the total project duration is hardly influenced by the distance for Concepts 1 and 11. This can be explained by the differences in transportation methods. Due to the transportation with barges and tugs, the Pioneering Spirit can install the foundations or wind turbines continuously in an ideal situation. Therefore, the total project duration of the wind farm will not be influenced by the shuttling operations with the barges, except for the single transit to and from the installation site (See Equation 5.14). Furthermore, Concept 13 seems to be the preferred option for installation sites that are located relatively close to shore, and Concept 1 for wind farm locations surpassing a distance of approximately 75 kilometres.

However, this chart does not take the weather downtime into account as a result of the operational limits. Therefore, the planned operational periods have to be corrected by their annual workabilities (See Section 5.2). The Equation to determine the total project duration corrected by the annual workability is shown below.

$$T_{total,(in-)cont.,cor.} = T_{oper.,(in-)cont.,cor.} + T_{trans.,(in-)cont.,cor.} \tag{5.16}$$

In this Equation, $T_{oper.,(in-)cont.,cor.}$ is the total duration of all the offshore operations, except for the transportation, corrected by their corresponding annual workability for the construction of all spar foundations and wind turbines. Due to workability variations, $T_{oper.,(in-)cont.,cor.}$ can be subdivided into contributions of spar and wind turbine structure installations as shown in the following Equation:

$$T_{oper.,(in-)cont.,cor.} = T_{oper.,(in-)cont.,cor.,spar} + T_{oper.,(in-)cont.,cor.,WTG} \tag{5.17}$$

Continuous installation is possible for Concepts 1 and 11. Therefore, the time for fully loading the Iron Lady has been included once, resulting in the following formulas for the spar and wind turbine contributions to $T_{oper.,cont.,cor.}$:

$$T_{oper.,cont.,cor.,spar} = T_{loading} \cdot n_{loading} + N \cdot \sum \frac{T_i \cdot n_i}{\eta_{i,spar}} \tag{5.18}$$

And,

$$T_{oper.,cont.,cor.,WTG} = T_{loading} \cdot n_{loading} + N \cdot \sum \frac{T_i \cdot n_i}{\eta_{i,WTG}} \tag{5.19}$$

For Concept 13, which installs the components in-continuously, the time for fully loading the Pioneering Spirit is included for every installation cycle. Therefore, the spar and wind turbine installation contributions to $T_{oper.,in-cont.,cor.}$ are calculated with the Equations below.

$$T_{oper.,in-cont.,cor.,spar} = N \cdot (T_{loading} \cdot n_{loading} + \sum \frac{T_i \cdot n_i}{\eta_{i,spar}}) \tag{5.20}$$

And,

$$T_{oper.,in-cont.,cor.,WTG} = N \cdot (T_{loading} \cdot n_{loading} + \sum \frac{T_i \cdot n_i}{\eta_{i,WTG}}) \tag{5.21}$$

In the above Equations for Concepts 1, 11, and 13, $\eta_{i,spar}$ and $\eta_{i,WTG}$ are the annual workability related to spar and wind turbine structures respectively. Also, the subscript refers to the following operations:

$$i = mooring, unloading, installation, unmooring \tag{5.22}$$

Since the workability for the transportation of spar and wind turbine structures is equivalent, the contribution of the transportation time to the total project duration can be calculated with the Equations below.

$$T_{trans.,(in-)cont.,cor.} = T_{trans.,(in-)cont.,cor.,spar} + T_{trans.,(in-)cont.,cor.,WTG} \tag{5.23}$$

With,

$$T_{trans.,cont.,cor.,spar} = T_{trans.,cont.,cor.,WTG} = \frac{2 \cdot s}{v_{sailing,IL} \cdot \eta_{trans.}} \tag{5.24}$$

,

$$T_{trans.,in-cont.,cor.,spar} = T_{trans.,in-cont.,cor.,WTG} = N \cdot \frac{2 \cdot s}{v_{sailing,PS} \cdot \eta_{trans.}} \tag{5.25}$$

In these Equations, $\eta_{trans.}$ is the annual workability for the transportation of the components with either the Pioneering Spirit or Iron Lady. The resulting total project duration for the construction of the reference wind farm, corrected by the annual workability and for variable distances, is shown in Figure 5.35. The intermediate results related to this Figure are included in Figure D.2 of Appendix D.

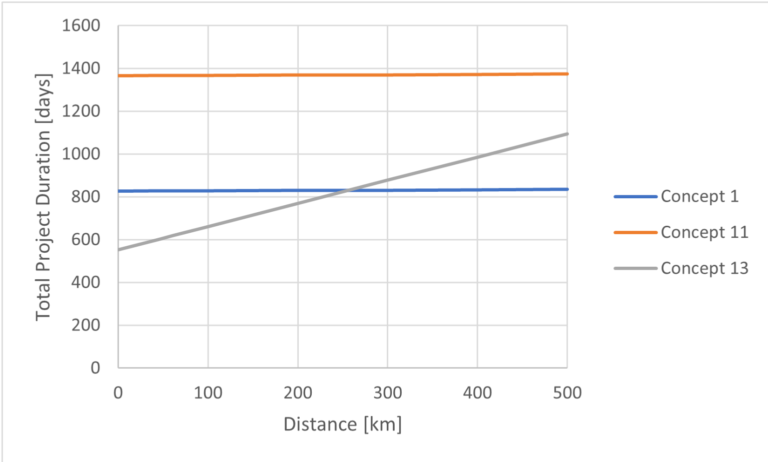


Figure 5.35: Total project duration corrected by weather downtime as function of the wind farm location for installation with different Concepts

When comparing Figures 5.34 and 5.35, it can be observed that the total project duration of Concept 13 is less affected by the weather constraints in comparison to Concepts 1 and 11. This can be expected since the installation procedure of Concept 13 consists of fewer offshore operations, which are susceptible to environmental conditions.

With the total project duration, the total cost for vessel usage can be determined. In addition to the total vessel cost, the expenditure for fuel consumption during all transportation and other offshore operations is also included in the computation of the total installation cost. This results in the following Equation:

$$C_{total,(in-)cont.} = C_{vessel,(in-)cont.} + C_{fuel,trans.,(in-)cont.} + C_{fuel,oper.,(in-)cont.} \tag{5.26}$$

$C_{vessel,(in-)cont.}$ refers to the total cost for operating the required vessels during the full project duration. Therefore, an overview of the number and type of vessels is needed per concept. For all the Concepts, the Pioneering Spirit will be deployed throughout the entire construction period of the reference wind farm. While Concepts 1 and 11 may require additional barges or towing tugs to enable continuous installation. The distance at which a second barge with auxiliary tugs will be required can be calculated with the Equation below.

$$s_{barge2} = \frac{v_{sailing,IL} \cdot (T_{available} - T_{loading} \cdot n_{loading})}{2} \tag{5.27}$$

Where $T_{available}$ is the available time for the Iron Lady to return fully loaded with components at the wind farm site after the final unmooring operation is completed. Since the TLS can carry two structures and the crane one structure after each mooring operation, $T_{available}$ for Concepts 1 and 11 are 20 (twice $T_{installation}$ for Concept 1) and 18 (once $T_{installation}$ for Concept 11) hours respectively. The resulting vessel requirements per concept are shown in Table 5.11. For both concepts, a third barge will not be necessary for distances between 0 and 500 kilometres, since the return time for the Iron Lady is smaller than twice the available time after the last unmooring operation together with the period to complete a single installation cycle.

Concept 1	Concept 11	Concept 13
Pioneering Spirit Barge (2 if s > 61 km) 2 Tugs (4 if s > 61km)	Pioneering Spirit Barge (2 if s > 46 km) 2 Tugs (4 if s > 46km)	Pioneering Spirit

Table 5.11: Vessel requirements for the different concepts

Furthermore, estimations of the day rates are based on values that were found in the literature (See Table 2.2) and are shown in Table 5.12.

Vessel	Day Rate [EUR/day]
Pioneering Spirit	360000
Barge	100000
Tug	15000

Table 5.12: Estimated day rate for the different vessels

The total vessel cost can be calculated by substituting the total project duration together with the vessel requirements and day rates into the following Equation:

$$C_{vessel,(in-)cont.} = T_{total,(in-)cont.} \cdot \sum dayrate_{vessel,i} \cdot n_{vessel,i} \tag{5.28}$$

With,

$$i = PioneeringSpirit, barge, tug \tag{5.29}$$

Moreover, $C_{fuel,trans.,(in-)cont.}$ represents the total cost as a result of the fuel consumption for all the transits to and from the wind farm site during the entire construction period. Again, fuel costs for transport between installation locations within the wind farm have not been taken into account. $C_{fuel,trans.,(in-)cont.}$ can be calculated with the following Equations:

$$C_{fuel,trans.,cont.} = 4 \cdot s \cdot (\frac{\dot{m}_{fuel,trans.,PS}}{v_{sailing,PS}} + \frac{N \cdot (\dot{m}_{fuel,trans.,IL} + 2 \cdot \dot{m}_{fuel,trans.,tug}}{v_{sailing,IL}}) \cdot P_{fuel} \tag{5.30}$$

And,

$$C_{fuel,trans.,in-cont.} = \frac{4 \cdot s \cdot N}{v_{sailing,PS}} \cdot \dot{m}_{fuel,trans.,PS} \cdot P_{fuel} \tag{5.31}$$

In the above Equations, $\dot{m}_{fuel,trans.,PS}$, $\dot{m}_{fuel,trans.,IL}$, and $\dot{m}_{fuel,trans.,tug}$ are the average fuel consumption during transportation for the Pioneering Spirit, Iron Lady, and tug respectively of which the estimations were provided by Allseas (See Appendix E). Furthermore, P_{fuel} is the price per weight of fuel. It has been assumed that the vessels use Marine Gasoil (MGO) as fuel for which the average bunker price in the port of Rotterdam amounted to approximately 800$/t on the date it was adopted *[70]*. $C_{fuel,trans.,cont.}$ is used for Concepts 1 and 11. Note that the fuel consumption of the Pioneering Spirit for these two concepts has been calculated for two shuttling operations since it stays at the wind farm site during the installation of the spar or wind turbine structures. Also, fuel consumption during transportation is not affected by the number of barges or tugs since these do not have an influence on the number of shuttle operations. For Concept 13, $C_{fuel,trans.,in-cont.}$ is used, including the fuel consumption for all shuttle operations with the Pioneering Spirit.

Apart from fuel consumption during transportation, the vessels will also use fuel while executing other offshore operations. The Equations for computing $C_{fuel,oper.,(in-)cont.}$ are stated below.

$$C_{fuel,oper.,cont.} = 2 \cdot T_{oper.,cont.} \cdot (\dot{m}_{fuel,oper.,PS} + (1 - \frac{N \cdot T_{available}}{T_{oper.,cont.}}) \cdot (\dot{m}_{fuel,oper.,IL} + 2 \cdot \dot{m}_{fuel,oper.,tug})) \cdot P_{fuel} \tag{5.32}$$

And,

$$C_{fuel,oper.,in-cont.} = 2 \cdot T_{oper.,in-cont.} \cdot P_{fuel} \cdot \dot{m}_{fuel,oper.,PS} \tag{5.33}$$

Here, $\dot{m}_{fuel,oper.,PS}$, $\dot{m}_{fuel,oper.,IL}$, and $\dot{m}_{fuel,oper.,tug}$ are the average fuel consumption during the offshore operations, excluding transportation, for the Pioneering Spirit, Iron Lady, and tug respectively of which the estimations were provided by Allseas (See Appendix E). Again, $C_{fuel,oper.,in-cont.}$ holds for Concept 13 and $C_{fuel,oper.,cont.}$ is used for Concepts 1 and 11. The difference between the two Equations comes mainly from the additional vessels that are required for continuous installation. However, the operational time for these vessels has been corrected by subtracting the $T_{available}$ for every installation cycle, since the empty barge can already be towed to shore after the final unmooring operation. Also, the number of barges or tugs does not influence the number of offshore operations and thus the fuel cost has been accounted for by a single barge and two tugs.

Ultimately, by substituting all the necessary expressions and formulas into Equation 5.26, the total installation cost for the construction of the reference wind farm as a function of the distance can be obtained for the different concepts. This has been plotted in Figure 5.36. The intermediate results related to this Figure are included in Figure D.3 of Appendix D.

