Exploring the feasibility of placing a wind turbine on top of an FPSO

Master of Science Thesis

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December 12, 2022

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Acknowledgements

Dear reader,

The document in front of you presents the content of my thesis, 'Exploring the feasibility of placing a wind turbine on top of an FPSO', as the final milestone during my master's of Offshore and Dredging Engineering at the Delft University of Technology. The assignment is provided by the company Bluewater Energy Services, a company that is leading in offshore technology and experienced in, among other things, the design and operation of floating, production, storage, and offloading (FPSO) systems.

With this report, I hope to have contributed to Bluewater's incentive to shift to and invest in new renewable energy solutions. I would like to thank all of the Bluewater colleagues that helped me during my thesis. A special thanks to Jaap-Jan van Nielen and Clemens van der Nat for providing me with this thesis topic and the opportunity to work on it at Bluewater. A special thanks to Teddy Simanjuntak for his guidance as my daily supervisor within Bluewater, which helped me a lot during the entire process. Another special thanks to Jeroen van der Cammen for his time and input during multiple discussions on my thesis progress.

From the Delft University of Technology, I would like to thank Pim van der Male as my supervisor for his input and guidance during my graduation period. Another thanks to André van der Stap, who functioned as my graduation chairman, for his enthusiasm concerning this topic.

Finally, I would like to thank my girlfriend, family, and friends for their great support, flexibility, and welcoming distractions during my graduation period. It has been a challenging time in which I learned a lot, and I look forward to the next challenges in my future career.

Youri Öhlschläger

December 12, 2022

Abstract

Changing the way of power production on a Floating, Production, Storage, and Offloading (FPSO) system by using renewable power can contribute to reducing an FPSO's carbon footprint while operating. Bluewater Energy Services is interested in the use of a wind turbine placed on top of an FPSO, to power the FPSO's internal electricity grid. This suggested configuration of a wind turbine and FPSO results in many different challenges that are new to the offshore industry. Therefore, this thesis considers the following research question: 'To what extent is placing a 5 MW wind turbine on top of an FPSO feasible?'

To answer this question this research is split into two parts. The first part consists of a literature research, in which two reference FPSOs, Bleo Holm and Haewene Brim, are introduced, and the decision of considering a 5 MW horizontal axis wind turbine is made. A wind turbine with this capacity can deliver approximately 75% of the FPSO's required power during its normal operations. This information is used as input for a hazard identification (HAZID), in which a group of experts was challenged to brainstorm on possible hazards concerning the topic. The second part introduces the first design concept and focuses on the assessment of feasibility. Both technical feasibility and non-technical feasibility are evaluated. For technical feasibility, topics such as vessel stability, vessel strength, vibrations, the system's motions, and wind turbine use during operational events on the FPSO are considered. From the non-technical feasibility, additional focus is put on the health, safety, and environmental (HSE) aspects of the project, and the project's business case.

From the technical evaluation of the chosen design configuration a motion analysis, which consists of a diffraction analysis in HydroStar and a time domain simulation in OrcaFlex, identified a limitation in the wind turbine's nacelle acceleration. This motion analysis was limited by the unavailability of a wind turbine model consisting of a yaw control system. In operations, the limit for nacelle acceleration is exceeded, which can be mitigated by performing more frequent wind turbine shutdowns. In extreme conditions for the vessel's fully loaded condition, this mitigation is not an option. Recommended is an improvement of the design, to reduce the nacelle's acceleration, with options such as reducing the wind turbine tower height or increasing the tower's bending stiffness. Also, the found result is linked to the location of the Haewene Brim in the central North Sea, which is generally considered a site with rough environmental conditions. A different location with calmer waters is likely to still facilitate this concept.

The considerable HSE-related risks that have been identified are related to the risk of a wind turbine's dropped objects onto the FPSO, which can occur from different causes such as fire, structural failure, or lightning. This risk comes with a low probability, while its impact can be high. The business case of the project shows the potential of saving 250,000 tonnes of CO2 emissions during a typical wind turbine's lifetime of 20 years. Also, it is estimated that a positive return on investment can be made in case the capital expenditures are less than €64.3 million. However, this result is sensitive to changes in, among other parameters, the wind turbine's power production.

Based on the findings described above the conclusion to the question: 'To what extent is placing a 5 MW wind turbine on an FPSO feasible?' is that it can be considered feasible in case a design concept is found for which the nacelle acceleration is no longer an issue. However, future research is recommended on comparing this concept to other renewable power alternatives for the FPSO, based on their risks and financials, to see if the safety risks are worth the financial gain. On top of that, the development of a wind turbine yaw-controlled model is suggested to capture the interaction between weathervaning FPSO and yaw-operating wind turbine. In addition, research can be done on the installation method for a wind turbine on an FPSO.

Contents

Nomenclature

Abbreviations

ABS	American Bureau of Shipping
AC	Alternating Current
AEP	Annual Energy Production
ALARP	As Low As Reasonably Practicable
CAPEX	Capital Expenditures
CCS	Carbon, Capture, and Storage
$CO2$	Carbon Dioxide
DAC	Direct Air Capture
DNV	Det Norske Veritas
DoF	Degree of Freedom
EAF	Equivalent Availability Factor
EMF	Electromagnetic Field
FLS	Fatigue Limit State
FPSO	Floating, Production, Storage, and Offloading
FSO	Floating, Storage, and Offloading
GHG	Green House Gas
HAWT	Horizontal-Axis Wind Turbine
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HSE	Health, Safety, and Environment or Health and Safety Executive
IEC	International Electrotechnical Commission
IMO	International Maritime Organisation
ISO	International Standards Organisation
JONSWAP	Joint North Sea Wave Project
LQ	Living Quarters
MGO	Marine Gas Oil
MSL	Mean Sea Level
MST	Multipurpose Shuttle Tanker

NOx	Nitrous Oxide
NPD	Norwegian Petroleum Directorate
NPV	Net Present Value
$NREL$	National Renewable Energy Laboratory
$OPEX$	Operating Expenditures
RAO	Response Amplitude Operator
$RIVM$	Dutch National Institute for Public Health and the Environment
RNA	Rotor-Nacelle-Assembly
ROI	Return On Investment
$SIMOPS$	Simultaneous Operations
SPM	Single Point Mooring
ULS	Ultimate Limit State
$VAWT$	Vertical-Axis Wind Turbine
WT	Wind Turbine
WTG	Wind Turbine Generator

Symbols

∇	Displaced water volume
ω	Wave frequency
ϕ	Heeling angle or Incident angle
ρ_{air}	Air density
θ_f	Angle of flooding
ζ_a	Wave amplitude
A	Area
BM	Bending Moment
c	Chord
C_D	Drag coefficient
c_f	Capacity factor
C_h	Height coefficient
C_L	Lift coefficient
C_s	Shape coefficient
C_T	Thrust coefficient
C_{solid}	Solidity coefficient
COG	Center Of Gravity

$Disp$	Displacement mass
f_D	Drag force
f_L	Lift force
GG_0	Free surface correction
GM	Metacentric height
GZ	Righting lever arm
H_s	Significant wave-height
HM	Heeling Moment
I	Mass moment of inertia
K	Radius if gyration
KG	Vertical height from keel to COG
KMT	Transverse metacentric height above baseline
KN	Righting lever arm measured from keel
LCB	Longitudinal Center of Buoyancy
LCF	Longitudinal Center of Flotation
LCG	Longitudinal Center of Gravity
m	Mass
MCT	Moment to Change Trim
P_{rated}	Rated power
R	Radius
RM	Righting Moment
T	Draught moulded or Thrust force
T_a	Draft aft
T_f	Draft fore
T_k	Draught extreme
T_m	Draft mean
T_p	Peak period
T_y	Number of hours in a year
T_z	Mean zero-up-crossing period
TCG	Transverse Center of Gravity
TR	Trim
V	Wind speed
VCG	Vertical Center of Gravity

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1 Introduction

This chapter gives an introduction to the thesis report. It describes the importance of sustainability and introduces the topic of Floating, Production, Storage, and Offloading (FPSO) systems. Furthermore, the problem statement and objective are described, together with the methodology, company description, and structure of the report.

1.1 The importance of more sustainable processes

It is generally known that greenhouse gas (GHG) emissions are largely causing the problem of global warming. To slow down or even prevent the increase of average global temperatures there are many companies, especially from the energy industry, that are making an effort to reduce their greenhouse gas emissions [1]. To achieve this goal there is a need for many new and sustainable solutions.

The use of oil and gas in the energy industry is receiving more and more criticism. Nevertheless, it is still important that these resources are available, to make sure that the worldwide supply of power can meet the demand. Within the sector, there is already a shift moving away from the extraction of oil towards the much less polluting gas. Next to this, the development of more renewable energy sources contributes significantly to emission reductions [2]. Since oil and gas are still a necessity in the energy industry, options to further reduce emissions are investigated continuously. This also holds for the application of FPSOs.

1.2 Floating, Production, Storage, and Offloading systems

FPSO systems are floating movable vessel-shaped platforms which can process hydrocarbons that are extracted from wells which are located in areas with deep water conditions which are not reachable for current fixed oil and gas platforms. FPSOs can either be newly designed or be created using an already existing hull which often originates from an oil tanker [3].

FPSOs provide a sequence of tasks available during their operations, starting with the extraction of hydrocarbons from their well, processing the hydrocarbons, and storing them inside the hull of the vessel. Often, gas is re-injected into the well to maintain the pressure in the well. Finally, it can offload the processed hydrocarbons towards pipelines or a transportation oil or gas tanker. Besides this, the personnel working on the FPSO are facilitated with a large accommodation on the vessel providing all their basic needs [4].

For an FPSO to be able to efficiently execute its operations, it has to be kept in place. This is done using a mooring system. There are many different types of mooring system configurations and technologies. The most advanced option is the use of an (internal) turret mooring system, which allows the FPSO to rotate based on the local environmental conditions in which it has to operate. This is also called weathervaning [5].

1.3 Problem statement

With the importance of having more sustainable processes, it is also relevant that FPSOs are adapting to fulfill the needs of society by reducing emissions as much as possible. This can (partly) be achieved by changing the way of power production from which an FPSO can operate.

The company Bluewater Energy Services B.V. is interested in the possibility of placing a wind turbine on top of an FPSO, to provide the FPSOs internal electricity grid with power to be able to perform its day-to-day operations. This will reduce the emissions of the FPSO, and will also save fuel costs in the power generation process of an FPSO.

1.4 Research objective

This report is providing an answer to the following main research question:

To what extent is placing a 5 MW wind turbine on top of an FPSO feasible?

This research question has been formed in the literature research which is shown in part I of this report. The main research question is supported by several sub-questions which are:

1. How can feasibility be described and assessed?
2. What will be the wind turbine characteristics of the chosen turbine?
3. What determines the placement of a wind turbine on an FPSO and is it possible to place a wind turbine on existing FPSOs?
4. What are the technical limitations that can impact the project's feasibility?
5. What are common non-technical aspects that can impact the feasibility of this project?
6. What are the Health, Safety, and Environmental (HSE) hazards and possible mitigations that can impact the feasibility of the project?
7. What is the business case of this project and which aspects can impact its financial attractiveness?

The objective of the research is to identify possible critical showstoppers for placing a 5 MW wind turbine on top of an FPSO.

1.5 Methodology

The answering and formulation of the research question are done based on a feasibility study and literature research. The literature research provides the fundamentals for the feasibility study for which a research plan is set up. The research plan provides an overview of the criteria which are evaluated in the feasibility study.

The focus of the feasibility study is put onto the FPSO's behavior during 'normal' day-to-day operations. These are the operations taking place when the FPSO is located at its site. This includes production, storage, offloading, and on-site maintenance. In the study, several different aspects are addressed, namely technical and non-technical aspects. From the non-technical aspects, additional attention is laid on HSE and the business case.

1.6 Company description

The research is conducted for the offshore company Bluewater Energy Services B.V., section Structural Engineering, at the main office in Hoofddorp, the Netherlands. The company is founded in 1978, and its main activities are providing oil companies worldwide with FPSOs, Floating, Storage, and Offloading (FSO) systems, and Single Point Mooring (SPM) systems. Besides, Bluewater is also looking into Offshore Floating Wind Systems.