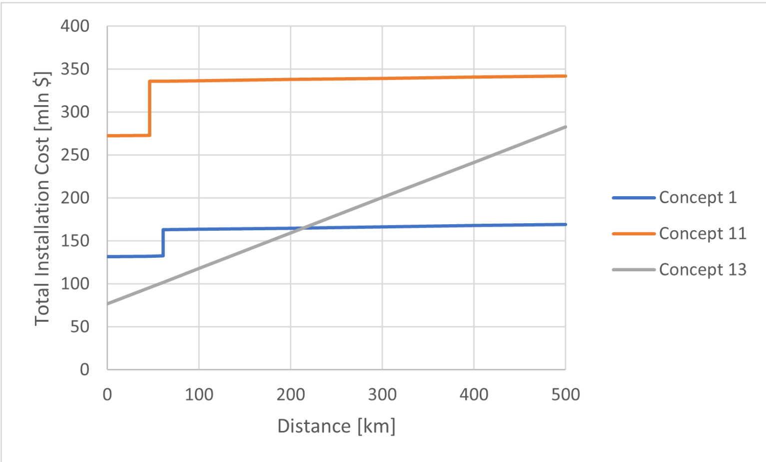


Figure 5.36: Total operational cost as function of the wind farm location for installation with different Concepts

From this Figure, it can be seen that constructing the reference wind farm with Concept 13 results in the lowest total installation cost for distances of approximately 210 kilometres or less. For wind farm sites exceeding this distance, Concept 1 becomes the most economically attractive. However, it is expected that the project delays due to weather downtime as a result of the operational limits have a great impact on the total installation cost because it is closely related to the total project duration. Therefore, the total installation cost will also be corrected by the annual workability by using the Equation below.

$$C_{total,(in-)cont.,cor.} = C_{vessel,(in-)cont.,cor.} + C_{fuel,trans.,(in-)cont.,cor.} + C_{fuel,oper.,(in-)cont.,cor.} \tag{5.34}$$

In which $C_{vessel,(in-)cont.,cor.}$ is the total vessel cost during the entire construction period of the reference wind farm including project delays due to operational limits and is calculated with the following Equation:

$$C_{vessel,(in-)cont.,cor.} = T_{total,(in-)cont.,cor.} \cdot \sum dayrate_{vessel,i} \cdot n_{vessel,i} \tag{5.35}$$

With,

$$i = PioneeringSpirit, Barge, Tug \tag{5.36}$$

Note that the vessel requirements for the different concepts have not been accounted for by the annual workability and thus are similar to those provided in Table 5.11.

If weather forecasts indicate that operational limits for transport will be exceeded, the vessels will have to wait on good weather either in a harbour or at the offshore wind farm. Another option is that the severe environmental conditions have to be avoided by sailing around it, but this is not included in the economic analysis. Therefore, it is assumed that the total fuel consumption and cost during transport will not be influenced by the annual workability which is expressed in the Equation below.

$$C_{fuel,trans.,(in-)cont.,cor.} = C_{fuel,trans.,(in-)cont.} \tag{5.37}$$

The total fuel consumption during the other offshore operations when accounting for the annual workability can be separated into two contributions as can be seen in the Equation below.

$$C_{fuel,oper.,(in-)cont.,cor.} = C_{fuel,oper.,(in-)cont.,cor.,1} + C_{fuel,oper.,(in-)cont.,cor.,2} \tag{5.38}$$

In this Equation, $C_{fuel,oper.,(in-)cont.,cor.,1}$ refers to the fuel consumption cost during the loading, mooring, unloading, installation and unmooring operations. It is calculated for Concepts 1 and 11 with the following Equations:

$$C_{fuel,oper.,cont.,cor.,1} = T_{oper.,cont.,cor.} \cdot (\dot{m}_{fuel,oper.,PS} + (1 - \frac{N \cdot T_{available,cor.}}{T_{oper.,cont.,cor.}}) \cdot (\dot{m}_{fuel,oper.,IL} + 2 \cdot \dot{m}_{fuel,oper.,tug})) \cdot P_{fuel} \tag{5.39}$$

In which $T_{available,cor.}$, is the available time for the Iron Lady to return fully loaded with components at the reference wind farm site after the final unmooring operation corrected by the annual workability and includes both spar and wind turbine installation cycles. The expression for $T_{available,cor.}$ is shown below.

$$T_{available,cor.} = \frac{T_{available}}{\eta_{install.,spar}} + \frac{T_{available}}{\eta_{install.,WTG}} \tag{5.40}$$

For concept 13, $C_{fuel,oper.,(in-)cont.,cor.,1}$ is determined with the following Equation:

$$C_{fuel,oper.,in-cont.,cor.,1} = T_{oper.,in-cont.,cor.} \cdot P_{fuel} \cdot \dot{m}_{fuel,oper.,PS} \tag{5.41}$$

Furthermore, $C_{fuel,oper.,(in-)cont.,cor.,2}$ represents the fuel consumption cost caused by waiting on good weather for transportation to or from the reference wind farm. For this, it has been assumed that the vessels that are used for the shuttling operations are 50% of the time in a port and 50% at the reference wind farm site while waiting on good weather. Also, the assumption has been made that the vessels do not consume any fuel when waiting in a port. This resulted in the following Equation for Concepts 1 and 11:

$$C_{fuel,oper.,cont.,cor.,2} = \frac{4 \cdot s \cdot (1 - \eta_{trans.})}{\eta_{trans.}} \cdot (\frac{\dot{m}_{fuel,oper.,PS}}{v_{sailing,PS}} + \frac{N \cdot (\dot{m}_{fuel,oper.,IL} + 2 \cdot \dot{m}_{fuel,oper.,tug})}{2 \cdot v_{sailing_{IL}}}) \cdot P_{fuel} \tag{5.42}$$

And for Concept 13:

$$C_{fuel,oper.,in-cont.,cor.,2} = \frac{4 \cdot s \cdot (1 - \eta_{trans.})}{\eta_{trans.}} \cdot \frac{\dot{m}_{fuel,oper.,PS}}{2 \cdot v_{sailing,PS}} \cdot P_{fuel} \tag{5.43}$$

The resulting total installation cost for the reference wind farm as a function of the distance and corrected by the annual workability is shown in Figure 5.37. The intermediate results related to this Figure are included in Figure D.4 of Appendix D.

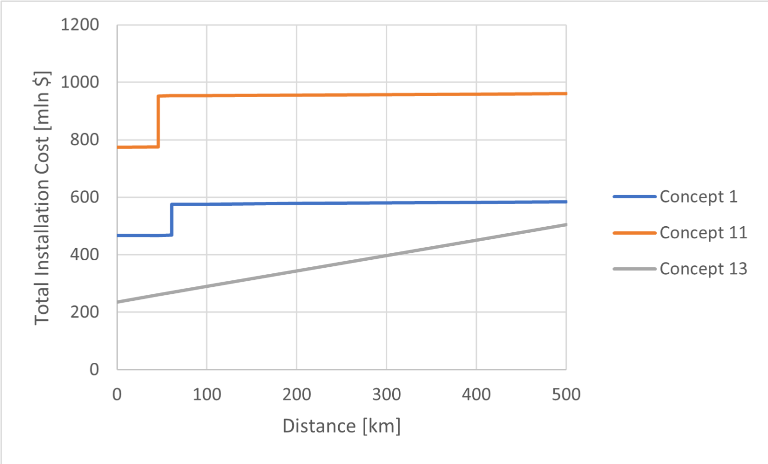


Figure 5.37: Total operational cost corrected by weather downtime as function of the wind farm location for installation with different Concepts

According to the economic analysis, installing the wind farm with Concept 13 results in the lowest cost for wind farm locations varying from 0 to 500 kilometres when accounting for project delays as a result of the annual workability. However, since the installation of offshore floating wind turbines will most likely be done during seasons with relatively lower probabilities for limiting environmental conditions in comparison to the annual statistics, Concept 1 could potentially be the most economically attractive for wind farms at larger distances from shore.

Besides looking into the total duration and cost associated with the construction of the reference wind farm, the carbon footprint is starting to become an equally important factor for project development in the future due to global warming. For example, the carbon tax could be raised, resulting in higher costs. Also, tenders could be lost because companies may choose the more expensive option with lower carbon emissions. Therefore, it is relevant to estimate the carbon footprint for the different installation procedures. According to *[55]*, the emissions factor of MGO is approximately 3.15 tonnes of CO2 per tonne of MGO fuel. The following Equation is used for determining the carbon footprint for the construction of the reference wind farm with the different concepts without including the annual workability:

$$m_{CO2-emission,(in-)cont.} = \frac{C_{fuel,trans.,(in-)cont.} + C_{fuel,oper.,(in-)cont.}}{P_{fuel}} \cdot emissionsfactor \qquad (5.44)$$

When solving this Equation, the total CO2 emission as a function of the wind farm distance for the different concepts can be obtained and is shown in Figure 5.38. The intermediate results related to this Figure are included in Figure D.5 of Appendix D.

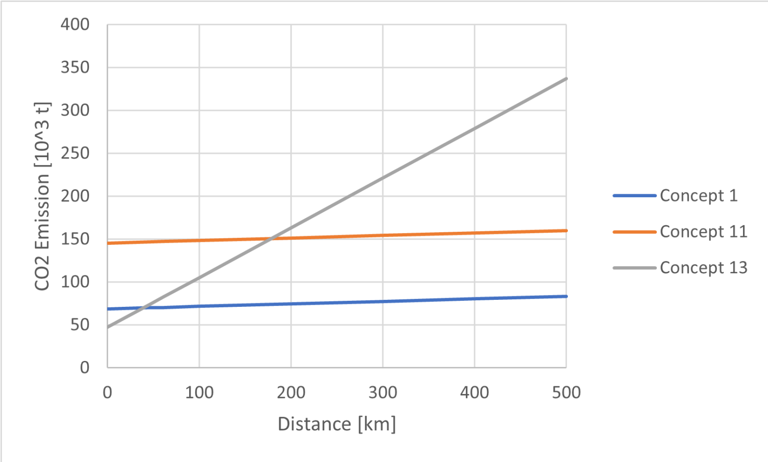


Figure 5.38: Total carbon emission as function of the wind farm location for installation with different Concepts

This graph shows that the carbon footprint of Concept 13 is considerably more sensitive to the wind farm location in comparison to Concepts 1 and 11. However, Concept 13 seems to have the lowest carbon emission for distances smaller than 40 kilometres after which Concept 1 provides the smallest carbon footprint.

Moreover, when taking the annual workability into account, the carbon footprint can be computed with the Equation below.

$$m_{CO2-emission,(in-)cont.,cor.} = \frac{C_{fuel,trans.,(in-)cont.,cor.} + C_{fuel,oper.,(in-)cont.,cor.}}{P_{fuel}} \cdot emissionsfactor \quad (5.45)$$

The results are depicted in Figure 5.39. The intermediate results related to this Figure are included in Figure D.6 of Appendix D.

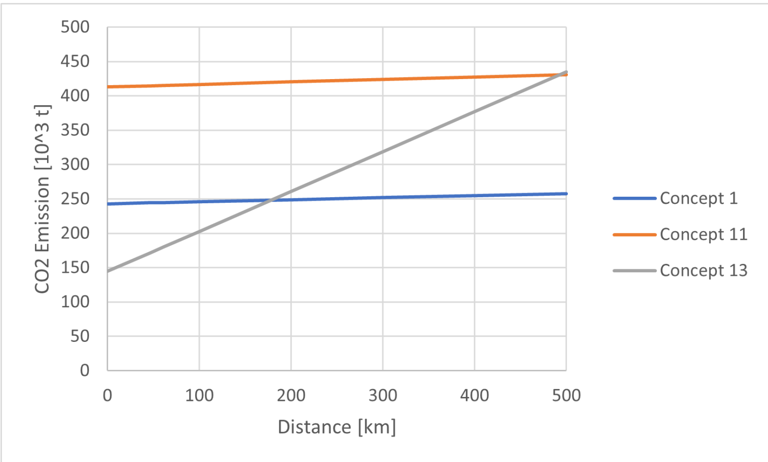


Figure 5.39: Total carbon emission corrected by weather downtime as function of the wind farm location for installation with different Concepts

To conclude, the economic analysis shows that Concept 13 has the best performance regarding the total project cost. However, taking the potential disadvantages relating to the carbon footprint into account, Concept 1 may potentially be the preferred option. Also, given the exclusion of any potential downtime, Concept 1 emerges as the most promising option for wind farms that are located further offshore. Furthermore, while Concept 11 seems to be the least attractive solution regarding all factors, it has the advantage that it could install both spar and TLP floating wind turbines. Note that this analysis gives estimations for the duration, cost, and carbon footprint based on multiple parameters for which the values can vary significantly. Therefore, the results can be used as an indication but do not have the level of reliability to make decisions for concept implementation. Finally, additional cost for potential upgrades or development of lifting tools is not included in this analysis while this could influence the judgement.

6 Conclusion

In conclusion, the increasing efforts regarding the transition to renewable energy sources result in a growing demand for offshore wind turbines and drive the technological development of larger wind turbines with increasing capacities. As a consequence, the availability of qualified installation vessels is at risk with a shortage already expected in 2024. Therefore, it is of societal importance that solutions will be found for this shortage for staying on track to become carbon neutral by 2050. Allseas Group S.A. currently owns the largest construction vessel in the world named the Pioneering Spirit. It is particularly interesting for the installation of floating offshore wind turbines because it is an advanced heavy-lift vessel that can perform lifting operations while floating. However, since the Pioneering Spirit has never installed floating structures to date, this study was conducted with the following research objective:

"to design a feasible concept for installing floating offshore wind turbines with the Pioneering Spirit".

However, this research also gives valuable insights that extend beyond the initial scope of this paper. By using a methodology that identifies crucial and limiting aspects during concept development associated with both the development of installation procedures and the customisation of heavy-lift vessels that are formerly unused in the floating offshore wind installation sector. As a result, an indication of the technical feasibility, workability and economic feasibility of other potential concepts for deployment in this area can be evaluated with this methodology. Also, the performance implications of the selected concepts related to the workability assessment and economic feasibility study can directly be linked to specific design choices and limitations. This, in combination with the exploration of floating wind turbine installation with alternative lifting equipment, can be used to provide recommendations for future designs of purpose-built vessels in this sector.

Furthermore, through the needs analysis, it was found that Spar- and TLP-type floating wind turbines are of particular interest for installation with the Pioneering Spirit. The large draught of spar foundations and the initial instability of tension leg platforms are making these designs often unsuitable for port assembly and tow-out installation. Hence, the installation of these structures typically necessitates the use of heavy-lift vessels. Also, installing the mooring system with the Pioneering Spirit is not economically viable, as smaller vessels with a significantly lower day rate and fuel consumption can perform this operation. Subsequently, from the case study and the concept exploration phase, it can be established that the Pioneering Spirit is a versatile heavy-lift vessel with unique lifting equipment and capabilities. This allows for the development of multiple concept designs that are in principle capable to install the relevant pre-assembled floaters and wind turbines with a single-lift operation.

Still, the technical feasibility study pointed out that modifications to the lifting equipment and the inclusion of additional tools are necessary for the selected concepts. In addition, it was discovered that the offshore installation of spar- or TLP-type floating wind turbines with the Pioneering Spirit is a highly complex and challenging operation due to the interaction of multiple floating structures, the environmental conditions at the installation site, and the low tolerance for motions. Therefore, minimising the number of offshore operations during concept development appears to be advantageous which is supported by the relative change in total project duration between Concept 13 compared to Concepts 1 and 11 after correcting for the annual workability. However, further research should be conducted to guarantee the technical feasibility of these concepts.

Moreover, the economic feasibility study revealed that the installation time and workability have a significant impact on the total project duration and ultimately on the total installation cost. This suggests that the weighting factors, used to adjust the relative importance of selection criteria in the Trade-Off Analysis, were assigned correctly to the downtime and installation time criteria. As a consequence, the outcome of the economic analysis first showed that both Concepts 1 and 13 could be favourable options for constructing the reference wind farm depending on the distance. Nevertheless, when accounting for potential weather downtime due to the operational limits, Concept 13 performed better for all variable distances of the wind farm location. However, the development of an installation strategy that minimises the effect of weather downtime could improve the results for Concept 1, making it potentially the preferred option for longer-distance installation sites. Especially because it is observed that transporting components with a barge makes the concept's performance less sensitive to the distance of the wind farm to shore due to the possibility of continuous installation.

When assessing the concepts on an environmental basis, it can be concluded that the carbon footprint of Concept 13 is more sensitive to the distance of the reference wind farm to shore due to the transportation with the Pioneering Spirit which has a relatively high fuel consumption. Therefore, if the carbon footprint would become an essential factor for the assignment of new projects by companies, this would be in favour of Concepts 1 and 11. Nonetheless, Concept 13 has a lower carbon footprint for installation sites relatively close to shore both with and without the workability correction.

Lastly, from a practical point of view, Concept 11 has an advantage over other concepts as it allows the installation of both Spar- and TLP-type floating wind turbines. In contrast, the installation of the reference wind farm with Concept 11 results in the longest project duration and highest cost for almost all variable distances. This implies that using the Topside Lift System instead of the 5000t Crane for the construction of floating wind farms is beneficial since the installation procedures for Spar-type floating wind turbines of Concepts 1 and 11 are similar in all other aspects. Therefore, it can be cautiously stated that the Pioneering Spirit presumably outperforms the currently available semi-submersible and monohull heavy-lift crane vessels in this field.

7 Discussion

The concept development stage of the systems engineering method can be utilised to look into the possibilities to install floating offshore wind turbines using vessels that have not been previously employed for this specific operation. By conducting a needs analysis, valuable insights regarding the operational environment can be obtained, enabling the establishment of concept requirements. These requirements serve as a foundation for generating diverse design options during the concept exploration phase. Subsequently, through the reduction of concepts by means of a trade-off analysis, an in-depth analysis of the installation procedure, technical requirements, and performance relating to the most promising concepts can be conducted in the concept definition phase, ultimately addressing the primary research question:

What is the feasibility and workability of floating offshore wind turbine installation with the Pioneering Spirit?

The outcomes derived from the concept development stage can then be employed in the subsequent advanced development phase of the engineering development stage, where the various components are further specified. Nevertheless, it is important to note that the concept development stage alone typically spans several years. However, due to the time constraints of this thesis, the concept development phase was expedited. Consequently, certain iterations and sensitivity studies could not be performed. As a result, it was not possible to assess the impact of parameter changes and compare the performance of concepts in different scenarios. For instance, an increase in the loading capacity of the Iron Lady could potentially enhance the performance of Concepts 1 and 11. Additionally, variations in planned operational periods, fuel consumption, day rates, and sailing speed could be introduced to evaluate their effect on the current results and conclusions.

Moreover, the workability assessment and the economic feasibility study for the selected concepts primarily rely on estimations of the operational limits and the aforementioned parameters. It is important to acknowledge that although these estimates are representative, they introduce a level of uncertainty that may result in deviations from actual outcomes. Consequently, these results are less suitable for the validation of certain propositions but rather serve as indicators of the potential impact of specific design choices relating to project duration, project cost and carbon footprint. Also, the economic analysis accounts for project delays arising from operational limits by correcting for the annual workability. This places Concepts 1 and 11 at a disadvantage as they include a greater number of offshore operations compared to Concept 13. To address this issue, it is advisable to incorporate workability values corresponding to shorter time periods in the economic analysis, thereby rectifying the effect.

Furthermore, the installation of the Spar-type floating wind turbine with the proposed concepts assumes that the Pioneering Spirit can perform the ballasting and lifting operations simultaneously. In the case of seawater ballasting, this assumption is likely to be feasible in reality since the Pioneering Spirit is equipped with an active ballast system capable of filling the tanks with seawater. Therefore, with a relatively low amount of modifications, a system could be added to enable the vessel to ballast the floaters with seawater. However, if ballasting with a higher-density material is required, it is almost certain that the Pioneering Spirit would need additional storage space to accommodate this type of ballast. Additionally, dredging equipment or the involvement of an auxiliary vessel may be necessary to supply these materials. Therefore, it can be stated that the integration of a ballast system suitable for higher-density materials into the Pioneering Spirit would require excessive modifications. As a consequence, for the installation of Spar-type floating wind turbines, which are ballasted with a heavier material, the need for a dredger will probably be inevitable. This will have an impact on costs, particularly for concepts associated with longer project durations, thereby influencing the results of the economic analysis. Nevertheless, the interpretation of the economic feasibility study will be minimally affected by this factor.

Also, the economic model that is used in this methodology could potentially contribute to the determination of the Levelised Cost of Electricity for a reference floating offshore wind farm. However, it is important to note that the Levelised Cost of Electricity is influenced by various factors beyond installation costs. Therefore, no conclusions can be drawn regarding the economic performance comparison between different types of floating wind turbines. Hence, there is a risk relating to the possibility that semi-submersible- or barge-type floating wind turbines will be standardised in the sector leaving no demand for spar- or TLP-type floating wind turbines and making the use of heavy-lift vessels in this field most likely obsolete. However, there are no indications that such a scenario will occur in the future. Therefore, this methodology is a good starting point for making investment decisions since it can be compared to alternating installation methods in which different vessels are used. Although the reliability of the inserted parameters should be improved to enhance the quality of the economic feasibility study.

Lastly, through the creation of storyboards, the evaluation of stability, and the provision of technical descriptions of procedures and additional required equipment, this study has contributed to partially confirming the technical feasibility of the proposed concepts. Nonetheless, it is important to recognize that there are other factors that could still affect the technical feasibility of the concepts. Therefore, further studies must be conducted to guarantee the technical feasibility. For instance, these additional studies could focus on the motions of the various structures during lifting operations or the stability of the Iron Lady for different heeling angles. Such studies would enable a more precise determination of the operational limits. This will allow a better understanding of the technical feasibility of the concepts.

8 Recommendations

This study looked into the technical and economic feasibility of floating wind turbine installation with the Pioneering Spirit. However, it was concluded that further research is required to guarantee the technical feasibility or to improve the performance of the concepts. Moreover, the workability assessment and economic feasibility study were largely based on estimations of various parameters. Also, multiple assumptions were made and factors were disregarded during the development of the concepts and analysis of their workability and feasibility. Hence, the following recommendations for future research resulted from this study.

- It is advised to perform a multi-body dynamic analysis for different operations included in the installation procedures. Since the installation of floating wind turbines is highly complex and challenging due to multiple interacting structures and a low tolerance for motions, it is considered essential to get a better understanding of the loads acting on the system interfaces and the relative motions of the structures. So that more reliable results can be obtained for the environmental limits in order to further evaluate the technical feasibility and to improve the quality of the workability assessment and economic feasibility study.

- In order to lift the pre-assembled components of Spar- or TLP-type floating offshore wind turbines, both the 5000t crane and TLS need specially designed lifting tools. Therefore, a study should be conducted to identify specific requirements that the design of different lifting tools should be able to accomplish. Then, multiple solutions have to be explored that meet these requirements. Finally, the performance of the explored concepts should be compared in order to select the most promising design. Therefore, the systems engineering method could potentially be applied to develop these lifting tools.

- Also, the 5000t crane should be upgraded to increase the maximum lifting height so that it can lift the pre-assembled 15-MW spar foundation or wind turbine. This could be realised by increasing the height of the crane base, extending and strengthening the crane boom or by a combination of both. A tailored solution for the 5000t crane upgrade should be developed in another research.

- The large draught of spar foundations and the instability of TLPs often necessitate installation with the Pioneering Spirit or other heavy-lift vessels. However, in some cases, these structures can be fully assembled at a port and installed by a tow-out with tugs when the water depth is sufficient or by employing buoyancy modules. Therefore, in order to assess the competitiveness of installing these types of floating wind turbines with the Pioneering Spirit, an economic analysis should be performed for a typical tow-out installation method. By improving the quality and scope of the economic analysis for both installation methods, a reliable comparison of the economic performances can be made which could potentially be used to make an investment decision on the realisation of a concept.

- The technical feasibility of the selected concept designs should be further evaluated by looking into different aspects of the installation procedures. First, during the development of the storyboards, it was observed that the 15-MW TLPs are extending from the edge of the Iron Lady due to the large pontoon length. Therefore, multiple Yokohamas have to be coupled in order to achieve the required clearance after the mooring operation. However, the feasibility of this solution and its effect on the dynamic behaviour of the barge should be investigated. Second, the Iron Lady is extending approximately 64 metres from the stern of the Pioneering Spirit. Even though Sinke has already addressed this in his research for an extension of 40 metres, it is still deemed necessary to investigate whether the proposed solutions by Sinke could be implemented in the concept designs. Third, regarding the Iron Lady, the initial stability for different load cases was evaluated and the operational limits during transportation have been estimated based on previous projects. In addition to this, the stability of the Iron Lady for different heeling angles could be assessed including the free surface effects in the ballast tanks. The results could be used to verify if the estimated operational limits for transportation are correct and gives more insight into the technical feasibility of the concepts. Fourth, during the installation of wind turbines onto the pre-installed floating foundation, lifting and ballasting are performed simultaneously. Since this operation is considered very complex, a more detailed analysis would be needed to ensure its technical feasibility. Lastly, more research should be conducted regarding the sea fastening of the various pre-assembled components together with the potential need for and design of sliding grippers, lifting yokes and guiding beams.