Bluewater values new sustainable developments and therefore it has its own sustainable development goal which describes [6][1]: 'Reducing its carbon footprint is the main challenge for the oil & gas industry. As a service provider in the oil & gas value chain, we aim to minimize the carbon footprint of our own operations, which boils down to using energy more efficiently and resources consciously. Subsequently, we are diversifying our product portfolio and technologies to support the creation of renewable offshore energy sources.'

[1]Reference coming from Bluewater's Intranet database (not publicly accessible).

1.7 Structure of report

The report is split up into two different parts. Part I contains a literature research leading to the research questions as described in section 1.4. From the literature research, a research plan is created to evaluate the feasibility of placing a 5 MW wind turbine on top of an FPSO. Part I consists of the following chapters:

- Chapter 2 provides an introduction to the literature research and describes the search strategy.
- Chapter 3 describes how sustainability can be related to FPSOs. It gives the steps to obtain a 'green' FPSO and ends with a description of the case study for this report.
- Chapter 4 focuses on the different types of FPSO layouts and introduces two different FPSOs which are used as a reference in this report. It also describes the power consumption of these FPSOs.
- Chapter 5 explains the choice for a 5 MW horizontal-axis wind turbine and a brief description of how it could be integrated into an FPSO's electricity grid.
- Chapter 6 describes the method and results of a hazard identification that is performed to identify the most critical hazards concerning this case study.
- A conclusion to the findings of the literature research is given, after which chapter 7 provides the research plan for the thesis report. Also, it describes what definition of the term feasibility is used for this thesis.

Part II of the report consists of an evaluation of the feasibility of the case study according to the research plan described in chapter 7. The part is divided into the following chapters:

- Chapter 8 describes a first design concept and explains the choices that are made to form this concept. Here the focus is put on the location of the wind turbine on an FPSO. One of the two reference FPSOs is selected for the continuation of the report.
- Chapter 9 focuses on the technical feasibility of the created design concept. Insight is provided into several technical aspects, which are vessel stability, vessel strength, vibrations, motions, and operational procedures.
- Chapter 10 explains the importance of several common non-technical related project issues, that could influence the project's feasibility.
- Chapter 11 provides more insight into several important health, safety, and environmental hazards that have been identified as part of the hazard identification of chapter 6. The hazards are evaluated as risks and possible mitigations are discussed.
- Chapter 12 explains the business case of the project. Here is described what the potential emission reduction of this project is, and insight is given into the financial attractiveness of this project.
- The report ends with a discussion, followed by the conclusion and several recommendations for future research.

Part I

Literature research

2 Introduction to the literature research

This chapter is an introduction to the first part of this thesis report which consists of a literature research and formulation of a research plan. It describes the goal of the literature research, as well as the search strategy, and the structure of the literature research.

2.1 Literature research objectives

The objective of the literature research is to formulate accurate and relevant research questions that will be the basis for the thesis report. This is done by providing insight into the growing relevance of sustainability, and how this can be applied to FPSOs.

This continues with the possibility of using a wind turbine placed on top of an FPSO to power the FPSOs internal electricity grid. The choice of a wind turbine is explained after which several preliminary design configurations are described. These choices are a necessity in the preparation of a hazard identification (HAZID) which is part of the literature research, where experts have evaluated the provided preliminary design configurations to identify possible showstoppers for the realization of this project.

2.2 Search strategy

The search strategy for this literature research consists of a review of the literature concerning several topics. These topics are:

- Sustainability
- FPSO configurations
- Power consumption of an FPSO
- Wind turbines
- Hazard identification
- Feasibility

The focus is put on using scientific reports, books, theses, and websites of recognized authorities. Additional attention is given to the source's objectivity. The tools which are mainly used to achieve this are TU Delft's WorldCat Discovery, TU Delft's Repository, Google Scholar, and Bluewater's internal database.

The HAZID requires another form of literature retrieval. Here experts with different backgrounds are counseled and their input is used to create new literature. The results of the HAZID are agreed upon by the different experts that participated in the process. This is further explained in chapter 6. An overview of the experts that participated and their expertise is given in appendix A.

2.3 Structure of literature research

The literature research contains several chapters starting with chapter 3 on sustainability related to FPSOs in which the case study is formulated. This is followed by chapter 4 which provides insight into FPSO configurations and FPSO power consumption. Chapter 5 describes the choice for a particular wind turbine. Chapter 6 contains the process and results of a HAZID concerning the case study. Finally, the conclusions of the literature research are given after which the definition of feasibility is discussed and a research plan is formulated in chapter 7.

3 Sustainability in relation to FPSOs

The use of the term sustainability has developed throughout the years. Jeremey L. Caradonna [7] shows that before 1970 the term sustainability was not to be found in any book of the English language after which since 1980 a rapid increase in the use of the term occurred. In 1987, the Brundtland Commission from the United Nations [8] gave the following definition to the word sustainability: 'meeting the needs of the present without compromising the ability of future generations to meet their own needs.'

Many people nowadays tend to mix up the terms 'sustainability' and 'green'. Misachi [9] explains in an article on World Atlas that sustainability concerns several aspects, namely environmental health, economic vitality, and social benefits, while the word green only concerns environmental health. Following his reasoning, it can be concluded that something sustainable can always be called green, while something green does not always have to be sustainable.

The need for more sustainable processes has been converted into rules and regulations. Therefore, several climate goals are set by governmental instances throughout the world mainly focused on reducing GHG emissions.

3.1 Climate goals

The European Union has set several goals for reducing greenhouse gas emissions. These goals were adopted in the European Climate Law in June 2021. Two of the main goals set are to reach a 55% reduction in emissions by 2030 and to become net zero when it comes to GHG emissions in 2050 [10]. Since carbon dioxide (CO2) and methane are two of the main emissions when it comes to GHG that are emitted in the offshore industry [11], reducing the carbon footprint becomes a priority.

Carbon emissions in the offshore industry can occur in several stages throughout a project. Namely construction, operation, decommissioning, and even the impact of the produced product [12]. During construction, emissions might occur during the manufacturing and processing of the material, the installation process, and even the transportation of constructed items. In operations, the emissions can occur during for example power production or required transportation for operational purposes. During decommissioning, again the material needs to be transported and decommissioned, which could lead to emissions for instance during the transport and burning of leftover materials. The emissions impact of the used product depends on the product. The hydrocarbons which are collected by an FPSO will result in emissions whenever they are used. To reach these climate goals, efforts to reduce the carbon footprint need to be made in every sector, as much as possible. For FPSOs this requires several efforts.

3.2 Green FPSOs

The emissions generated by FPSOs are created in different parts of the operations that take place on an FPSO. An overview of the typical FPSO emission sources is given in figure 3.1. As can be seen, the largest part of the emissions occurs due to the power generation on an FPSO. To obtain more sustainable FPSOs, changes are required that reduce the emissions of the sources shown in figure 3.1.

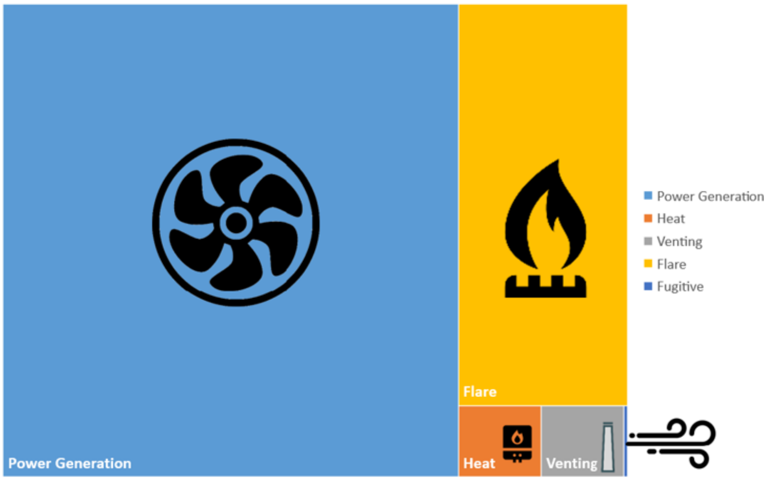


Figure 3.1: Typical FPSO emission sources [13][2].

According to the UK energy transition company Stellae Energy [14], four steps need to be combined to reach the target of having a fully 'green' FPSO:

1. 'Improving energy usage efficiencies'
2. 'Reducing waste and GHG emissions'
3. 'Implementing carbon capture measures'
4. 'Increasing the use of clean energy renewables into the energy mix'

These steps require multiple adjustments in the FPSO systems and configurations which cannot be achieved by making one specific change. Therefore it is important to investigate several options to achieve the goals described above. Changing the way of power production on an FPSO is therefore one of many steps to in the end achieve having a fully 'green' FPSO.

In the literature, several methods which are explored for FPSOs to become more sustainable are described. These methods are all related to the 4 targets to obtain a 'green' FPSO. One of them is changing the way of power generation on an FPSO. Replacing (part of) the conventional methods causing emissions, which are gas turbines and diesel engines [15], with renewable energy sources.

An example of this is the use of solar panels to power the living quarters of an FPSO located in Angola [16]. Another example is the possibility to couple an FPSO to an existing offshore (floating) wind farm to be able to power a larger share of the FPSOs power usage [17]. Feasibility is also concluded possible by Aker Solutions [18] on electrification of an FPSO by using a low-frequency AC (Alternating Current) transmission and distribution system connecting the FPSO to an onshore power generation facility. Nevertheless, full electrification of an FPSO is not seen as the best option by Samarakoon [19] due to the occurring unavailability of power supply while being connected to an external electricity grid. Instead, partial electrification would be a better working principle.

Bluewater is working on the decarbonizing of the FPSO Aoka Mizu, for which multiple technologies such as renewable fuels and power import, carbon capture and storage, efficient energy management, and power and heat optimization need to be combined to achieve this goal [13].

3.3 Energy security

That Samarakoon [19] is in favor of partial electrification of an FPSO, is also something that can be related to the global energy market. In the global energy market, a lot of individual parties are dependent on electricity or other forms of energy, expecting energy security. The International Energy Agency describes energy security as [20]: 'Ensuring the uninterrupted availability of energy sources

[2]Reference coming from Bluewater's Intranet database (not publicly accessible).

at an affordable price'. This market consists of one big balance of power originating from different sources, from which a part is renewable, but also other sources such as fossil fuels and nuclear power contribute to this energy mix. Less dependence on a single power source increases energy security and reduces the sensitivity of the energy market. Current (October 2022) developments in the energy market for example show Europe's high dependence on gas while experiencing reduced availability, with prices ranging between 15 and 20 times higher, compared to the average gas price between the years 2015 and 2020 [21]. By adding other power sources (renewable) to the energy mix of an FPSO's internal electricity grid, energy security can be increased and sensitivity from existing power sources can be reduced.

3.4 Case study: Wind turbine on FPSO

Connecting the FPSO to an external power source is seen as one of the feasible options to (partially) electrify an FPSO. But situations can occur when an FPSO is located in such a remote area that these resources might not be available. This results in the idea of placing a wind turbine on top of an FPSO, being able to power (part of) the FPSO's internal electrical grid. If this solution is found feasible it can power (part of) an FPSO independent of its location, for example, nearby an external power source.

The idea to put a wind turbine on an FPSO topside to power the FPSO's internal electricity grid has not been considered yet in the existing literature. The power which is generated by the wind turbine can always be used by the FPSO and (partially) saves the use of conventional fuels which have a lot of emissions. This increases the energy security of an FPSO. It is expected that a significant emission reduction occurs, accompanied by an economic incentive where a sufficient amount of money is saved due to the decreasing fuel costs.

The idea also raises multiple questions. First of all, what will be the wind turbine characteristics of the chosen turbine? Second, what determines the placement of a wind turbine on an FPSO? Besides, on a complex facility as an FPSO where people are working in a remote area, the safety of personnel and the facility is one of the most important things. This raises the question of what hazards can occur due to the interaction between a wind turbine and FPSO.

To obtain more insight into the above questions an explanation of FPSO configurations and FPSO power consumption is given. Also, a choice for a wind turbine is made. These items are then used in a hazard identification procedure to create new literature by using experts' opinions in a discussion of which the findings are registered.

4 FPSO configurations and power consumption

Currently, there are more than 270 FPSOs worldwide [22]. Each FPSO has its origin and complicated design, which go hand-in-hand with complicated layouts of both systems and deck space. This chapter describes typical FPSO configurations and introduces two FPSOs that are used as a reference for the continuation of the report. Besides, insight is given into the power consumption of these FPSOs.