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A
Mooring Systems

In principle, floating structures have 6 degrees of freedom in which they can move or rotate as a consequence of the environmental conditions. These motions are surge, sway, heave, roll, pitch and sway. To limit some of the previously described motions of floating structures, it has to be connected to the seabed with a mooring system. A mooring system consists of anchors, mooring lines and other auxiliary components (e.g. fairleads, shackles, buoyancy modules and clump weights). The type of mooring system depends on the environmental conditions, hydrostatic restoring mechanism of the floating structure, water depth, soil type and cost. There exist multiple mooring system configurations. Below a brief description of the different mooring system characteristics is given.

A.1. Configurations

Mooring system configurations can be split up into catenary, taut and semi-taut systems. The amount of mooring lines and anchors depends on the project requirements. Generally, between three and six mooring lines are used per floating wind turbine. However, this will most likely be higher when turbines and foundations increase in size. Below a brief summary of the mooring configurations can be found.

Catenary mooring system

The catenary mooring system can be identified by mooring lines that hang loosely in a vertical position from the offshore floating structure and have a catenary shape with the lower part of the mooring line laying on the seabed where it is connected to an anchor. Due to this configuration, only vertical or horizontal loads are applied at the fairleads of the floating structure or anchors respectively. Also, the mooring line is longer compared to the water depth because of its catenary curve which results in a larger environmental footprint. Catenary mooring systems are the most deployed configuration in the floating offshore wind sector, where it is used for ballast- and buoyancy-stabilized substructures such as a spar, semi-submersible and barge. The optimal depth of the mooring system is between 100 to 250 meters and its purpose is station keeping. However, the structure can move in all directions in the 6 degrees of freedom reference system. As a last remark, the installation of catenary-mooring systems is relatively simple compared to taut-mooring systems.

Taut mooring system

The taut mooring system can be recognized by mooring lines that are connected vertically or under a maximum angle of 45 degrees. It has a straight line shape because of the tension in the mooring lines. Therefore, a vertical, as well as a horizontal force, is applied to the anchors. A taut mooring system is typically used for mooring-stabilized structures such as TLP platforms. However, it could also be applicable to other floating structures especially when it has to be installed in extremely deep waters. The elastic restoring force applied by the taut mooring system provides greater turbine stability in comparison to a catenary system. Furthermore, the environmental footprint is smaller due to shorter mooring lines. As mentioned before, the installation method of taut-mooring systems is more complex in comparison to catenary mooring systems.

Another challenge is related to the high loads that are applied to the tendons which is also the reason that taut mooring systems are not preferable in locations with significant earthquake risks.

Semi-taut mooring system

The semi-taut mooring system is a combination of the catenary and taut mooring systems. It is especially applicable for deeper waters where a catenary mooring system is not economically viable.

A.2. Mooring lines

A single mooring line can consist of multiple line segments which can be different in terms of type and material. The commonly used line types are chains or ropes. These line types together with their material composition and applications are explained in more detail below.

Chain

Chain mooring lines are made out of steel and can be used for catenary or semi-taut mooring systems. Since chains are very stiff, they are not suitable for taut mooring systems. The advantages of using this type of mooring line are that the manufacturing and installation technology are more commercially mature due to its applications in the oil and gas industry. Also, because chains have a greater weight in comparison to steel wire rope mooring lines, a larger part of the lower segment remains on the seabed which reduces the risk that anchors are vertically loaded. Finally, chains are more resistant to abrasion. However, a negative aspect is that greater handling capacity is required because of heavier lines.

Rope

Rope mooring lines can be made out of steel or synthetic material (e.g. nylon, polyester, and High-modulus polyethylene). This mooring type can be used for both catenary and taut systems because it has better elasticity properties compared to chains. Moreover, the rope mooring lines are lighter with respect to chain types while capable to withstand the same amount of force. A downside of steel wire ropes is that it is more susceptible to corrosion and damage, but this can be improved by the use of coatings. Especially synthetic ropes are a promising solution for floating applications, but the technology is less developed at the moment. It is beneficial in terms of weight, fatigue, material and installation requirements which is expected to reduce the cost significantly. Furthermore, synthetic ropes could be used for floating structures in shallower water sights because it has better elasticity properties needed for the hydrodynamic conditions.

A.3. Anchors

The anchor type mostly depends on the soil and the direction of the applied forces. As mentioned before, the load that is acting on the anchor in catenary mooring systems is directed horizontally. For taut mooring systems, a combination of vertical and horizontal directed loads could be acting on the anchors. Below a brief overview is given of the commonly used anchor types.

Drag embedment anchors

Drag embedment anchors are used for catenary mooring systems because the anchor can only withstand horizontal forces. For this reason, it is also not suitable for taut or (semi-taut) mooring systems. The anchor can be easily installed by dragging it along the seabed causing the anchor to penetrate the soil. The soil must be soft enough for the anchor to be able to impede it. The installation and decommissioning of drag embedment anchors is relatively simple compared to some other anchor types.

Driven pile anchors

Driven pile anchors consist of a cylindrical tube that is installed by driving it into the seabed with a hydraulic pile driver. When the anchor is fully penetrated into the seabed, it can withstand horizontal and vertical forces due to the resulting friction forces between the pile and soil. Therefore, it can be used for both catenary and taut mooring systems. The driven pile anchor can be installed in a broader range of soil conditions. A downside is that the installation process produces more noise and decommissioning is difficult.

Suction pile anchors

The suction pile anchor is a shorter and wider cylindrical tube in comparison to the driven pile anchor and is closed at the top. The anchor is installed by pumping water out of the pile when it is placed on the seabed. This creates suction forces which drive the pile into the seabed. The anchor type is suitable for catenary and taut mooring systems. The advantages with respect to a driven pile anchor are that the installation and decommissioning process is simpler and the environmental impact is reduced compared to driven pile anchors.

Vertical load anchors

The vertical load anchor is principally the same as the drag-embedded anchor. The only difference is that the vertical load anchor can be penetrated deeper into the seabed and can rotate. This makes it able to withstand vertical and horizontal loads and thus can be applied in the catenary and taut mooring systems.

Gravity anchors

Gravity anchors can be used for catenary and taut mooring systems. The weight and the frictional forces between the seabed and the anchor provide the necessary holding forces. It is suitable for seabed conditions with hard soil. A downside is that the additional weight potentially results in greater handling capacity which could increase the cost. The previously described topics are widely known so only a single source (*[26]*) is used in this Appendix.

B Installation location

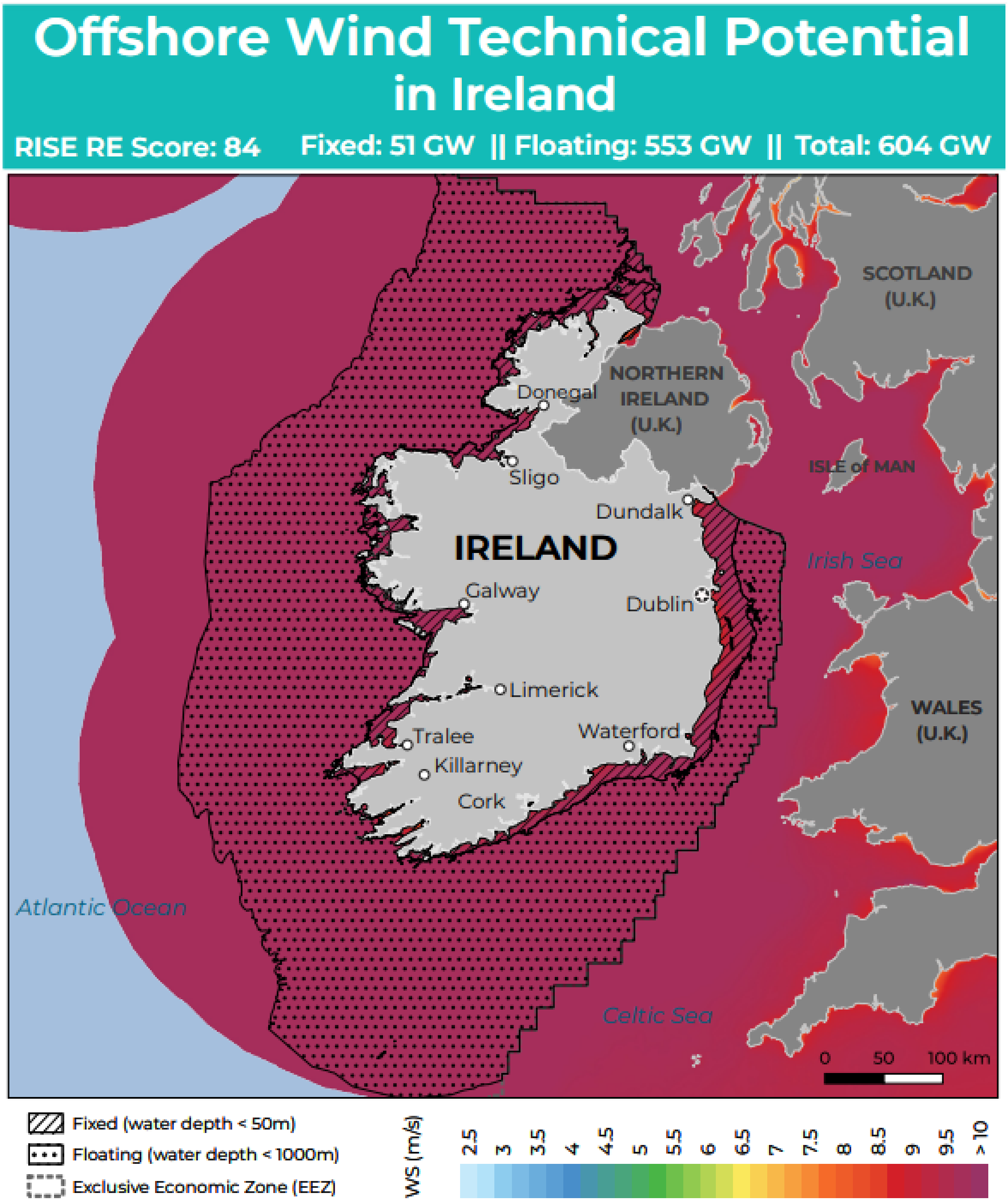


Figure B.1: Offshore wind technical potential in Ireland *[59]*

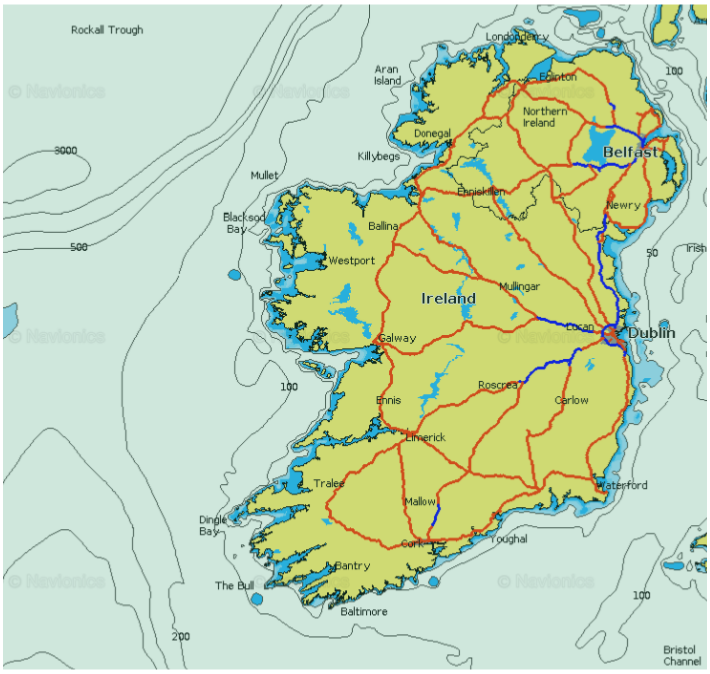


Figure B.2: Water depth chart offshore Ireland *[54]*

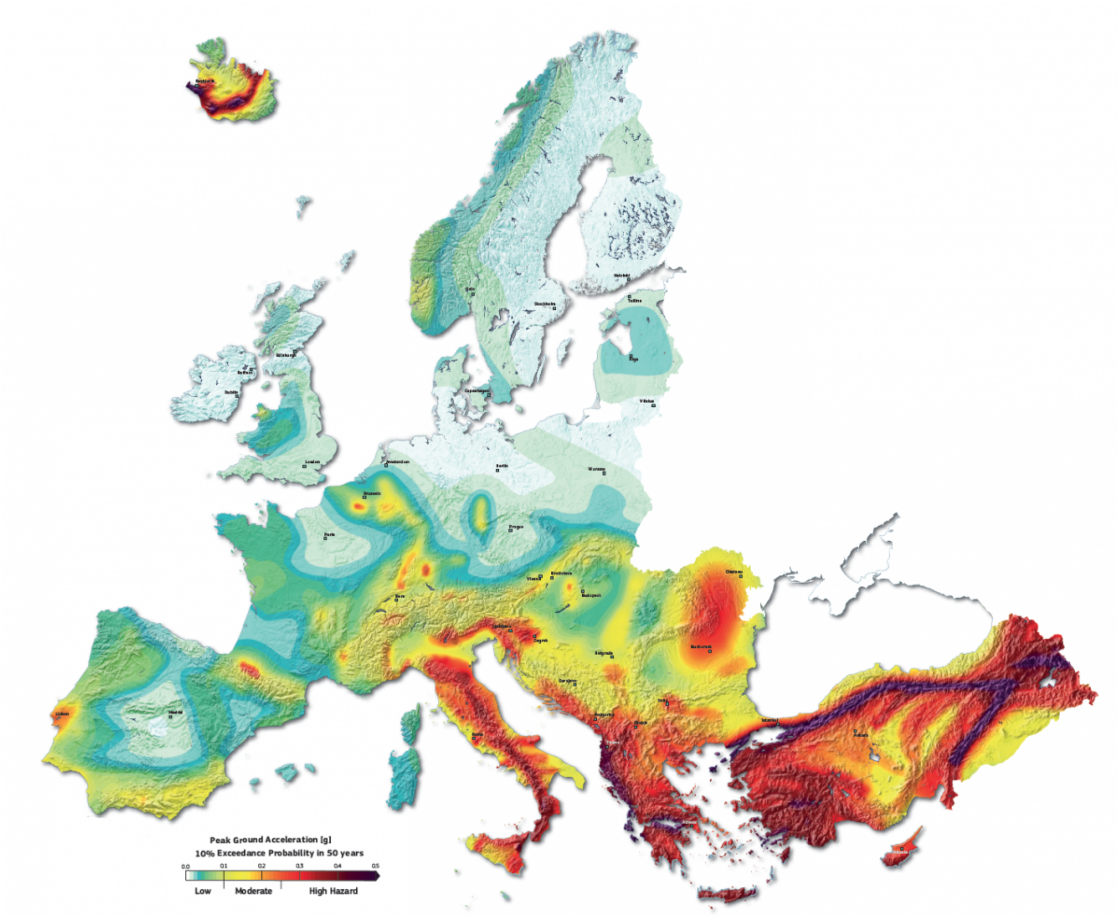


Figure B.3: Earthquake risk map of Europe *[23]*

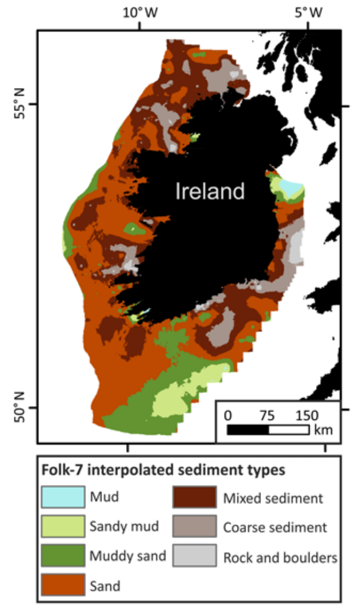


Figure B.4: Sediment type distribution of Ireland's seabed *[62]*

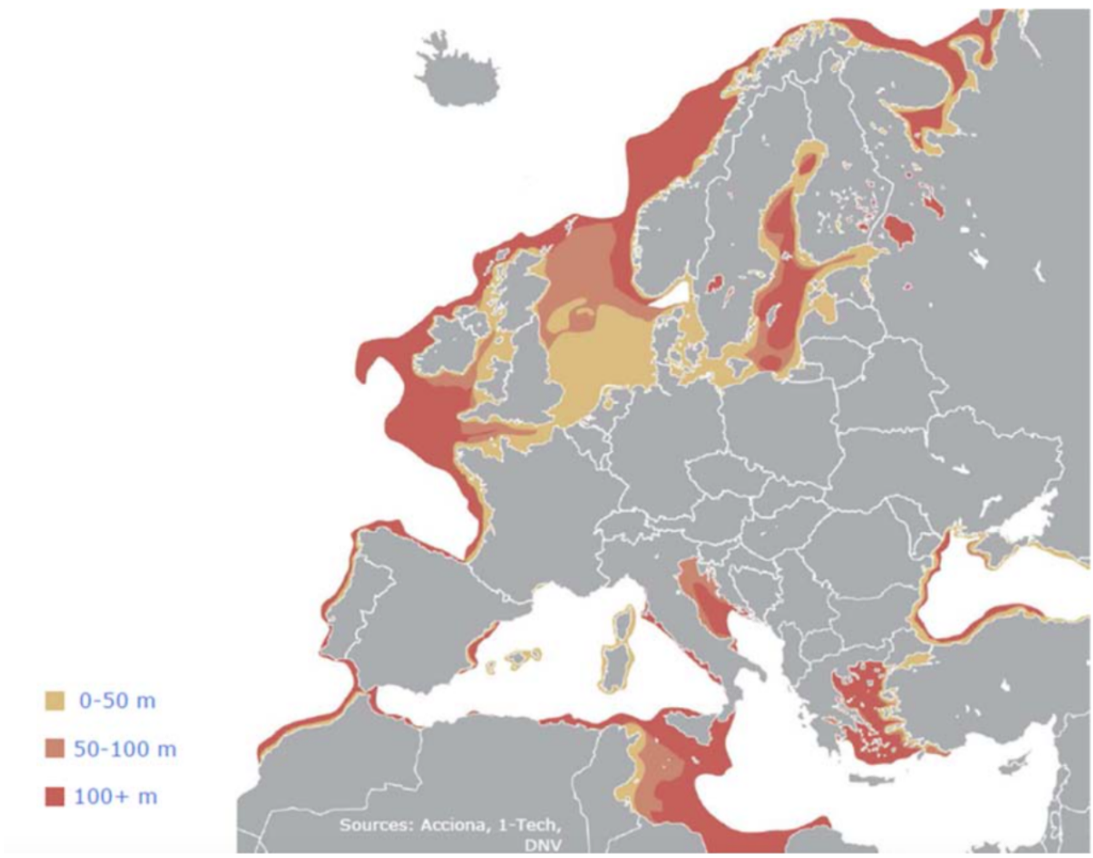
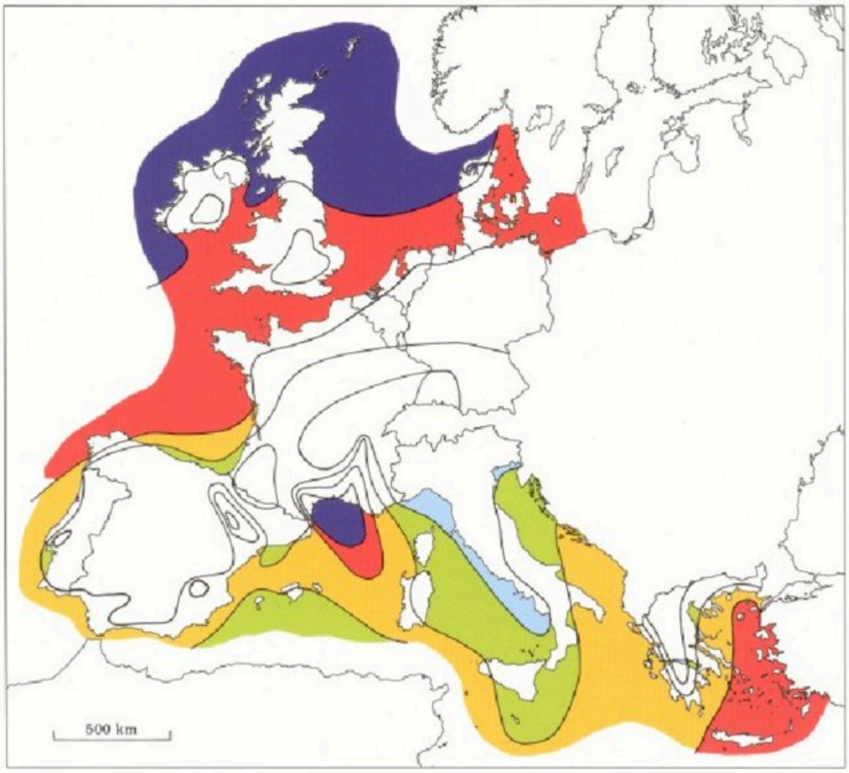


Figure B.5: Water depth map of European seas, Source DNV-GL, 2014 via *[45]*



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure B.6: Wind speeds map for different elevations of European seas, Source Risø National Laboratory, Denmark

C
Scatter Diagrams

	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1 - 1.5	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	<0.1%	0,30%	0,40%	0,50%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	0%	<0.1%	2%	2%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,20%	<0.1%	0%	0,10%	0,50%	0,70%	0,80%	0,80%	0,80%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	0%	4%	6%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,20%	0,70%	1,20%	1,30%	1%	0,60%	0,50%	0,20%	0,10%	<0.1%	<0.1%	0%	6%	12%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,20%	0,40%	0,20%	0,50%	1,50%	1,60%	2,10%	1%	0,40%	0,30%	0,20%	<0.1%	<0.1%	<0.1%	8%	20%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,40%	1,40%	2,20%	2,20%	1,70%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	9%	30%
3.5 - 4	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,30%	0,40%	1,20%	2%	2,10%	1,50%	0,70%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	9%	38%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,80%	1,70%	2,80%	2,10%	1,10%	0,40%	<0.1%	<0.1%	<0.1%	<0.1%	9%	48%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,70%	1,50%	2,60%	1,80%	1,10%	0,60%	0,30%	<0.1%	<0.1%	<0.1%	9%	56%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	1,50%	2,30%	2,20%	1,20%	0,40%	0,10%	<0.1%	<0.1%	0%	8%	65%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,80%	1,80%	2,10%	1,40%	0,60%	0,30%	<0.1%	<0.1%	<0.1%	7%	72%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,50%	1,40%	2,20%	1%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	6%	78%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,70%	1,60%	1,30%	0,60%	0,30%	<0.1%	<0.1%	<0.1%	5%	83%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,60%	1,20%	1,10%	0,60%	0,40%	0,10%	<0.1%	<0.1%	4%	87%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,60%	0,70%	0,60%	0,50%	<0.1%	<0.1%	<0.1%	3%	89%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,50%	0,70%	0,50%	0,50%	<0.1%	<0.1%	0%	2%	92%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,50%	0,30%	0,40%	0,20%	<0.1%	0%	2%	93%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0,20%	0,30%	0,30%	0,20%	0,20%	<0.1%	0%	1%	94%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,20%	0,40%	0,10%	<0.1%	0%	1%	95%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,10%	0,20%	0,10%	<0.1%	0%	1%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,30%	<0.1%	<0.1%	<0.1%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
15.5 - 16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
16 - 16.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
16.5 - 17	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17 - 17.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	0%	1%	1%	3%	9%	15%	21%	20%	13%	7%	5%	1%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	3%	6%	15%	30%	51%	71%	84%	91%	96%	96%	96%	96%		

Figure C.1: Wave scatter diagram of January at The Rian Offshore Array (Phase 1) location *[37]*