4.1 Typical FPSO layouts

FPSOs occur from two different origins. Either they are specially designed to function as an FPSO, or they are converted from an existing oil tanker [23]. An FPSO consists of a lot of different components. An overview of this is shown in figure 4.1.

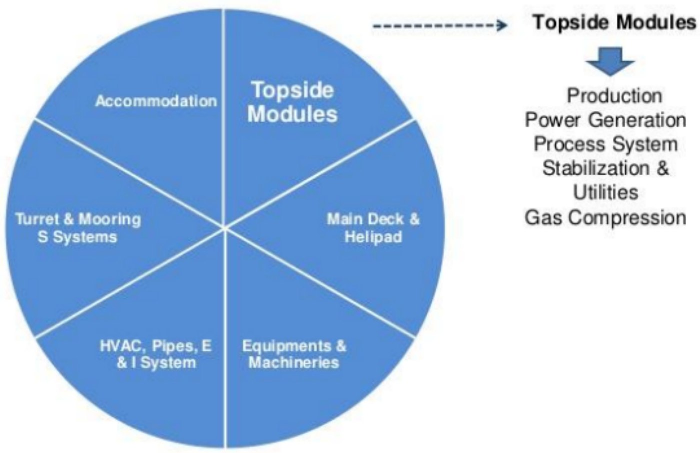


Figure 4.1: FPSO main components [24].

Often FPSOs are designed from a very hazardous area on one side (far away from the living quarters), towards the less and less hazardous area on the other side (close to the living quarters) [25]. This is based on the distribution of process equipment over the topside. A typical FPSO layout is shown in figure 4.2.

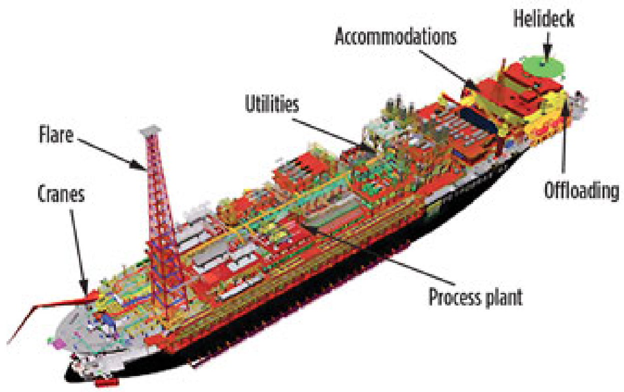


Figure 4.2: Typical FPSO layout [26].

Considering the FPSO configurations 2 different cases can be identified. These are mainly based on the location of the helideck and flare tower. The 2 cases are:

- FPSO with helideck at the forward and flare tower at the aft.
- FPSO with helideck at the aft and flare tower at the forward.

The helideck is in both cases accompanied by the accommodation facilities. Besides this, there is also the turret, which is always at the forward, and many process equipment accompanied by cranes, mostly spread out over the middle of the deck.

4.2 Bluewater's FPSOs

To be able to more specifically analyze the possible placement of a wind turbine on an FPSO topside, two FPSOs with different configurations as explained in 4.1 are chosen that are used as a reference for the continuation of this report. The company Bluewater has a fleet containing 5 different FPSOs. Both of these FPSOs are currently a part of that fleet. These are the Bleo Holm and the Haewene Brim. The choice for these two FPSOs is based on their different configurations. The placement of a possible wind turbine is likely to be different for both of these FPSOs. Also, different types of hazards might occur based on the different configurations. Both of these FPSOs use a Single Point Mooring (SPM) system. FPSOs with a spread mooring system are expected not to be suitable for the application of a wind turbine on top, since these FPSOs have no weathervaning capabilities, which would result in definite large offsets between vessel heading and wind turbine orientation.

4.2.1 The Bleo Holm

The first FPSO taken into consideration is the Bleo Holm which is shown in figure 4.3a. It currently operates in the offshore UK at the Ross, Parry, and Blake Fields in the North Sea. This FPSO is constructed in 1997 in Japan. With a length of 242.3 meters, a breadth moulded of 42 meters, and a depth moulded of 21.2 meters, the hull of the Bleo Holm has been designed especially for its purpose as an FPSO. The mooring system of the Bleo Holm is using a permanently connected turret.

4.2.2 The Haewene Brim

The second FPSO that is used is the Haewene Brim, shown in figure 4.3b. This FPSO operates in the offshore UK at the Pierce field in the North Sea. Unlike the Bleo Holm, the Haewene Brim was not specifically designed to function as an FPSO, but as a Multipurpose Shuttle Tanker (MST). Originally it was built in 1996 in Korea, after which it has been converted into an FPSO which started operations in 1999. It is in operation for one of Bluewater's clients, namely Shell UK Exploration & Production. With a length of 252 meters, a breadth moulded of 42 meters, and a depth moulded of 23.2 meters, the Haewene Brim is larger than the Bleo Holm. The mooring system of the Haewene Brim is using a disconnectable turret.

(a) Bleo Holm **(b)** Haewene Brim

Figure 4.3: Bluewater's reference FPSOs [27].

4.3 Power on an FPSO

Since there are many different FPSOs, there are also many different designs. This influences the design of the electricity grid on an FPSO, but also the installed power capacity on an FPSO. For FPSOs in general, the electrical loads may even go up to 40 to 50 MW and in special cases, it can even be more [28]. In this report, the FPSO power usage taken into consideration is related to the two reference FPSOs shown in section 4.2.

4.3.1 Power generation capacity

The power that an FPSO requires can come from different methods of power generation. According to MacDonald [15] there are two types of conventional power sources on offshore platforms that are currently used, which are the diesel engine and the gas turbine. Nevertheless, besides these two there is also the dual-fuel engine [29], which combines gas and diesel as its fuel. Each of these types of conventional engines runs on fossil fuels, and are by now proven technologies, but no longer interesting when it comes to sustainability and reducing GHG emissions.

The power generation capacity of an FPSO is the maximum available amount of power that can be generated that an FPSO can use at the same time. The FPSOs Bleo Holm and Haewene Brim both have different installed power capacities and different methods of power generation. An overview of which methods of power generation are present on the Bleo Holm and Haewene Brim and their capacities are shown in table 4.1 below.

FPSO	Bleo Holm	Haewene Brim
Installed diesel generators	1 x 5.3 MW	-
Installed gas turbines	2 x 10 MW	-
Installed dual fuel main diesel generator	-	4 x 5.2 MW
Total capacity	25.3 MW	20.8 MW
Diesel emergency generator	1 x 0.5 MW	1 x 0.46 MW

Table 4.1: FPSOs installed capacities [30].

4.3.2 Power consumption

The actual power consumption of an FPSO is often lower than the full installed capacity. This depends on the type and number of operations that are performed at the same time. For the Haewene Brim, an estimation of the power consumption is specified for three different cases [31][3]:

- Case 1: Normal operations require 6.7 MW. In the case of sea states with a significant wave height of 10 m or more, propulsion motors are required for Position Mooring assistance, which requires an additional 1.32 MW. In total, this makes 8.02 MW.
- Case 2: Thrusters, during supply vessel operation one Azimuth thruster is running up to 60% of nominal power while performing normal operations. In total, this requires 7.31 MW from which the thruster consumes 0.62 MW.
- Case 3: Thrusters & Offloading, during offloading one Azimuth thruster is always running based on a continuous load. In total, this operation requires 11.10 MW, from which 1.94 MW is used by the thrusters.

The actual power consumption of the Haewene Brim is expected to fluctuate about the above-given values, since the processes on the FPSO are not always constant, but also fluctuate in for example the FPSOs oil and gas production speed. As observed in section 4.3.1, the Bleo Holm has a different power generation system compared to the Haewene Brim. However, there is no available data on its actual power consumption. Therefore, only the values of the Haewene Brim are used as a reference.

[3] Reference coming from Bluewater's Meridian database (not publicly accessible).

5 Wind turbine choice & FPSO grid integration

This chapter contains an explanation for the choice of wind turbine that will be placed on an FPSO. Besides, it is briefly described how the wind turbine can be integrated into the FPSO's electricity grid. An extensive recommendation on the electrical integration is out of scope for this report and is recommended for future research in a later design stage.

5.1 Wind turbine development

Wind power, in general, has a long history and mankind has tried to capture power from the wind to use for their benefit for a long time. The first concrete invention was the use of windmills to work grain and move water in the 12^{th} century. From the 14^{th} century the windmills further developed for farming purposes and water recovery. By the end of the 19^{th} century, the option to use wind as a power source for electricity gained much attention. This resulted in the first renewable wind turbine occurring in Scotland in 1887. Denmark became the front runner when it comes to wind power having over 2000 windmills producing over 30 MW by the year 1900 [32].

During the 20^{th} century the use of wind turbines increased. In the beginning, it was seen as a possible competitor to power generation companies using fossil fuels. As soon as the oil crisis started, the use of wind turbines started to become the alternative source of energy, which further developed in the early 21^{st} century, where the use of wind turbines increased rapidly [33]. An overview of the rapid increase of wind turbine sizes and capacities is given in figure 5.1.

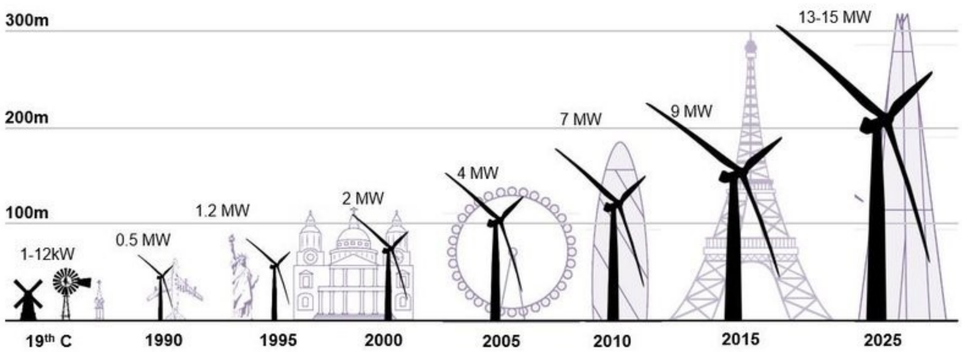


Figure 5.1: Development of wind turbine capacities and sizes [34].

5.2 Turbine capacity

The wind turbine placed on the FPSO will have a certain specific power capacity. The choice of the desired capacity is very important since it influences other characteristics of the wind turbine and the implementation and interaction with the FPSO.

In section 4.3.2, the power consumption of the Haewene Brim is estimated to use approximately 6-12 MW during operations. Because the wind turbine is powering the FPSOs internal electricity grid, one aspect that should be avoided is power grid overloads while the wind turbine would operate at its rated capacity, to prevent the need for significant changes in the wind turbine's control system. To make sure that this is not the case, the choice for the wind turbine power capacity that will be used is 5 MW. With this capacity, the wind turbine can make a significant contribution to power generation during operations, whereas the existing gas turbines or diesel engines can provide the additional required power for the FPSO. This way, the gas turbines or diesel engines keep on running at a low level, instead of being completely shut down. This benefits the system since complete start-ups often take quite some time. A power monitoring system can make sure that the power supply is in balance with the demand. This way, the FPSO can be partially provided with renewable power, while still being able to produce an adequate amount of power. This increases the system's energy security. Part of the fuel consumption is reduced, saving costs and reducing emissions. The details of the financial business case and an estimation of how much emissions are reduced by this implementation are topics that are further described in chapter 12 of this report.

The capacity can be provided by either a single wind turbine, two turbines, or even multiple turbines. Several considerations are relevant that determine this choice, which are:

- In power production multiple turbines are preferred since they can operate separately from each other, while if a single turbine is not operational, no wind power will be produced. However, the total downtime when using multiple turbines becomes larger, due to maintenance on the multiple different turbines.
- The space that is required on the FPSO increases when using multiple turbines compared to using a single turbine.
- Placement of a single turbine depends on demands that are based on the FPSO only, while for multiple turbines this is also based on the wind turbines with respect to each other, where topics such as wake effects and sufficient blade clearance become even more relevant.
- Different wind turbine designs result in different dimensions of a wind turbine. As can be seen in figure 5.1, the increase in wind turbine size is less compared to the increase in wind turbine capacity. Considering for example two 2.5 MW wind turbines or a single 5 MW turbine is the same as considering two very large structures both with a rotor diameter of 90 meters or a single slightly larger structure with a rotor diameter of 120 meters.
- Wind turbine efficiency is highly related to how close wind turbines are with respect to each other and other obstructions. Using more than a single turbine creates more obstructions and it becomes likely that at least one of the turbines will decrease in efficiency.