	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%
1 - 1.5	0%	0%	0%	0%	<0.1%	0,10%	<0.1%	0%	0,20%	0,40%	0,30%	0,50%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	2%	2%
1.5 - 2	0%	0%	0%	0%	0%	0,10%	<0.1%	0,10%	0,20%	0,40%	1,10%	1,40%	0,70%	0,60%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	5%	7%
2 - 2.5	0%	0%	0%	0%	0%	0,10%	0,30%	0,10%	0,30%	0,60%	1,30%	1,80%	1,60%	0,70%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	7%	14%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,30%	0,30%	0,30%	0,50%	1,60%	2,30%	1,70%	1,10%	0,50%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	9%	23%
3 - 3.5	0%	0%	0%	0%	0%	0%	0%	0,40%	0,40%	0,60%	1,30%	2%	2,60%	1,90%	0,60%	0,30%	0,20%	<0.1%	<0.1%	0%	10%	33%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,20%	0,30%	0,70%	1%	1,90%	2,80%	2%	0,80%	0,30%	0,20%	<0.1%	<0.1%	<0.1%	10%	43%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,50%	0,50%	1,90%	2,50%	2,30%	1,20%	0,40%	0,10%	<0.1%	<0.1%	0%	10%	53%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,30%	1,50%	2,20%	2,10%	1,20%	0,50%	0,40%	0,10%	<0.1%	<0.1%	9%	61%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	1,10%	1,80%	2,10%	1,20%	0,50%	0,40%	0,10%	<0.1%	<0.1%	8%	69%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,80%	1,40%	1,70%	1,50%	0,40%	0,40%	0,10%	<0.1%	<0.1%	7%	76%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	1,10%	1,40%	1,20%	0,80%	0,30%	0,10%	<0.1%	0%	5%	81%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,80%	1,10%	1%	0,50%	0,40%	0,20%	0,10%	<0.1%	4%	85%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	0,80%	0,80%	0,50%	0,40%	<0.1%	<0.1%	<0.1%	3%	88%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,50%	0,70%	0,30%	0,40%	0,10%	<0.1%	<0.1%	2%	90%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0,20%	0,30%	0,60%	0,30%	0,30%	0,10%	<0.1%	<0.1%	2%	92%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,30%	0,40%	0,20%	0,10%	<0.1%	0%	1%	94%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	0,30%	0,30%	<0.1%	<0.1%	<0.1%	1%	95%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,30%	<0.1%	<0.1%	<0.1%	1%	95%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	<0.1%	0,20%	<0.1%	<0.1%	<0.1%	0%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,20%	<0.1%	<0.1%	0%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
15.5 - 16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	96%
16 - 16.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
16.5 - 17	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17 - 17.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
17.5 - 18	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
18 - 18.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	1%	1%	2%	4%	8%	16%	20%	19%	13%	6%	5%	1%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	4%	8%	16%	32%	52%	72%	84%	90%	95%	96%	96%	96%		

Figure C.2: Wave scatter diagram of February at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	0%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%
1 - 1.5	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0,40%	0,90%	0,90%	0,40%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	0%	0%	3%	3%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,20%	0,50%	1,20%	1,70%	1,70%	0,80%	0,40%	0,20%	0,10%	0,10%	<0.1%	<0.1%	0%	7%	11%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	0,50%	0,40%	0,50%	1,30%	2,20%	2,30%	1,90%	0,90%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	0%	11%	21%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,30%	0,40%	0,40%	1,20%	2,20%	2,80%	2,60%	1,40%	0,60%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	12%	34%
3 - 3.5	0%	0%	0%	0%	0%	0%	0,10%	0,40%	0,60%	1%	1,90%	2,90%	2,50%	1,80%	0,60%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	12%	46%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,20%	0,40%	0,70%	1,60%	2,60%	2,60%	1,80%	0,60%	0,20%	0,20%	<0.1%	0%	0%	11%	56%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,60%	1,20%	2,10%	2,20%	1,90%	0,70%	0,20%	<0.1%	<0.1%	<0.1%	0%	9%	66%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,70%	1,40%	1,90%	1,80%	0,90%	0,30%	0,10%	<0.1%	<0.1%	0%	7%	73%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	1,10%	1,90%	1,80%	0,90%	0,40%	0,10%	<0.1%	0%	<0.1%	7%	79%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,60%	1,40%	1,20%	0,90%	0,50%	0,30%	<0.1%	<0.1%	<0.1%	5%	84%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	1%	1,30%	0,80%	0,40%	0,30%	<0.1%	<0.1%	0%	4%	89%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,60%	1,20%	0,50%	0,20%	0,30%	0,10%	<0.1%	0%	3%	92%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,80%	0,60%	0,30%	0,10%	<0.1%	<0.1%	0%	2%	94%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,50%	0,40%	0,30%	0,30%	<0.1%	0%	0%	2%	95%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,30%	0,10%	<0.1%	<0.1%	0%	1%	96%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	0%	1%	97%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	<0.1%	0,10%	<0.1%	<0.1%	0%	0%	97%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	97%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	97%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	97%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	0%	97%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	0%	0%	0%	97%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	97%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	97%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	97%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	97%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	97%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	3%	7%	13%	18%	20%	17%	9%	4%	2%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	3%	6%	13%	26%	44%	65%	82%	91%	95%	97%	97%	97%	97%		

Figure C.3: Wave scatter diagram of March at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,10%	0,40%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	1%	1%
1 - 1.5	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,50%	1,50%	1,70%	2,30%	1,20%	0,60%	0,20%	<0.1%	<0.1%	<0.1%	0%	0%	0%	8%	9%
1.5 - 2	0%	0%	0%	0%	0%	0,20%	0,30%	0,70%	1,80%	3,40%	3,90%	3,50%	1,50%	0,50%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	16%	25%
2 - 2.5	0%	0%	0%	0%	0%	0,10%	0,40%	0,50%	1,50%	3,10%	4,20%	4,60%	2,40%	0,90%	0,40%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	18%	43%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,10%	0,90%	1,20%	2,30%	3,50%	3,30%	3,20%	1,40%	0,50%	0,10%	0,10%	<0.1%	0%	0%	17%	60%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,90%	1,70%	2,60%	2,80%	2,20%	1,30%	0,50%	<0.1%	0,10%	<0.1%	<0.1%	0%	13%	72%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,20%	0,50%	0,90%	1,70%	2,10%	1,50%	0,90%	0,40%	0,20%	<0.1%	0%	0%	0%	8%	81%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,60%	1,40%	1,50%	1,10%	1%	0,40%	0,20%	<0.1%	<0.1%	0%	0%	6%	87%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,80%	1,10%	0,90%	0,90%	0,50%	<0.1%	<0.1%	0%	<0.1%	0%	4%	91%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,60%	0,60%	0,50%	0,30%	0,10%	<0.1%	0%	0%	0%	2%	94%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,30%	0,40%	0,30%	<0.1%	<0.1%	0%	<0.1%	0%	2%	95%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,20%	0,10%	<0.1%	<0.1%	0%	0%	0%	1%	96%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,10%	0,20%	<0.1%	<0.1%	0%	0%	0%	1%	97%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,20%	<0.1%	<0.1%	0%	0%	0%	0%	97%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	<0.1%	0%	0%	0%	97%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	0%	0%	0%	97%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	97%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	97%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	97%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	1%	3%	8%	14%	21%	21%	15%	8%	4%	1%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	5%	12%	26%	48%	69%	84%	92%	96%	97%	97%	97%	97%	97%		

Figure C.4: Wave scatter diagram of April at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																			Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,80%	1%	0,40%	0,10%	0,10%	0,10%	<0.1%	<0.1%	0,20%	<0.1%	<0.1%	3%	3%
1 - 1.5	0%	0%	0%	0%	0,10%	0,20%	0,60%	1,80%	3,90%	4,20%	2,40%	1%	0,50%	0,30%	0,20%	0,10%	0,20%	<0.1%	0%	16%	19%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,70%	1,20%	2%	4,20%	5,60%	4,90%	2,60%	0,90%	0,40%	0,10%	0,10%	<0.1%	0%	<0.1%	23%	41%
2 - 2.5	0%	0%	0%	0%	0%	0,20%	1%	1,30%	2,60%	4,80%	4,30%	3%	1,40%	0,40%	<0.1%	<0.1%	0%	<0.1%	0%	19%	61%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,20%	1%	1,60%	3,70%	3,30%	2%	1,40%	0,50%	0,10%	<0.1%	<0.1%	<0.1%	0%	14%	74%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	1%	2,20%	2,60%	1,70%	0,70%	0,50%	0,10%	<0.1%	<0.1%	0%	0%	9%	83%
3.5 - 4	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,40%	1,20%	1,60%	1,50%	0,70%	0,50%	<0.1%	<0.1%	<0.1%	0%	0%	6%	89%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,60%	1,20%	0,90%	0,90%	0,20%	0,10%	<0.1%	<0.1%	0%	0%	4%	93%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	0,70%	0,40%	0,30%	<0.1%	<0.1%	0%	0%	0%	2%	95%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	0,20%	0,20%	<0.1%	0%	0%	0%	0%	1%	96%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,30%	0,10%	<0.1%	<0.1%	0%	0%	0%	1%	97%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,20%	<0.1%	<0.1%	0%	0%	0%	1%	98%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	98%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	98%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	98%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	98%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	98%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	98%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	98%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	98%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	98%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	98%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	98%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	3%	7%	15%	24%	21%	14%	8%	4%	1%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	4%	11%	26%	49%	70%	85%	93%	97%	97%	97%	98%	98%	98%		

Figure C.5: Wave scatter diagram of May at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																			Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0,10%	<0.1%	0,30%	0,80%	1,80%	0,90%	0,20%	<0.1%	0,20%	0,30%	0,10%	0,10%	0,10%	0%	0%	5%	5%
1 - 1.5	0%	0%	0%	0%	0,20%	0,30%	0,90%	3%	5,10%	5,40%	2,80%	0,90%	0,40%	0,30%	0,20%	0,10%	0,10%	<0.1%	0%	20%	25%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,60%	1,20%	3,50%	5,50%	6,90%	4,40%	1,70%	0,70%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	25%	49%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	1,10%	1,70%	3,20%	5,50%	4,50%	2,40%	0,80%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	0%	20%	69%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,30%	0,90%	2,10%	3,90%	3,20%	1,80%	0,60%	0,30%	<0.1%	0%	<0.1%	0%	0%	13%	82%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	1,20%	2,10%	2,70%	1,30%	0,90%	0,20%	0,10%	<0.1%	0%	0%	0%	9%	91%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0%	0,30%	1%	1,60%	0,80%	0,40%	0,20%	<0.1%	0%	0%	0%	0%	4%	95%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,70%	0,50%	0,40%	0,10%	<0.1%	0%	0%	0%	0%	2%	97%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,40%	0,40%	0,20%	0,10%	<0.1%	0%	0%	0%	0%	1%	98%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	<0.1%	0,10%	0%	0%	0%	0%	0%	0%	98%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	0%	0%	0%	0%	0%	98%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,10%	<0.1%	0%	0%	0%	0%	0%	98%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	98%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	98%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	98%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	4%	10%	19%	26%	21%	10%	5%	3%	0%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	5%	15%	34%	60%	81%	91%	96%	98%	98%	98%	98%	98%	98%		

Figure C.6: Wave scatter diagram of June at The Rian Offshore Array (Phase 1) location *[37]*

	Wave peak period T_p [s]																					
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	Occurrence Probability H_s	Cumulative occurrence probability H_s
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	<0.1%	0,30%	1%	1%	0,70%	<0.1%	<0.1%	0,10%	0,20%	0,20%	0,10%	<0.1%	0%	0%	0%	4%	4%
1 - 1.5	0%	0%	0%	0%	0,10%	0,40%	1%	3,80%	7,50%	5,10%	1,60%	0,60%	0,20%	0,20%	0,10%	0,10%	0,30%	<0.1%	<0.1%	<0.1%	21%	25%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,50%	1,60%	3,60%	8,50%	8,40%	3,70%	0,90%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	<0.1%	<0.1%	27%	52%
2 - 2.5	0%	0%	0%	0%	0%	0,10%	0,90%	2,50%	5,10%	7,50%	4,30%	1,30%	0,30%	0,10%	<0.1%	0%	<0.1%	0%	<0.1%	0%	22%	74%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,20%	1,10%	3%	4%	2,40%	1%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	12%	87%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	1,10%	2%	1,40%	0,50%	0,30%	0,10%	<0.1%	0%	0%	<0.1%	0%	0%	6%	92%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,80%	0,90%	0,60%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	3%	95%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,70%	0,50%	0,20%	<0.1%	0%	0%	<0.1%	0%	0%	0%	2%	96%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,20%	0,20%	<0.1%	<0.1%	0%	<0.1%	0%	0%	0%	1%	97%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0,10%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	97%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	97%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	97%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	4%	12%	26%	29%	15%	6%	2%	1%	0%	0%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	5%	17%	44%	73%	88%	94%	96%	97%	97%	97%	97%	97%	97%	97%		

Figure C.7: Wave scatter diagram of July at The Rian Offshore Array (Phase 1) location *[37]*

	Wave peak period T_p [s]																					
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	Occurrence Probability H_s	Cumulative occurrence probability H_s
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0,10%	1%	1%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	3%	3%
1 - 1.5	0%	0%	0%	0%	0,20%	0,30%	1,10%	4,30%	6,50%	4,10%	1,20%	0,30%	0,10%	0,20%	0,20%	0,10%	0,20%	<0.1%	0,20%	<0.1%	19%	22%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,70%	1,20%	3,40%	7,20%	7,10%	2,80%	0,90%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	0%	<0.1%	0%	24%	45%
2 - 2.5	0%	0%	0%	0%	0%	0,20%	1,10%	2,40%	5,40%	6,80%	3,30%	1%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	0%	0%	0%	21%	66%
2.5 - 3	0%	0%	0%	0%	0%	<0.1%	0,30%	1,40%	3,20%	5%	3,10%	1,50%	0,60%	0,20%	<0.1%	<0.1%	0%	0%	0%	0%	15%	81%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	1,10%	2,80%	2,10%	1,40%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	0%	0%	0%	8%	89%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	1,10%	1,50%	0,60%	0,40%	0,20%	<0.1%	<0.1%	<0.1%	0%	0%	0%	4%	94%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	0%	0,10%	0,50%	1%	0,60%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	0%	0%	0%	3%	96%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	0,40%	0,30%	<0.1%	<0.1%	0%	0%	0%	0%	0%	1%	97%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,20%	0,10%	<0.1%	0%	0%	0%	0%	0%	1%	98%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	98%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	<0.1%	0%	0%	0%	0%	0%	98%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	98%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	0%	98%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	98%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	98%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	4%	13%	25%	28%	16%	7%	3%	1%	0%	0%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	5%	18%	43%	71%	87%	93%	96%	97%	97%	98%	98%	98%	98%	98%		

Figure C.8: Wave scatter diagram of August at The Rian Offshore Array (Phase 1) location *[37]*

	Wave peak period T_p [s]																					
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	Occurrence Probability H_s	Cumulative occurrence probability H_s
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,50%	0,60%	0,10%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	0%	<0.1%	0%	2%	2%
1 - 1.5	0%	0%	0%	0%	0,10%	0,10%	0,20%	0,90%	2,60%	3,10%	1,70%	0,70%	0,40%	0,20%	0,10%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	10%	12%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,40%	0,50%	1,40%	3,10%	4,10%	3,30%	1,40%	0,80%	0,30%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	16%	28%
2 - 2.5	0%	0%	0%	0%	0%	0,20%	0,50%	0,90%	2,40%	5,20%	4,40%	2,60%	0,90%	0,50%	0,20%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	18%	45%
2.5 - 3	0%	0%	0%	0%	0%	<0.1%	0,40%	0,80%	1,90%	3,40%	4,50%	2,70%	1,50%	0,50%	0,20%	0,10%	0,10%	0%	<0.1%	<0.1%	16%	62%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,50%	1,20%	2,50%	3,20%	2,50%	1,40%	0,90%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	12%	74%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,20%	0,60%	1,10%	2,40%	2%	1,40%	0,80%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	9%	83%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,70%	1,60%	1,60%	1,20%	0,60%	0,30%	<0.1%	0,10%	<0.1%	<0.1%	0%	6%	89%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,30%	1%	1%	0,70%	0,60%	0,20%	<0.1%	<0.1%	<0.1%	0%	0%	4%	93%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,30%	0,70%	0,50%	0,40%	0,10%	<0.1%	<0.1%	0%	0%	0%	2%	95%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,40%	0,30%	<0.1%	<0.1%	0%	0%	0%	0%	1%	96%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,20%	0,10%	<0.1%	<0.1%	0%	0%	0%	0%	0%	96%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,20%	<0.1%	<0.1%	0%	0%	0%	0%	0%	96%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	97%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	0%	0%	97%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	<0.1%	<0.1%	0%	0%	97%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	97%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	97%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	97%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	97%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	2%	5%	13%	21%	23%	16%	9%	6%	2%	0%	0%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	2%	7%	20%	41%	63%	79%	88%	94%	96%	96%	97%	97%	97%	97%		

Figure C.9: Wave scatter diagram of September at The Rian Offshore Array (Phase 1) location *[37]*

	Wave peak period T_p [s]																					
Significant height of wind and swell waves H_s [m]	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	Occurrence Probability H_s	Cumulative occurrence probability H_s
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	0,10%	0,30%	0,20%	0,10%	0,10%	<0.1%	<0.1%	0%	0%	<0.1%	0%	0%	0%	1%	1%
1 - 1.5	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,20%	1,10%	1,60%	1,30%	0,70%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	0%	<0.1%	0%	5%	6%
1.5 - 2	0%	0%	0%	0%	0%	0,20%	0,20%	0,60%	1,60%	2,70%	2,40%	1,40%	0,70%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	10%	16%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	0,60%	0,60%	1,30%	3%	3,30%	2,20%	1,10%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	12%	29%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,40%	0,80%	1,10%	2,80%	3,60%	3,10%	1,60%	0,90%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	15%	43%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,60%	0,80%	2,20%	2,80%	2,70%	2,10%	1%	0,20%	<0.1%	<0.1%	0%	0%	<0.1%	12%	56%
3.5 - 4	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	1,40%	2,50%	2,70%	2,10%	1,10%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	0%	11%	66%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	1%	1,90%	2,40%	2%	1,30%	0,50%	0,20%	<0.1%	0%	0%	0%	10%	76%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,50%	1%	1,80%	1,60%	1,20%	0,50%	0,30%	<0.1%	<0.1%	0%	<0.1%	7%	83%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	1,10%	1,30%	1%	0,60%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	5%	88%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,60%	1%	0,60%	0,30%	0,20%	<0.1%	<0.1%	<0.1%	0%	3%	91%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,60%	0,80%	0,70%	0,30%	0,20%	<0.1%	<0.1%	0%	0%	3%	93%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,50%	0,40%	0,20%	<0.1%	0,10%	<0.1%	<0.1%	0%	1%	95%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,50%	0,30%	<0.1%	0,10%	<0.1%	<0.1%	0%	1%	96%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,10%	<0.1%	0,20%	<0.1%	0%	<0.1%	1%	96%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	0%	0%	96%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	96%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	96%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	<0.1%	0%	0%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	0%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	<0.1%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	<0.1%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	1%	3%	7%	16%	20%	20%	15%	10%	4%	1%	1%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	5%	11%	27%	47%	66%	81%	91%	95%	96%	96%	96%	96%	96%		

Figure C.10: Wave scatter diagram of October at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%
1 - 1.5	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,50%	0,50%	0,70%	0,50%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	0%	<0.1%	<0.1%	3%	3%
1.5 - 2	0%	0%	0%	0%	0%	0,10%	<0.1%	<0.1%	1%	1,40%	2,10%	1,20%	0,80%	0,40%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	7%	10%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	0,40%	0,30%	0,80%	1,70%	2,60%	1,90%	1,20%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	0%	10%	20%
2.5 - 3	0%	0%	0%	0%	0%	<0.1%	0,20%	0,50%	0,70%	1,50%	2,80%	2,50%	1,70%	0,80%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	0%	11%	31%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,80%	0,90%	2,70%	3,10%	2,20%	1,30%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	12%	42%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,20%	0,30%	0,90%	2,20%	2,90%	2,60%	1,40%	0,70%	0,10%	0,10%	<0.1%	<0.1%	0%	11%	54%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,50%	1,50%	2,60%	2,50%	1,70%	0,80%	0,20%	<0.1%	<0.1%	0%	<0.1%	10%	64%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	0%	0,20%	0,30%	1,20%	2,20%	2,40%	1,70%	0,80%	0,30%	0,10%	<0.1%	<0.1%	0%	9%	73%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,60%	1,40%	2,20%	1,70%	0,70%	0,10%	0,10%	<0.1%	<0.1%	0%	7%	80%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,40%	1%	1,40%	1,30%	0,80%	0,30%	0,10%	<0.1%	0%	0%	5%	85%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,60%	1,20%	1%	0,80%	0,20%	0,30%	<0.1%	0%	<0.1%	4%	89%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,70%	0,70%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	2%	92%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,40%	0,70%	0,40%	0,20%	0,20%	<0.1%	<0.1%	0%	2%	94%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,30%	0,10%	<0.1%	<0.1%	0%	<0.1%	1%	95%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,20%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	1%	95%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,10%	0,10%	0,10%	<0.1%	<0.1%	0%	0%	96%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	0%	96%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	0%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	96%
15.5 - 16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
16 - 16.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	5%	8%	17%	20%	20%	14%	7%	2%	1%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	7%	14%	31%	52%	71%	85%	92%	94%	96%	96%	96%	96%		

Figure C.11: Wave scatter diagram of November at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1 - 1.5	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0,20%	0,30%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	1%	1%
1.5 - 2	0%	0%	0%	0%	0%	0,20%	<0.1%	<0.1%	0,30%	0,80%	1,10%	1,10%	0,60%	0,30%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	0%	5%	6%
2 - 2.5	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,30%	1,10%	1,80%	1,60%	1,50%	0,90%	0,40%	0,20%	0,10%	<0.1%	<0.1%	0%	8%	14%
2.5 - 3	0%	0%	0%	0%	0%	0%	0,20%	0,30%	0,50%	0,80%	1,90%	2%	1,90%	1%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	9%	23%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,40%	0,90%	1,80%	2,60%	1,90%	1,50%	0,50%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	10%	33%
3.5 - 4	0%	0%	0%	0%	0%	0%	0%	0,10%	0,40%	0,90%	1,40%	2,70%	2,10%	1,80%	0,60%	0,30%	0,20%	<0.1%	0%	<0.1%	11%	44%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	1,40%	2,40%	2,50%	1,90%	0,90%	0,30%	0,20%	<0.1%	<0.1%	0%	10%	54%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,40%	0,70%	1,70%	2,30%	1,70%	0,90%	0,50%	0,10%	<0.1%	<0.1%	<0.1%	8%	62%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	1,20%	2,60%	1,80%	0,90%	0,30%	0,20%	<0.1%	<0.1%	0%	8%	70%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,80%	1,60%	1,60%	0,90%	0,40%	0,30%	<0.1%	<0.1%	<0.1%	6%	75%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	1,50%	1,50%	1%	0,50%	0,20%	<0.1%	0%	<0.1%	5%	81%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,70%	1,10%	1,10%	0,50%	0,30%	<0.1%	<0.1%	<0.1%	4%	85%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,50%	0,80%	0,80%	0,40%	0,30%	<0.1%	<0.1%	<0.1%	3%	87%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,30%	0,70%	0,60%	0,40%	0,40%	0,20%	<0.1%	<0.1%	3%	90%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,50%	0,70%	0,30%	0,20%	<0.1%	<0.1%	0%	2%	92%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,40%	0,20%	0,40%	0,10%	<0.1%	0%	1%	93%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,30%	0,20%	0,20%	<0.1%	<0.1%	<0.1%	1%	94%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,20%	0,20%	0,10%	<0.1%	0%	1%	95%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,10%	0,20%	<0.1%	0,10%	<0.1%	1%	95%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	0%	95%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	95%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	<0.1%	<0.1%	0%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	0%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	0%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	0%	0%	1%	2%	6%	11%	17%	20%	18%	11%	5%	4%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	0%	1%	2%	4%	10%	21%	38%	58%	75%	86%	91%	95%	95%	96%	96%		

Figure C.12: Wave scatter diagram of December at The Rian Offshore Array (Phase 1) location *[37]*