Due to the little space available on an FPSO, the little gain in size reduction when choosing a lower capacity wind turbine, and the expectation of reduced wind turbine efficiency in case of multiple wind turbines, the choice of using a single 5 MW wind turbine is made. The use of two or even more turbines would highly complicate the matter, by providing more restrictions, on top of the already expected restrictions by the FPSO.

5.3 Turbine type

There are two different types of wind turbines. These are the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT) as can be seen in figure 5.2. The names of both turbines already address the fact that these turbines rotate around the horizontal and vertical axis respectively. Due to the different orientations of the blades, and the placement of the generator and gearbox, the weight distribution of these two turbine types is very different. The center of gravity in the case of the VAWT occurs lower compared to the HAWT. This makes the VAWTs an interesting option in the case of floating sub-structures since it will give more stability. Another benefit of the VAWT compared to the HAWT is that the VAWT can produce power with the wind coming from any direction without having to change its orientation. Nevertheless, the HAWTs are the ones that are generally used. This is because the HAWT has several advantages compared to the VAWT. First of all, the HAWT generally has a larger power coefficient than the VAWT [35]. Second, the HAWT is economically more interesting compared to the VAWT in terms of the costs per kilowatt [36].

The largest VAWT ever constructed is the ÉOLE with a rated power of 3.8 MW [37]. The capacity of the HAWTs increases quickly with new designs becoming available continuously. In the summer of

2021, the largest HAWT is the Vestas V236 with a capacity of 15 MW [38]. In the case of 5 MW wind turbines, the HAWT is a proven technology. VAWTs of 5 MW do not yet exist. Besides, the use of a HAWT on an FPSO is much more convenient in terms of deck space. The large rotor diameter of a VAWT would require much more deck space since the width of the structure is much larger at the deck level. Because of these reasons together with the advantages regarding the power coefficient and economic benefits of the HAWT over the VAWT, the choice of turbine type is the HAWT.

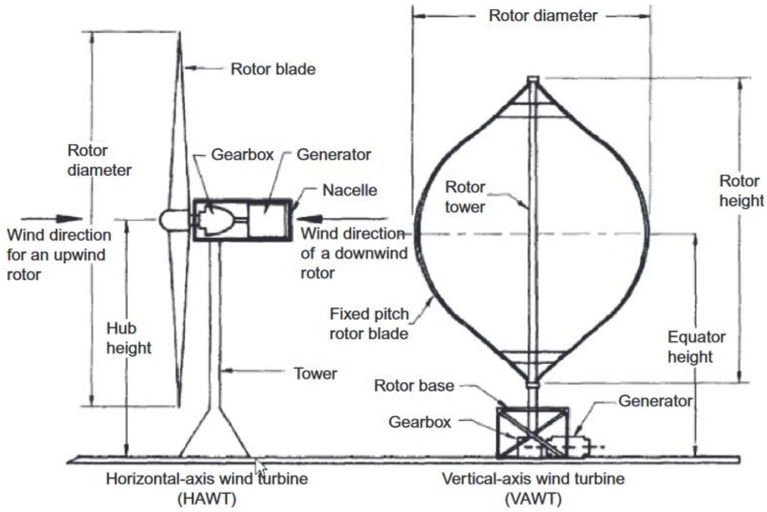


Figure 5.2: Types of wind turbine [35].

The type of turbine is further determined by the number of blades. There are wind turbines that have only one blade, two blades, the most common designs have three blades, and even multi-bladed turbines that have more than three blades exist. The number of blades has a large influence on the performance of the wind turbine [39]. The larger the number of blades, the greater the resistance it gives to the wind. This slows down the rotational speed and therefore results in lower efficiency of the wind turbine. From that respect, the ideal number of blades would be one. Nevertheless, one blade results in instability of the turbine. Even a turbine with two blades still comes with instability issues. It is especially vulnerable to the phenomenon called gyroscopic precession, causing wobbling [40]. A turbine with 3 blades does not show similar stability issues. Therefore it is the most ideal combination of efficiency and stability for a wind turbine, which is the reason that 3 blades are chosen for the wind turbine that will be used. The choices are in line with what is observed in the industry, where 3-bladed HAWTs are mostly used.

5.4 Tower type

For HAWTs, there can be made use of different support structures to hold the Rotor-Nacelle-Assembly (RNA) in place. Figure 5.3 shows different types of wind turbine tower structures. The three main types are the steel tower, the concrete tower and the lattice tower [41].

In light of the application of a wind turbine on an FPSO, the different tower types have several advantages and disadvantages. First of all, a disadvantage of the concrete tower is that it will be very heavy, which is unfavorable for the FPSO. Often, the concrete tower types are manufactured by pouring the concrete on-site [42]. This can result in a complicated operation in this offshore application. Besides, the concrete tower is unrecyclable after its use [43].

The lattice tower structure has several advantages. First of all, the structure is lightweight and the wind loads on the structure are less since wind can move through the structure. It is an ideal tower for small wind turbine systems, while for the larger wind turbine systems the tower is lacking stiffness to support the heavier RNAs, especially in offshore applications where the tower is exposed to multiple different loads and not only wind [43]. Another disadvantage of the lattice tower in the required application is that additional protection is needed for the cabling, especially offshore, since the frame is an open structure [41]. This open frame structure also results in challenging conditions for maintenance and inspection in the accessibility of the RNA. This would require a climbing operation on external cage ladders outside in the wind, whereas for the tubular steel tower this climbing takes place inside the turbine, where the climber is safe from direct contact with the wind.

Figure 5.3: Wind turbine tower types [44].

The tubular steel tower is the most commonly used wind turbine tower concept in the industry. For offshore applications, it has the advantage over the lattice structure that the internal cabling and other components are well protected, but the disadvantage is that wind loads on the tower are bigger than that of the lattice structure [41]. Since the other tower types will bring several issues that are not favorable in the foreseen application, the tubular steel tower is chosen for the design concept. It can provide sufficient strength, and no insurmountable issues will show up using this type of tower. Also, the steel tower is recyclable at the end of its lifetime.

Besides the use of vertical straight towers, the idea of using inclined wind turbine towers is gaining more attention in the industry. There are two directions in which the turbine tower can be inclined. From aft-to-front, in which case the loads on the tower are reduced [45] or from side-to-side as part of the TwinWind concept by Hexicon [46]. In this case, the loads on the tower are even increased compared to a straight vertical tower.

The use of an inclined tower for the wind turbine application on an FPSO raises several advantages, but also disadvantages. The main advantage is that by using a side-to-side inclined tower the RNA can be positioned such that it is not (completely) above the FPSO deck. For an aft-to-front inclined tower, this is not an option, and the use of such a tower will only require more space available above the FPSO. Another disadvantage of an inclined tower is that the wind turbine will be limited in its yaw direction, likely resulting in less power production. Besides this, a side-to-side inclined tower generates more roll for the FPSO due to the RNA's weight being placed far from the vessel's center line.

Based on the above, the final choice of the tower is therefore a vertical straight tubular steel tower. This way power production can be maximized, and loads on the tower are not increased, saving the use of additional material and costs.

5.5 Turbine model and initial dimensions

Many different HAWT models have a capacity of 5 MW. For modeling purposes the National Renewable Energy Laboratory (NREL) [47] provided a 5 MW reference turbine for offshore system development. This model is made based on turbine characteristics that often occur in the case of a 5 MW turbine. The benefit of this model is that there is a lot of information about the turbine specifications. Several important characteristics are shown in table 5.1. The NREL 5MW reference turbine is continuously under development to be improved even further.

This NREL 5 MW is not an actual existing turbine. The database of thewindpower.net [48] consists of 37 different turbine models with a capacity of 5 MW. Some models are still under development, and some models are already seen as old. Nevertheless, this report considers the NREL 5 MW as its reference.

The typical lifetime of a wind turbine is between 20 and 25 years [49]. For sustainability purposes, the reuse of existing turbines also becomes an interesting option. This saves the need for new raw materials and the efforts of the production process and prevents the already used turbine from becoming waste. Nevertheless, this does require a very good maintenance strategy, to prevent a lot of downtime during its operations. Also, it has to be evaluated whether this refurbished turbine fits the purpose of being put onto an FPSO since the design conditions of every turbine can be different.

There is a distinction that can be made in wind turbine types when it comes to the drive-train. There are wind turbines that have a gearbox, and there are direct-drive wind turbines without a gearbox. Not having the gearbox often reduces required maintenance, and prevents downtime, since fewer moving parts are present inside the drive train [50]. The NREL 5 MW reference turbine has a drive train with a gearbox.

The cut-in, rated, and cut-out wind speeds can be visualized in the wind turbine's power curve. This is shown in figure 5.4. The power curve consists of three different regions. In region 1, the wind speed is too low for the wind turbine to produce power. In region 2, the power curve increases towards the wind turbine's capacity between cut-in and rated wind speed. Between the rated wind speed and cut-out wind speed, region 3, the wind turbine produces a constant amount of power equal to its maximum capacity. Above the cut-out wind speed, no power is produced by the wind turbine. The wind speed used to compute the power curve is the wind speed at the hub height of the wind turbine.

Turbine	NREL 5MW reference turbine
Control	Variable speed, collective pitch
Drivetrain	High speed Multiple-Stage Gearbox
Operational data	
Rated power [MW]	5
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	25
Rated wind speed [m/s]	11.4
Cut-in speed [rpm]	6.9
Nominal speed [rpm]	12.1
Rated tip speed [m/s]	80
Rotor	
Orientation, configuration	Upwind, 3 blades
Diameter [m]	126
Hub diameter [m]	3
Tower	
Hub height [m]	± 90 (project dependent)
Tower mass [ton]	347.5 (project dependent)
Masses [ton]	
Rotor (hub + blade)	110
Generator	Included in nacelle
Nacelle	240
Total top mass	350

Table 5.1: Turbine specifications [47]

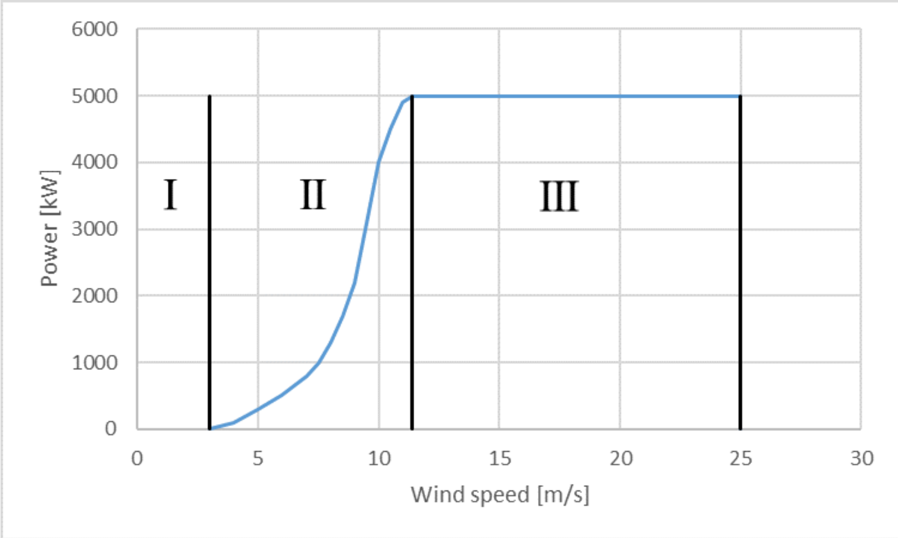


Figure 5.4: Power curve NREL 5 MW turbine for wind speeds at hub height.

5.6 Integration into an FPSO's electricity grid

As shown in section 4.3.1, the installed capacity on an FPSO is much higher than the actual power consumption during operations, which lies in the range of 6-12 MW. During normal operations, which is the case that occurs the most often, a 5 MW wind turbine can often deliver approximately 75% of the required power whenever the turbine reaches its full capacity (rated power).

Each FPSO has its own already existing complex electricity grid, powered by conventional power sources. The wind turbine has to fit in with this already existing grid. Since on already existing FPSOs such as the Bleo Holm and Haewene Brim, this grid is already present, one possible thing to do is to make the wind turbine an addition to the already existing grid. This means that even though the wind turbine will produce a significant amount of power, which will reduce the use of the already present gas turbines and diesel engines, the current methods of power generation will stay in place. These can in the end function as backup power generators, and as additional power sources to let the supply meet the demand. This energy mix increases energy security, which is important for an FPSO's operations. Due to the large variations in wind availability, an active monitoring system of the power balance will be required, where the use of gas turbines and diesel generators has to be adjusted continuously based on the amount of wind power provided and the actual power demand at that time.

During this balancing of power, the efficiency and condition of the existing conventional engines on the FPSO also have to be maintained. The efficiency of these engines can become less in case they are not utilized at their full capacity [51], and also can cause more wear to the engine itself. It is therefore recommended, to use the least number of conventional engines at the same time while the wind turbine is in operation, to keep the efficiency as high as possible, and reduce the amount of wear as much as possible. In a later stage, possibilities for power storage techniques might be able to further develop the power balance, optimizing the use of the different energy sources.

The electricity grid on an FPSO works on specific voltages. Depending on the choice of a specific turbine, a transformer might be needed to convert the voltage of the generated wind power. For the Haewene Brim the required voltage would be 6.6 kV [31].

The above provides some insight into electrical system integration. It is out of the research scope to provide a detailed design concerning this matter. However, since an existing grid is already in place and the wind turbine can function as an addition, the electrical system design is expected to be possible, as electrical additions to existing grids are commonly performed. Therefore, the design of the electrical system is not considered to be a showstopper for the project's feasibility.

6 Hazard identification

A wind turbine on an FPSO topside can result in new risks that the industry has not dealt with before. Many different methods deal with risks. It is important to be aware of risks and to find mitigations where necessary, to have a successful and especially safe project in the end. This requires good evaluation and management of the risks. Therefore, several steps have to be taken. These are shown in figure 6.1.

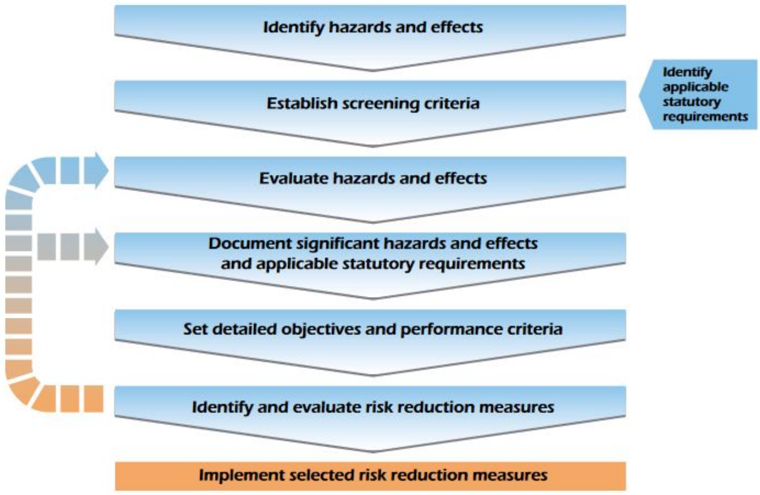


Figure 6.1: Steps for risk evaluation and management [52].

From figure 6.1 can be observed that risk management starts with the identification of hazards and their effects. The steps that follow show evaluation and mitigation of the hazard are a necessity. This chapter describes how the first step of risk evaluation is performed, in the form of a hazard identification (HAZID) analysis. First, an overview of how HAZID is considered in literature is given, after which the methodology and results of the HAZID are explained.

6.1 Hazard identification in literature

A hazard identification analysis is one of the methods that can identify possible hazards in an early stage of the project. According to Crawley [53], HAZID is a consequence-driven hazard analysis that originates from the cause-driven hazard and operability analysis (HAZOP). Molland [54] considered that because people tend to be more focused on the consequences of an event instead of the cause of it, it becomes difficult to improve safety. Therefore it is critical to also keep in mind the causes of events, especially when providing scope for possible mitigations of risk.

HAZID studies have already been applied to many different projects to identify any possible hazards. When the hazards are identified, they can be classified, and a choice can be made on how to mitigate them in a later project stage.

A HAZID analysis includes often a typical worksheet that is used to list the hazards. There are several variations of these worksheets. Crawley [53] uses three columns indicating generic hazard, cause, and effect. Wadhwani et al. [55] used four columns indicating: threats and concerns, causes, consequences, and safeguards. Joung et al. [56] shows a worksheet with four columns, where the cause, consequence, and existing safeguards are shown. Here a split is made in existing safeguards, making a distinction between preventive safeguards, and mitigating safeguards. The American Bureau of Shipping (ABS) guides how to deal with risk assessments considering marine and offshore industries. They have developed a worksheet for a HAZID analysis from which an example is shown in table 6.1.

Hazardous Event	*Hazards*	*Causes*	*Consequences*	*Safeguard*	*Recommendations*	*Comments*
No propulsion	Main engine fire	• Fuel/lube oil pipe failure • Flammable fluids on hot surface • Atmospheric build up of fuel/lube oil mist	• Loss of propulsion • Personnel injury/fatality	• Maintenance • Oil mist detector • Temperature monitoring • Visual inspection • Engine room watch • Firefighting system	• Separation to prevent escalation • Global/local suppression system • Proper ventilation with enough air change • Emergency escape	

Table 6.1: HAZID example American Bureau of Shipping (ABS) [57].

Furthermore, Xu [52] explains that it is important that the different phases of a project are taken into account. Hereby can be looked at commissioning, operation, and even decommissioning. In the end, it is observed that the different worksheets are always created in the form of first identifying the hazard, then its cause and/or consequence, already existing mitigation, and additional room for comments.

The content of the worksheet is considered to be determined by a team. Guidewords are often used to guide the HAZID session to stimulate the discussion [58]. In the case of a HAZID analysis, the use of a team is generally considered critical. Siddiqui et al. [58] describe that it should always be a multi-disciplinary team that will work on the HAZID. Eventually, the findings of the brainstorming session can be documented in a report for which the team is not required.

A HAZID analysis has several advantages and disadvantages. Wadhwani et al. [55] only describe several advantages which explain that HAZID is a good method to identify Health, Safety, and Environmental (HSE) hazards in an early stage of a project, for which mitigation can be found to avoid the hazards in the first place. Furthermore is explained that this will lead to fewer costs and delays due to unidentified hazards. Crawley [53] emphasizes the flexibility and the result of the HAZID which can lead to the first quantified risk assessment. Nevertheless, Crawley [53] also mentions that the success and quality of the HAZID highly depend on the experience of the team and that it can be a mentally exhausting process.

6.2 Methodology

The technique HAZID is used to identify possible hazards in the early stage of the project. To identify these hazards, a 4-hour during brainstorm session is organized with experts from different backgrounds participating in the HAZID. The goal of the HAZID analysis is described as:

- Recognise and identify the Health, Safety, and Environmental issues rather than discuss the consequences and propose solutions;
- Evaluate alternatives, techniques, and technologies to maximize the positive and minimize the negative effects;
- Establish the requirements for further study and assessment in subsequent project activities.

Here the interaction between the wind turbine and FPSO is important to take into account. As figure 6.2 represents, both the effect of the wind turbine on the FPSO and the effect of the FPSO on the wind turbine are important.

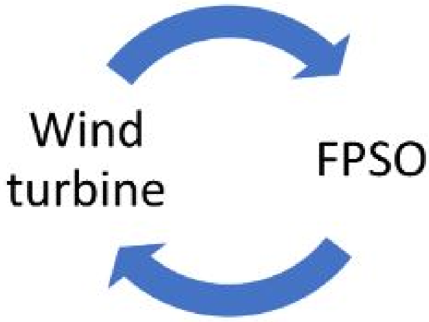


Figure 6.2: Interaction wind turbine and FPSO

For the HAZID a scope is determined. First of all, the scope puts focus on additional hazards due to a wind turbine on an FPSO topside. The hazards identified during the brainstorming session should not be present if there was not a turbine on an FPSO. Besides this, the focus is put on normal operations. These are the operations taking place when the FPSO is located at its site. This includes production, storage, offloading, and on-site maintenance. Other project phases, such as installation, can be shortly discussed but a future study is required for these events. Next to this, the HAZID focus lies on Health, Safety, and Environmental hazards.

An overview of different wind turbine and FPSO configurations is created. This is to be able to identify hazards that might specifically occur for a specific configuration and to visualize the situation which benefits the discussion. The different possible configurations that were provided are based on the typical FPSO configurations as explained in section 4.1. Here Haewene Brim and Bleo Holm are used as references. Six different cases are suggested during the HAZID discussion. These cases are visualized in figure 6.3 for the Haewene Brim and figure 6.4 for the Bleo Holm. Larger versions of these images can be found in the terms of reference in appendix B. The six cases are:

- For the Haewene Brim:
  - Figure 6.3 left, placing the turbine at the aft when the flare tower is at the aft and the helideck at the forward.
  - Figure 6.3 middle, placing the turbine in the middle, when the flare tower is at the aft and the helideck at the forward.
  - Figure 6.3 right, placing the turbine at the forward, when the flare tower is at the aft and the helideck at the forward.
- For the Bleo Holm:
  - Figure 6.4 left, placing the turbine at the aft when the helideck is at the aft and the flare tower at the forward.
  - Figure 6.4 middle, placing the turbine in the middle, when the helideck is at the aft and the flare tower at the forward.
  - Figure 6.4 right, placing the turbine at the forward, when the helideck is at the aft, and the flare tower at the forward.

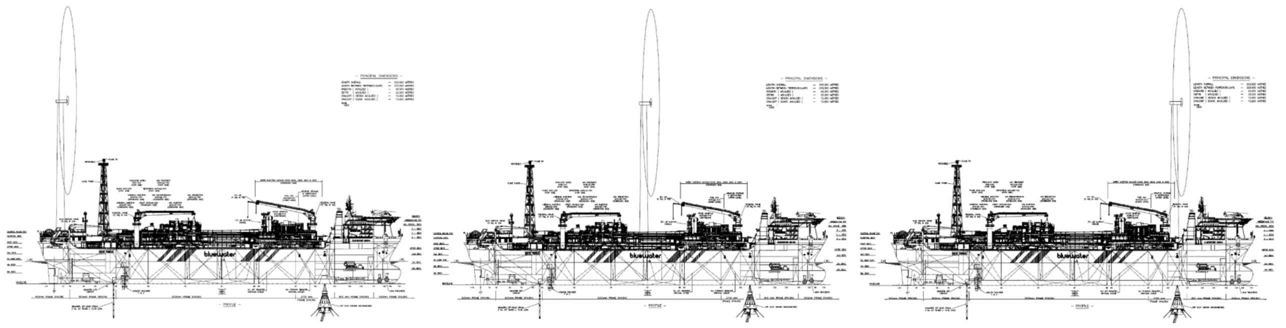


Figure 6.3: Different configurations of Haewene Brim with a turbine on the topside.

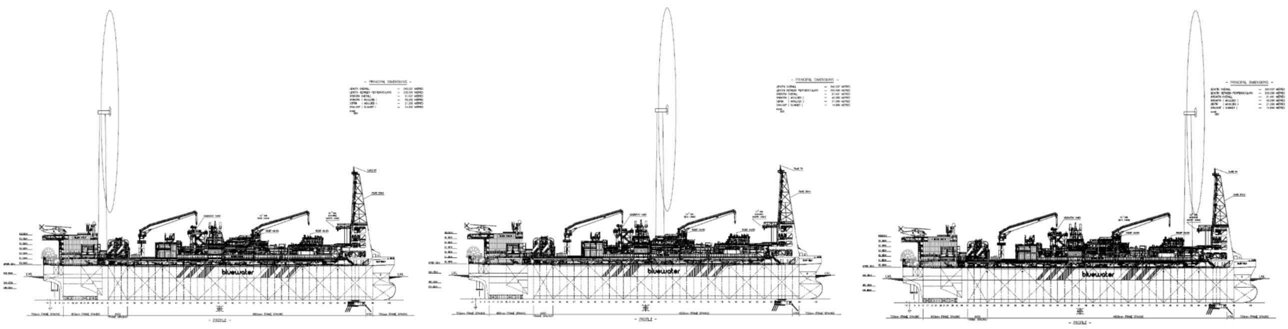


Figure 6.4: Different configurations of Bleo Holm with a turbine on the topside.