Significant height of wind and swell waves H_s [m]	Wave peak period T_p [s]																				Occurrence Probability H_s	Cumulative occurrence probability H_s
	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20		
0 - 0.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0.5 - 1	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,30%	0,50%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	1%	1%
1 - 1.5	0%	0%	0%	0%	<0.1%	0,10%	0,40%	1,20%	2,50%	2,30%	1,30%	0,60%	0,30%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	9%	10%
1.5 - 2	0%	0%	0%	0%	<0.1%	0,30%	0,60%	1,30%	2,90%	3,60%	2,70%	1,60%	0,70%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	14%	24%
2 - 2.5	0%	0%	0%	0%	0%	0,10%	0,60%	0,90%	2%	3,50%	3,10%	2,20%	1,20%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	14%	39%
2.5 - 3	0%	0%	0%	0%	0%	<0.1%	0,30%	0,80%	1,40%	2,50%	2,80%	2,20%	1,60%	0,80%	0,30%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	13%	52%
3 - 3.5	0%	0%	0%	0%	0%	0%	<0.1%	0,40%	0,80%	1,60%	2,20%	2,10%	1,60%	1%	0,30%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	10%	62%
3.5 - 4	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,40%	0,90%	1,60%	1,90%	1,50%	1%	0,40%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	8%	69%
4 - 4.5	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,20%	0,50%	1,20%	1,60%	1,50%	1,10%	0,50%	0,20%	<0.1%	<0.1%	<0.1%	<0.1%	7%	76%
4.5 - 5	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,70%	1,20%	1,30%	1%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	5%	81%
5 - 5.5	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0,10%	0,30%	0,80%	1,20%	1%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	4%	86%
5.5 - 6	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,50%	0,80%	0,80%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	3%	89%
6 - 6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,30%	0,70%	0,70%	0,50%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	3%	91%
6.5 - 7	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,40%	0,50%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	2%	93%
7 - 7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,20%	0,40%	0,40%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	1%	94%
7.5 - 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	0,20%	0,30%	0,20%	0,10%	<0.1%	<0.1%	<0.1%	1%	95%
8 - 8.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,20%	0,20%	0,10%	0,10%	<0.1%	<0.1%	<0.1%	1%	96%
8.5 - 9	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,10%	0,10%	0,10%	<0.1%	<0.1%	0%	0%	96%
9 - 9.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0,10%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
9.5 - 10	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
10 - 10.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
10.5 - 11	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
11 - 11.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
11.5 - 12	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12 - 12.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
12.5 - 13	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13 - 13.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0%	96%
13.5 - 14	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	96%
14 - 14.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	0%	96%
14.5 - 15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	<0.1%	<0.1%	0%	0%	96%
15 - 15.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	96%
15.5 - 16	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0%	96%
16 - 16.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	<0.1%	0%	96%
16.5 - 17	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17 - 17.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
17.5 - 18	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	96%
18 - 18.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	<0.1%	0%	0%	96%
Occurrence Probability T_p	0%	0%	0%	0%	0%	1%	2%	5%	11%	16%	16%	15%	13%	10%	5%	2%	1%	0%	0%	0%		
Cumulative occurrence probability T_p	0%	0%	0%	0%	0%	1%	2%	7%	18%	34%	50%	65%	78%	88%	93%	95%	96%	96%	96%	96%		

Figure C.13: Annual wave scatter diagram of The Rian Offshore Array (Phase 1) location *[37]*

Wind Speed W_s [m/s]	Wind Direction								Occurrence Probability W_s	Cummulative Occurrence Probability W_s
	N	NE	E	SE	S	SW	W	NW		
0 - 5	2,10%	2%	1,80%	1,70%	1,90%	2,30%	2,50%	2,30%	16,60%	16,60%
5 - 10	4,60%	3,90%	2,90%	3,40%	6,20%	8,50%	8,60%	6,20%	44,30%	60,90%
10 - 15	2,20%	1,20%	1,20%	2,20%	5,50%	7,10%	6,70%	3,70%	29,80%	90,70%
15 - 20	0,40%	0,20%	0,20%	0,60%	1,70%	1,90%	2,30%	1%	8,30%	99,00%
20 - 25	<0.1%	<0.1%	<0.1%	<0.1%	0,20%	0,20%	0,40%	0,10%	0,90%	99,90%
25 - 30	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0,00%	99,90%
30 - 35	0%	0%	0%	0%	0%	<0.1%	<0.1%	<0.1%	0,00%	99,90%
35 - 40	0%	0%	0%	0%	0%	0%	<0.1%	0%	0,00%	99,90%

Figure C.14: The annual wind speed and direction probability at The Rian Offshore Array (Phase 1) location *[37]*

D

Economic Analysis Intermediate Results

	T_{oper, (in-)cont.} [hours]		
	concept 1	concept 11	concept 13
	2802	5772	2160
	T_{trans., (in-)cont. [hours]		
Distance [km]	concept 1	concept 11	concept 13
0	0	0	0
46	6	6	406
61	8	8	539
100	13	13	884
200	26	26	1767
300	39	39	2651
400	52	52	3534
500	65	65	4418
	T_{total, (in-)cont} [days]		
Distance [km]	concept 1	concept 11	concept 13
0	234	481	180
46	234	482	214
61	234	482	225
100	235	482	254
200	236	483	327
300	237	484	401
400	238	485	475
500	239	486	548

Figure D.1: Intermediate results for the computation of the total project duration

	T_{oper.,(in-)cont.,cor.,spar} [hours]		
	concept 1	concept 11	concept 13
	9012	14879	5985
	T_{oper.,(in-)cont.,cor.,WTG} [hours]		
	concept 1	concept 11	concept 13
	10829	17904	7283
	T_{trans.,(in-)cont.,cor.,spar/WTG} [hours]		
Distance [km]	concept 1	concept 11	concept 13
0	0	0	0
46	9	9	598
61	12	12	793
100	19	19	1299
200	38	38	2599
300	57	57	3898
400	77	77	5197
500	96	96	6497
	T_{total,(in-)cont.,cor.} [hours]		
Distance [km]	concept 1	concept 11	concept 13
0	827	1366	553
46	827	1367	603
61	828	1367	619
100	828	1368	661
200	830	1369	769
300	831	1371	878
400	833	1372	986
500	835	1374	1094

Figure D.2: Intermediate results for the computation of the total project duration corrected by the annual workability

Distance [km]	C_{vessel,(in-)cont.} [mln $]		
	concept 1	concept 11	concept 13
0	114,66	235,69	64,8
46	114,66	236,18	77,04
46	114,66	**298,84**	77,04
61	115,15	298,84	81
61	**145,08**	298,84	81
100	145,7	298,84	91,44
200	146,32	299,46	117,72
300	146,94	300,08	144,36
400	147,56	300,7	171
500	148,18	301,32	197,28
Distance [km]	C_{fuel,trans.,(in-)cont.} [mln $]		
	concept 1	concept 11	concept 13
0	0	0	0
46	0,34	0,34	6,77
46	0,34	0,34	6,77
61	0,46	0,46	8,98
61	0,46	0,46	8,98
100	0,75	0,75	14,73
200	1,5	1,5	29,45
300	2,25	2,25	44,18
400	3	3	58,9
500	3,75	3,75	73,63
	C_{fuel,oper.,(in-)cont.} [mln $]		
	concept 1	concept 11	concept 13
	17,41	36,9	11,95
Distance [km]	C_{total,(in-)cont.} [mln $]		
	concept 1	concept 11	concept 13
0	132,07	272,59	76,75
46	132,41	273,42	95,76
46	132,41	**336,08**	95,76
61	133,02	336,2	101,93
61	**162,95**	336,2	101,93
100	163,86	336,49	118,12
200	165,23	337,86	159,12
300	166,6	339,23	200,49
400	167,97	340,6	241,85
500	169,34	341,97	282,86

Figure D.3: Intermediate results for the computation of the total installation cost

Distance [km]	C_{vessel,(in-)cont.,cor.} [mln $]		
	concept 1	concept 11	concept 13
0	405,23	669,34	199,08
46	405,23	669,83	217,08
46	405,23	**847,54**	217,08
61	405,72	847,54	222,84
61	**513,36**	847,54	222,84
100	513,36	848,16	237,96
200	514,6	848,78	276,84
300	515,22	850,02	316,08
400	516,46	850,64	354,96
500	517,7	851,88	393,84
Distance [km]	C_{fuel,trans.,(in-)cont.,cor.} [mln $]		
	concept 1	concept 11	concept 13
0	0	0	0
46	0,34	0,34	6,77
46	0,34	0,34	6,77
61	0,46	0,46	8,98
61	0,46	0,46	8,98
100	0,75	0,75	14,73
200	1,5	1,5	29,45
300	2,25	2,25	44,18
400	3	3	58,9
500	3,75	3,75	73,63
Distance [km]	C_{fuel,oper.,(in-)cont.,cor.} [mln $]		
	concept 1	concept 11	concept 13
0	61,68	104,88	36,71
46	61,76	104,96	36,72
46	61,76	104,96	36,72
61	61,78	104,98	36,72
61	61,78	104,98	36,72
100	61,84	105,04	36,72
200	62,01	105,21	36,74
300	62,17	105,37	36,75
400	62,33	105,53	36,76
500	62,5	105,7	36,77
Distance [km]	C_{total,(in-)cont.,cor.} [mln $]		
	concept 1	concept 11	concept 13
0	466,91	774,22	235,79
46	467,33	775,13	260,57
46	467,33	**952,84**	260,57
61	467,96	952,98	268,54
61	**575,6**	952,98	268,54
100	575,95	953,95	289,41
200	578,11	955,49	343,03
300	579,64	957,64	397,01
400	581,79	959,17	450,62
500	583,95	961,33	504,24

Figure D.4: Intermediate results for the computation of the total installation cost corrected by the annual workability

Distance [km]	m_{CO2-emission,(in-)cont.} [10^3 t]		
	concept 1	concept 11	concept 13
0	68,55	145,29	47,05
46	69,89	146,63	73,71
46	69,89	146,63	73,71
61	70,36	147,11	82,41
61	70,36	147,11	82,41
100	71,51	148,25	105,05
200	74,46	151,2	163,01
300	77,41	154,15	221,01
400	80,36	157,11	278,97
500	83,32	160,06	336,97

Figure D.5: Intermediate results for the computation of the total carbon emission

Distance [km]	m_{CO2-emission,(in-)cont.,cor.} [10^3 t]		
	concept 1	concept 11	concept 13
0	242,87	412,97	144,55
46	244,2	414,62	171,24
46	244,2	414,62	171,24
61	244,68	415,17	179,94
61	244,68	415,17	179,94
100	245,82	416,55	202,58
200	248,77	420,17	260,62
300	251,72	423,75	318,66
400	254,68	427,34	376,66
500	257,63	430,96	434,7

Figure D.6: Intermediate results for the computation of the total carbon emission corrected by the annual workability

E
Confidential Appendix

In order to comply with the agreement regarding the confidentiality of knowledge shared by Allseas, this Appendix has been created. The Appendix consists of Sections with similar headings to those in which certain information has been removed. The corresponding Sections will be referred to in the paper.

E.1. Case Study

E.1.1. Pioneering Spirit Characteristics

E.1.2. Topside Lift System

E.1.3. Jacket Lift System

E.1.4. 5000t Special Purpose Crane

E.2. Technical Feasibility

E.2.1. Storyboards

E.2.1.1. Concept Limitations

E.2.2. Technical Description

Mooring System

E.3. Workability Analysis

E.4. Economic Analysis

F

Data Workability Assessment

Table F.1: Coordinates of the lifting points used in the workability assessment for different concepts and operations

TLP unloading			
Concept	**x**	**y**	**z**
1	-	-	-
11	11	115,44	76,4
13	-	-	-
TLP installation			
Concept	**x**	**y**	**z**
1	-	-	-
11	-53,02	43,62	76,4
13	-	-	-
spar unloading			
Concept	**x**	**y**	**z**
1	335,96	0	37
11	11	94,4	136,4
13	-	-	-
spar installation			
Concept	**x**	**y**	**z**
1	335,96	0	37
11	-32,4	51	136,4
13	335,96	0	37
WTG unloading for spar or TLP			
Concept	**x**	**y**	**z**
1 (only for spar)	335,96	0	37
11	11	94,4	176
13	-	-	-
WTG installation on spar or TLP			
Concept	**x**	**y**	**z**
1 (only on spar)	335,96	0	37
11	-32,4	51	176
13 (only on spar)	335,96	0	37

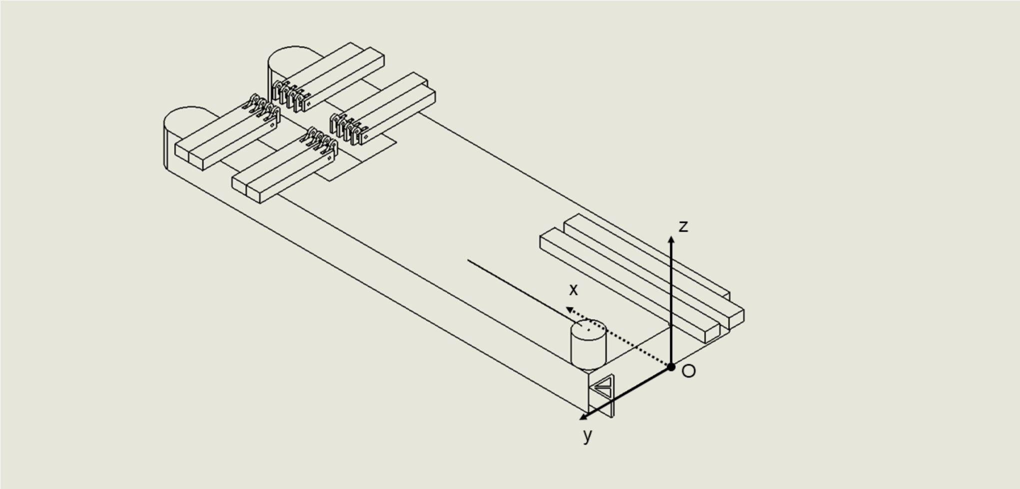


Figure F.1: Reference system for the definition of the lifting point coordinates