During the HAZID a worksheet is used to provide guidewords to assist in the discussion. These guidewords are split into four different categories:

- Facility hazards
- External and environmental hazards
- Health hazards
- Project implementation issues

Participants for the HAZID session are collected to represent different backgrounds and expertise in the discussion. This starts with an expertise in wind turbines and FPSOs and is further divided into more specific department backgrounds. An overview of the experts that participated in the HAZID including their function or discipline is given in appendix A. A terms of reference is set up to inform HAZID participants with information regarding the background information of the case study, the scenery of several reference configurations, and the goal, scope, and procedure during the HAZID session. The full terms of reference can be found in appendix B.

The HAZID session included an introductory presentation explaining the goal, scope, and background to the participants, followed by free brainstorming on different configurations accompanied by the use of guide words facilitating the discussion. Important to state is that during this 4-hour HAZID it is not considered the goal to identify every hazard, since that would not fit in the available time frame, but to get insight into the major hazards that the team can identify. The findings are used to establish new literature on the topic of placing a wind turbine on top of an FPSO and are described in section 6.3.

6.3 Results of HAZID brainstorm

The results of the HAZID are recorded in a HAZID worksheet. The full worksheet can be found in appendix C. Several important hazards that are considered critical are explained below. The hazards are shown per category. The explanations also include several important safeguards or actions that have been discussed. Besides, the opportunities that were discussed during the brainstorming are also listed in this section.

6.3.1 Facility Hazards

Most of the hazards that were identified belong to the category of facility hazards. The major hazards from this category are:

- The loss of integrity of the wind turbine is one of the hazards that is seen as most critical. In the case of this event, this might result in dropped objects (wind turbine blades/parts) from the wind turbine onto the FPSO or even a tower collapse, possibly leading to a catastrophic failure of the FPSO. Several causes are identified that might lead to this consequence. It could for example occur because of an external fire occurring due to emergency flaring on the FPSO, an internal fire occurring in the rotor-nacelle-assembly (RNA), or because of a structural failure of the wind turbine itself, such as thermal-induced fatigue, motion-induced fatigue, or a bolt failure. Several other causes are explained further below.
- The potential interaction between the wind turbine and flare tower results in several hazards. First of all the hazard of the wind turbine being affected by the flare tower's flame and thermal radiation as a result of emergency flaring. Second, the possible wind turbulence that occurs due to wind flowing around the flare tower creates additional variable loading onto the wind turbine.
- The potential interaction between the wind turbine and the cranes, possibly leading to a collision and loss of structural integrity of both crane and wind turbine. This results in similar dropped object scenarios as explained above. Nevertheless, enough clearance between the different objects can be created through design. Also, the wind turbine can be shut down during crane operations.
- The potential interaction between the wind turbine and the helideck including its helicopter operations, where the impact of the wind turbine on its surroundings possibly leads to a helicopter crash or prevents the helicopter to perform safe operations and therefore reduces the accessibility of the FPSO. Similar to crane operations, an identified safeguard is to stop and restart the wind turbine whenever helicopter operations take place. Nevertheless, frequent starts/stops of the wind turbine should be further assessed since this is not normal wind turbine behavior.
- The load due to the addition of a wind turbine has an impact on the FPSO. The vessel strength has to be assessed to check if the vessel is strong enough to carry this load.
- The interaction of motions between the wind turbine and FPSO, including variable loading onto the wind turbine, could lead to other hazards in case their limitations are exceeded. Therefore the motions of FPSO and wind turbine should be further analyzed.
- The wind turbine can impact the weathervaning capabilities of the FPSO.
- The momentum due to the wind force on the wind turbine might lead to a heeling motion of the FPSO, resulting in an FPSO that should be able to continue its operation having this heeling angle. To see if this is the case, the stability of the vessel should be assessed. The trim of the vessel is not considered to be an issue.
- The hazard of vibrations due to the interaction between the wind turbine and FPSO or FPSO components can lead to unsafe situations for personnel working on-site in case the vibrations are significant. The natural frequencies of these components will have to be evaluated to make sure resonance or excessive vibrations will not occur.
- Additional risks can occur during large maintenance since that requires a multi-vessel operation where an additional vessel is required to perform the heavy lifting. Also, another vessel might be necessary to place large parts of a wind turbine (blades) on since the FPSO cannot accommodate this space. The probability of the hazard of dropped objects increases, since also man-made mistakes can occur during this operation.

- Besides that the loss of integrity of the wind turbine possibly leads to damage to the FPSO, it is also a hazard for the mooring and subsea equipment. Here dropped objects into the sea possibly hit mooring lines, risers, or sub-sea equipment, resulting in damage to this equipment.
- The wind turbine has the potential of impacting the FPSOs telecommunication system, possibly leading to the FPSO being unreachable.
- A full wind turbine control system failure resulting in an out-of-control wind turbine creating a dangerous situation and possible further damage to both FPSO and wind turbine.

6.3.2 External and Environmental Hazards

External factors and the environment can result in extreme situations. Often these situations have a low probability of occurrence but can result in a very high impact. The main hazards from this category are:

- The occurrence of extremely high wind speeds possibly leads to excessive failure of the wind turbine potentially resulting in a high impact of broken wind turbine parts onto the FPSO.
- Potential of lightning impact on the wind turbine, leading to fractures inside the wind turbine blades resulting in dropped object scenario or the wind turbine catching fire.
- A created man-made hazard is the possibility of a helicopter crash into the wind turbine due to a human mistake, leading to escalation on the FPSO. To reduce the probability of this hazard occurring, one mitigation could be to stop and restart the wind turbine whenever a helicopter operation takes place. Nevertheless, this would lead to a new hazard questioning the impact of frequent starts/stops on the wind turbine.
- An external vessel collision might in case of high impact lead to significant damage to, and even loss of integrity of the wind turbine.

6.3.3 Health Hazards

The health and safety of personnel are important factors. The main identified hazards related to this are:

- Additional noise on the FPSO would be caused by the wind turbine. This could lead to health implications for the personnel. Since there is already much noise present due to other equipment on the FPSO, it should be assessed how the wind turbine noise relates to the already present noise levels. Too much noise can eventually lead to sleeping problems for personnel. Additional noise can also be caused by vibrations due to the interaction between the wind turbine and FPSO.
- The rotating wind turbine leads to flickering effects (shadow) of the blades possibly leading to shock reactions of personnel. In the long term, this might lead to both mental and physical issues.
- A working hazard is that the wake effect due to the operating wind turbine can result in wind vortices which might be a danger to people walking on the FPSO deck.
- People possibly experience fear of/for the wind turbine, since it is in the middle of their working and living area. This can cause a mental struggle for personnel on the FPSO.

6.3.4 Project Implementation Issues

Project implementation issues have not been assessed in detail during the HAZID. Nevertheless, the following factors have been addressed:

- Wind turbine manufacturers will not just provide any wind turbine for this purpose. Cooperation with the manufacturer is therefore important to obtain the necessary wind turbine which is fit for purpose.
- From a regulatory compliance point of view, design standards will need adjustment for this new configuration, since it is outside the regular FPSO flag, state, or coastal regime. The design will have to be checked and eventually approved.

6.3.5 Opportunities

Besides all the hazards that were identified during the HAZID, several opportunities were suggested. These opportunities are not guaranteed and will have to be further evaluated. These are:

- A transformer with the size of approximately a container can be placed inside the wind turbine tower. This reduces the need for additional space elsewhere on the FPSO.
- The motions (especially pitch and heave) excited by the FPSO onto the wind turbine are least in the middle or just aft of the middle of the FPSO, resulting in lower forces on the wind turbine equipment compared to forces on the equipment in case of wind turbine placement further to the forward or aft of the vessel.
- The placement of the wind turbine on one of the sides of the FPSO can result in a similar structural integration for the wind turbine as that of the existing cranes.
- The use of an inclined wind turbine tower provides the possibility to move the wind turbine hub further away from the FPSO.
- The use of a downwind wind turbine instead of an upwind wind turbine results in a different load configuration for the wind turbine tower. Also, this might result in more options for effective wind turbine placement.

Conclusion to the literature research

In this literature research, the relationship between sustainability and FPSOs is described. Several targets that are required to obtain a 'green' FPSO are given, together with some existing solutions on how to achieve those targets.

A new case study is described with the idea of placing a wind turbine on top of an FPSO. This case study raised several questions such as what will be the wind turbine characteristics of the chosen turbine? What determines the placement of a wind turbine on an FPSO? And what hazards can occur due to the interaction between a wind turbine and FPSO?

Insight into these questions is (partially) provided in this literature research by looking into the power generation and consumption of FPSOs. This resulted in the choice of a 5 MW wind turbine. The NREL 5MW is used as a reference for this 5 MW turbine.

A HAZID is conducted where multiple different HSE and technical hazards are identified by a team of experts. With all these identified hazards it raises one particular question: To what extent is placing a 5 MW wind turbine on top of an FPSO feasible? This question will be the main research question for the thesis, where the identified hazards form the first critical items that have to be assessed to conclude the feasibility of the suggested idea of placing a wind turbine on top of an FPSO. To structure the feasibility analysis, a research plan is described in chapter 7.

7 Feasibility & Research plan

This chapter describes the definition of the term 'feasibility' and how this definition is applied to this thesis report. Also, it explains the place of feasibility within the design circle. Besides, it gives an overview of the research plan used to assess the feasibility in case a 5 MW wind turbine is placed on top of an FPSO. The goal is to find an answer to the question: To what extent is placing a 5 MW wind turbine on top of an FPSO feasible?

7.1 Definition of feasibility

The term feasibility is a term that is widely used. Its basic definition is: "the possibility that can be made, done, or achieved, or is reasonable" [59]. Feasibility studies are conducted in different fields to investigate the feasibility of new projects, designs, or technologies in an early stage.

UK's National Institute for Health and Care Research defines feasibility studies as [60]: "Feasibility Studies are pieces of research done before a main study in order to answer the question 'Can this study be done?'. They are used to estimate important parameters that are needed to design the main study." The Corporate Finance Institute describes [61]: "A feasibility study is part of the initial design stage of any project/plan. It is conducted to objectively uncover the strengths and weaknesses of a proposed project or an existing business. It can help to identify and assess the opportunities and threats present in the natural environment, the resources required for the project, and the prospects for success."

To have a more concrete view of feasibility concerning the project idea, the definition of feasibility for this research is made more specific. The fundamentals of its definition are illustrated by figure 7.1. The figure illustrates the definition of feasibility as: "something can be considered feasible when it is technically achievable, follows the health, safety, and environmental guidelines, and is financially attractive."

This definition holds three different main topics, namely technical aspects, HSE, and financials of the project, which are considered as the fundamentals to in the end state feasibility of the project at its current stage. Besides these topics, awareness of other non-technical project risks is important to achieve a successful project. Part of these non-technical risks are topics that are recommended for future research when it comes to feasibility. These are topics such as scheduling and planning and legal and regulatory aspects. Due to the current stage of the project, these topics are at this point not considered critical but are considered important in case the project would develop further.

To assess the feasibility a feasibility study is performed. The goal of the study is to identify the possible strengths and weaknesses of a project in an early stage. In this thesis, the main topics on which the focus is put are shown in the feasibility triangle of figure 7.1. Additionally, insight is provided into the most-common non-technical risks.

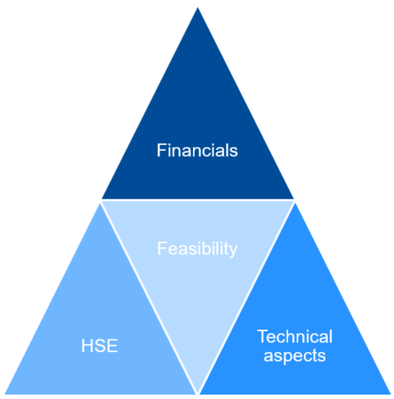


Figure 7.1: Fundamentals of feasibility.

7.2 Feasibility as part of the design circle

Feasibility is part of the design cycle. The design cycle contains several steps that are usually taken while establishing a design for a project. These steps are shown in the design circle shown in figure 7.2. Engineering design is often an iterative process, where new findings result in a revision of earlier made decisions [62].

Within this feasibility study, three different steps of the design circle are undertaken. First, identification of the possible design issues, which is done through literature research including a hazard identification as described in chapters 2 until 6. From this problem identification, several constraints have formed that influence the design conceptualization which is explained in chapter 8. Within the design conceptualization, the focus is put on the position of the wind turbine on the FPSO, where the choice of turbine has already been made as part of the literature research in chapter 5. After the design conceptualization, feasibility is researched. The next section provides the research plan for exploring the feasibility of the project.

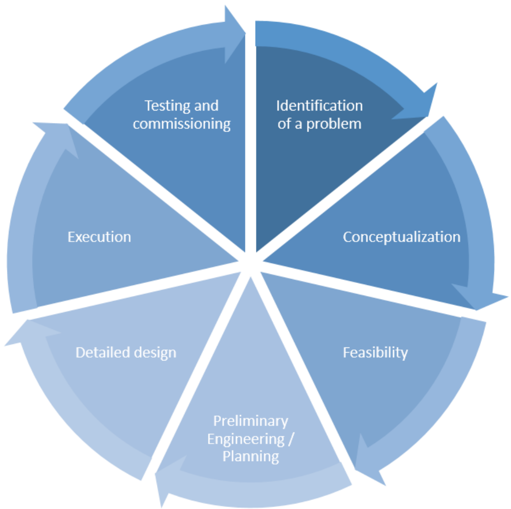


Figure 7.2: Typical stages of design [63].

7.3 Research plan: exploring feasibility

The research plan for finding an answer to the question: 'To what extent is placing a 5 MW wind turbine on top of an FPSO feasible?', is structured by analyzing the project against several different criteria. The criteria follow from the definition of feasibility. The criteria and their associated research questions are:

1. Technical feasibility
   - What are the technical limitations that can impact the project's feasibility?
2. Non-technical feasibility
   - What are common non-technical aspects that can impact the feasibility of this project?
3. Health, Safety, Environment
   - What are the Health, Safety, and Environmental (HSE) hazards and possible mitigations that can impact the feasibility of this project?
4. Business case
   - What is the business case of this project and which aspects can impact its financial attractiveness?

In the evaluation of the criteria, both the effect that the wind turbine has on the FPSO and the effect that the FPSO can have on the wind turbine is taken into account. The relationship is a continuous interaction between these two components and is visualized in figure 7.3.

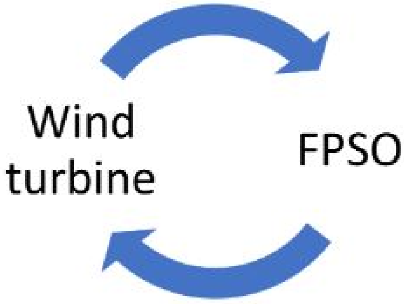


Figure 7.3: Relationship between the wind turbine and FPSO.

The chosen criteria for evaluating the project's feasibility consists of several topics which are taken into consideration. Mostly for technical feasibility and HSE the selection for these topics is made based on the identified hazards during the hazard identification of chapter 6. The goal is to eventually pinpoint any critical showstoppers for placing a 5 MW wind turbine on top of an FPSO. The criteria and their related research questions are:

1. Technical feasibility
   (a) Vessel stability
      - How does the wind turbine influence the FPSO's stability relative to the existing hydrostatic stability criteria?
   (b) Vessel strength
      - Does an FPSO has sufficient vessel strength to carry the wind turbine?
   (c) Vibrations
      - Can vibrations be a possible showstopper for the feasibility of this project?
   (d) Motion analysis
      - How does the wind turbine influence the FPSO motions?
      - How does the wind turbine operate on the FPSO with respect to its operational limits?
   (e) Operations
      - How does the interaction between the wind turbine and FPSO impact the operations taking place on the FPSO?
2. Non-technical feasibility
   (a) Stakeholders
      - What stakeholders are involved in this project?
      - What role can stakeholders play with respect to the feasibility of this project?
   (b) Acceptability
      - How can acceptability affect feasibility?
   (c) Alternative solutions
      - What are possible alternative solutions and how can they impact the feasibility of this project?

3. Health, Safety, and Environment
    (a) HSE risks and mitigations
        - What are the risks for the already identified HSE-related hazards?
        - What are possible mitigations for these risks?
4. Business case
    (a) Environmental benefits
        - What is the environmental benefit in terms of emissions due to generating power using a wind turbine on an FPSO?
    (b) Financial benefits
        - What are the financial benefits of powering an FPSO using a wind turbine?
    (c) Economic sensitivity
        - What parameters can influence the financial attractiveness of this project?

The above criteria form the structure of the thesis report, where each of the criteria is evaluated in relation to the project's feasibility. The focus here is put on the wind turbine and FPSO functioning during their normal day-to-day operations, which are the operations taking place when the FPSO is located at its site. This includes production, storage, offloading, and on-site maintenance. Other project phases such as installation or decommissioning can be critical for the project's feasibility but are recommended for future research.

Part II

Evaluation of feasibility

8 Conceptualization of design

This chapter gives an overview of the different established design concepts. It describes a few minor changes to the chosen wind turbine design from chapter 5. From the hazard identification in chapter 6, several constraints are identified regarding the placement of the wind turbine. These constraints result in three different design configurations that are further explained. Besides this, two different load cases of the Haewene Brim are described which are used as reference load cases for the continuation of the report. The created design concepts are applied to the different load cases, resulting in new load cases which are later used to further assess the (technical) feasibility of the project in more detail.

8.1 Choice for wind turbine and FPSO configuration

8.1.1 Identified constraints

In chapter 6 several hazards are described that can result from the interaction between the wind turbine and FPSO. From these hazards, several constraints can be established when it comes to the placement of the wind turbine. Some of the hazards can already be eliminated by choosing a particular wind turbine placement. Besides possible hazards, there are also a few practical issues and design codes which influence the turbine placement. The identified constraints are shown in table 8.1.

The constraints already eliminate a particular type of FPSO, namely those with the flare tower in the front of the vessel. Therefore as a reference, the Bleo Holm is no longer taken into consideration, and the focus is put on the Haewene Brim. A schematic side view of the Haewene Brim is given in figure 8.1.

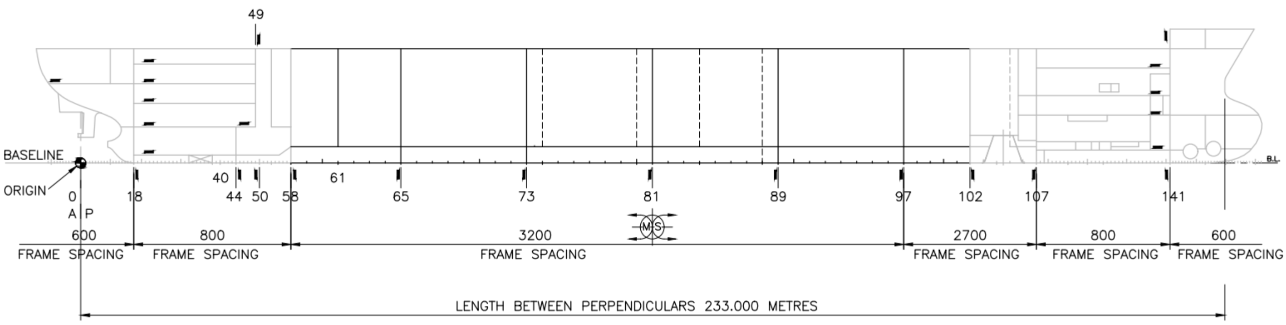


Figure 8.1: Schematic side-view Haewene Brim [64][4].

8.1.2 Vessel coordinate system and general properties

Three possible different design configurations are specified for the continuation of the thesis. To place them in a better perspective, a coordinate system is set up as shown in figure 8.2.

Several general properties of the Haewene Brim are shown in table 8.2. The distance from the after perpendicular where x is equal to 0, in the negative x-direction for the Haewene Brim is equal to 11.5 meters.

[4]Reference coming from Bluewater's Meridian database (not publicly accessible).

Object	Constraints
Wind & waves & current	Environmental data is site specific. The FPSO weathervanes and is mostly aligned based on the interaction of wind, waves, and current. Wind can still come from every direction with respect to the FPSOs orientation. In design codes an offset combination of 30 degrees between wind and waves and 45 degrees between current and waves are given [65]. Allowing the wind turbine to move in its yaw direction is therefore recommended to capture more power.
Flare tower	Flare tower should be placed aft of the wind turbine to prevent the influence of the flare tower's thermal radiation and flare flame on the wind turbine as much as possible.
Helideck	Since flare tower and helideck are always placed opposite of each other, the helideck should be in front of the turbine with sufficient distance to maintain a 210 degrees obstacle-free sector for the helicopter operating area [66].
Cranes	The operable area of the cranes should be avoided by the wind turbine. Sufficient clearance should be present to prevent accidents from occurring.
Process/other equipment	Sufficient clearance between process/other equipment and wind turbine.
Deck space	The wind turbine tower of the NREL 5 MW has a diameter of 6 meters on deck, for which an available area should be available to have sufficient space for structural integration. Additional space is beneficial to have room for expansion and structural integration.
Structural integration	Underneath the deck there should be space to provide room for structural integration, the connection between the wind turbine tower and vessel is likely to be made there. Preferably the location of the wind turbine would be above one of the vessel's bulkheads, which can be used as start for the foundation of the vessel and wind turbine tower connection.

Table 8.1: Constraints for wind turbine placement on an FPSO

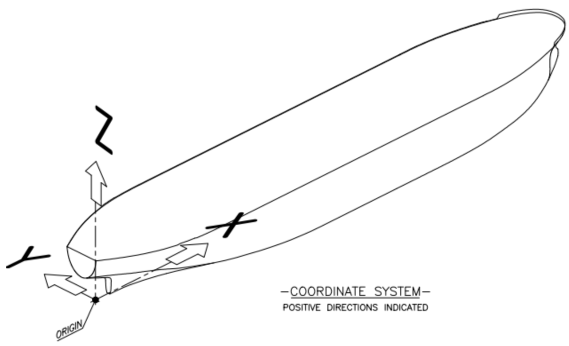


Figure 8.2: Coordinate system of vessel Haewene Brim [64][5].

Total length	252 m
Length between perpendiculars	233 m
Width	42 m
Height of main deck	23.2 m
Height of upper deck	24.1 m
Lightweight	31767.7 t
Total deck area	7280 m^2

Table 8.2: Haewene Brim properties.

[5]Reference coming from Bluewater's Meridian database (not publicly accessible).

8.1.3 Chosen wind turbine placements

To satisfy the constraints there are two regions on the Haewene Brim that in case of sufficient wind turbine heights can fulfill the constraints. These areas are highlighted in yellow in figure 8.3. The figure also shows the positions of the bulkheads underneath the deck in red. For the highlighted areas, it holds that the flare tower is placed aft of the turbine, and the helideck and living quarters are located in front of the turbine. Also, there is sufficient deck space available in these areas where only minor above-deck adjustments might be needed.

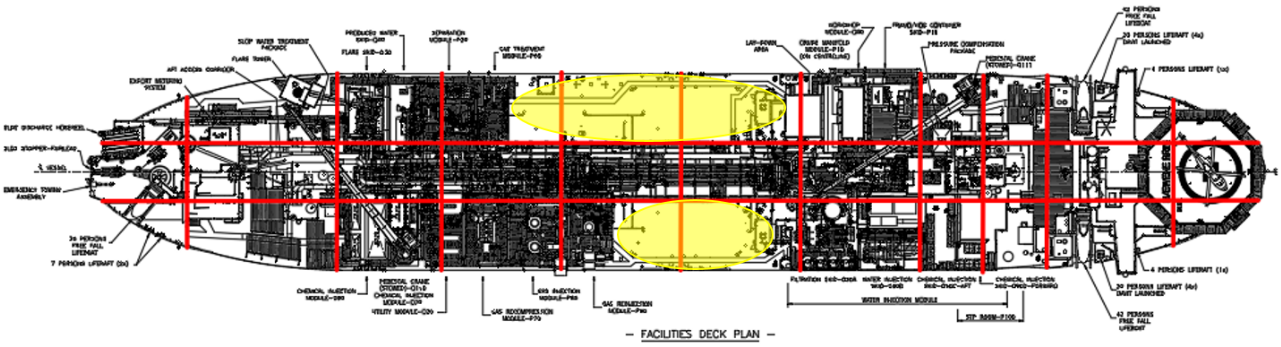


Figure 8.3: Top view Haewene Brim: Areas considered suitable for wind turbine placement.

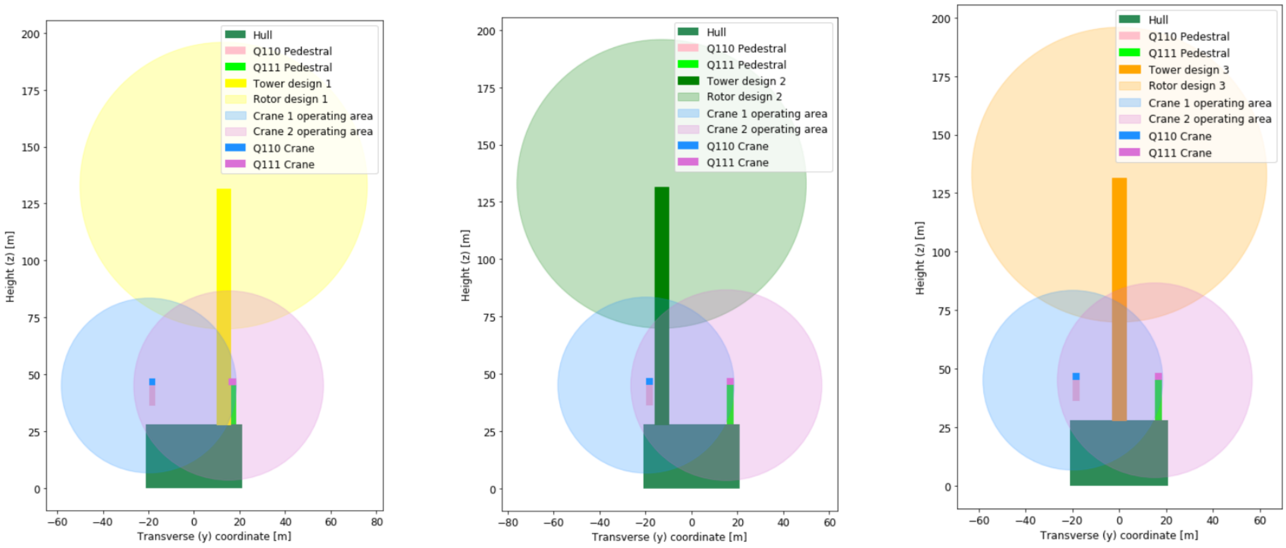
For structural integration placement of the wind turbine above one of the vessel's bulkheads is preferred since this can be the start of the wind turbine's foundation. Within the highlighted areas as shown in figure 8.3 the position of a bulkhead is found at a longitudinal x-coordinate of 117 meters according to the coordinate system of figure 8.2, and at frame 81 indicated in figure 8.1. The bulkhead inside the hull runs along the entire width of the vessel. This is the starting point for determining wind turbine placement.

Next to this bulkhead, inside the hull and underneath the deck there are storage tanks present that can hold liquid cargo. In the end, it might be necessary to give up some of this storage space for the structural integration of the wind turbine. In this stage of the design, it is assumed that structural integration is possible at the chosen locations by making the necessary adjustments to the FPSO.

Based on the constraints and available locations, three different design configurations are chosen. The wind turbine taken into consideration is the NREL 5 MW, which has already been described in chapter 5. Design 1 and design 2 have the turbine placement in the two different yellow zones as shown in figure 8.3. For these two designs, the space is available without making large adjustments on the FPSO deck. Design 3 consists of turbine placement on the vessel's center line. In that case, more adjustments should be made to the FPSO to create the required space for the turbine.

Later in the process of writing the thesis, it was considered that placing the wind turbine on an intersection between a transverse and a longitudinal bulkhead is for load transfer from the wind turbine to FPSO an even better option. However, the longitudinal bulkheads lie 6.24 meters off the center line of the vessel outside the yellow zones of figure 8.3, where in both directions equipment is placed above the bulkhead, so significant changes would need to be made to the FPSO's deck layout, similar to the chosen configuration of design 3. For the continuation of the report, the initially chosen placements as explained above are used.

Design 3 is expected to be the ideal placement of the wind turbine when it comes to the FPSO's roll motions since less moment is generated for this motion due to the weight offset of the wind turbine from the center line. Therefore, it is taken into account to represent the placement of a wind turbine on a possible newly built FPSO. The three designs are illustrated in figure 8.4 by their simplified front views. Also, the cranes located on the FPSO and a front view of their operational areas are illustrated in these figures. Figure 8.5 shows the longitudinal separation between the crane's operational areas and the wind turbine's operational area. The three designs are located on a line having the same x-coordinate of 117 meters, where the transverse bulkhead is located. The coordinates of the center of the tower base of the three different designs are shown in table 8.3.



(a) Design 1 **(b)** Design 2 **(c)** Design 3

Figure 8.4: Front view of three different design configurations.

Coordinates tower base			
	Design 1	Design 2	Design 3
FPSO	Haewene Brim	Haewene Brim	New design
x	117 m	117 m	117 m
y	13 m	-13 m	0 m
z	24.1 m	24.1 m	24.1 m

Table 8.3: Coordinates of tower base for different design configurations

To capture more power, yawing of the turbine should be possible in the different designs. Furthermore, the crane's operational area should not conflict with the wind turbine's operational area. To make sure that this is not the case it is required to increase the tower height of the wind turbine compared to the tower height of 87.6 m of the NREL 5 MW wind turbine. Based on the requirement of having sufficient clearance between the wind turbine operational area and the cranes' operational areas, a new tower height of 105 meters above the tower base is chosen, where the center of the rotor is 1.5 meters above this at 106.5 meters above the tower base. As can be seen from the side-view in figure 8.5, which is valid for all three designs, the operational areas of the cranes do not intersect with that of the wind turbine.

Based on the coordinates of the wind turbine rotor center and crane operational center together with the operational radius of both wind turbine and cranes, the minimum distance that is always maintained between the rotor blades and crane in any orientation of both wind turbine and cranes can be calculated. This can be done using equation 8.1. The relevant coordinates used to compute this distance are shown in table 8.4. It is found that in the worst-case alignment of the wind turbine, for design 1, the smallest distance between the wind turbine rotor and the operational area of one of the cranes is 1.2 meters (in this case crane 2). For design 2, this is 3.1 meters from the operational area of crane 1, and for design 3, this distance is 2.5 meters from the operational area of crane 2. In operations, it can be chosen to not have the worst-case turbine alignment during crane operations, by shutting the turbine down.

$$Distance = \sqrt{|x_{Rotor} - x_{Crane}|^2 + |y_{Rotor} - y_{Crane}|^2 + |z_{Rotor} - z_{Crane}|^2} - R_{Turbine} - R_{Crane} \quad (8.1)$$

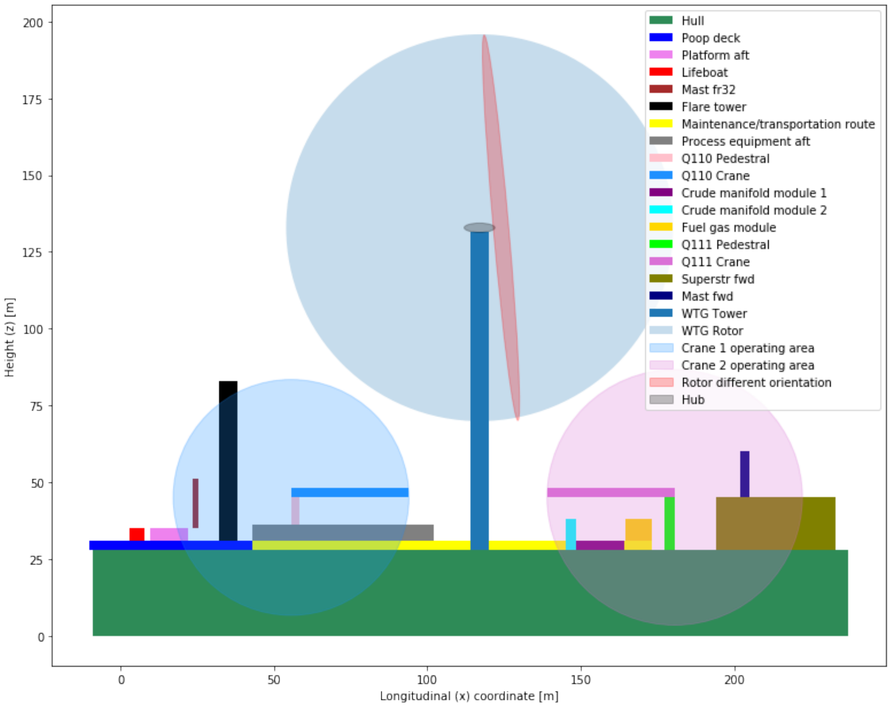


Figure 8.5: Side view valid for all 3 design configurations.

	x [m]	y [m]	z [m]	Radius [m]
Rotor 1	117	13	132.85	63
Rotor 2	117	-13	132.85	63
Rotor 3	117	0	132.85	63
Crane 1	57.2	-17	45	38.4
Crane 2	179	17	45	41.6

Table 8.4: Relevant coordinates of operating areas wind turbine designs and cranes.

8.1.4 Increase of wind turbine tower height

The wind turbine tower height has to be increased due to the design constraint that addresses the clearance between the wind turbine and the cranes of the FPSO. With this the properties of the wind turbine tower change. The tower length increases from 87.6 meters of the NREL 5 MW to 105 meters. This increases the weight and changes the location of the center of mass of the tower. The new tower properties are approximated by linear interpolation, keeping the diameter and wall thickness of the top and base of the tower the same as the original tower. A material density of 8500 kg/m^3 for steel in the tower is used, similar to the original NREL 5 MW tower model [47]. The adjusted tower properties are shown in table 8.5.

Length [m]	105
Mass [t]	417.64
Diameter base [m]	6
Diameter top [m]	3.87
Wall thickness base [mm]	35
Wall thickness top [mm]	25
Height center of mass [m]	45.82
Hub-height [m]	106.5

Table 8.5: Wind turbine adjusted tower properties valid for all 3 designs.

Over the entire height of the wind turbine tower, the diameter over wall thickness ratio lies between 150 and 175, where values between 75 and 250 are normally accepted [67]. In case later design iterations require that the stiffness of the tower needs to be increased, it can be solved by an increase in the wall thickness. All other wind turbine properties are based on the NREL 5 MW reference turbine as documented by Jonkman in [47] and explained in section 5.1. For these other wind turbine specifications, see table 5.1 in section 5.1.

8.1.5 Structural integration

When it comes to structural integration the connection between the vessel and the wind turbine tower is very important. The positioning of the wind turbine is chosen such that it is located above a bulkhead of the FPSO, as a start for the wind turbine's foundation. In the current phase of the project, the shape, size, and weight of this connection are yet to be determined. Nevertheless, it is for sure that additions and adjustments to the vessel are necessary to properly connect the wind turbine tower to the vessel.

To take into account the fact that additional material will be placed on the vessel to form this connection, an assumption is made on the weight of the connection and how this is distributed inside the vessel. The assumption is based on a transition piece, which is commonly known to connect wind turbine towers to monopile foundations. To obtain the weight of the transition piece several dimensions are assumed. The diameter is taken as 6 meters, equal to that of the wind turbine tower base, the wall thickness is 80 millimeters, and a length of 20 meters for the entire transition piece. Using the same steel density as for the wind turbine tower results in a total weight of approximately 250 tons, which is about 33% of the wind turbine's weight. The weight is assumed to be distributed vertically below the wind turbine tower, resulting in the same longitudinal center of gravity (LCG) and transverse center of gravity (TCG) as those of the 3 different designs, and a vertical center of gravity (VCG) of 10 meters below the tower base. The connection between the FPSO and the wind turbine tower is assumed to be rigid at the deck level. Nevertheless, in its real-life application, some bending might occur depending on the exact structural interface due to the transfer of relatively large bending moments between the tower and FPSO.

These assumptions do not imply that the shape or system used for the connection will be similar to that of a transition piece, but only function to take into account possible additions for structural integration. Depending on the strength that a single bulkhead can provide, reinforcements inside the hull might be necessary, which is likely to occupy some space in the liquid storage tanks. In this case, the flexibility of the hull (hogging and sagging) provides an additional challenge. A more detailed design is required in a later project stage. An overview of the structural integration's center of gravity coordinates in each of the designs is given in table 8.6.

	Design 1	Design 2	Design 3
Weight [t]	250	250	250
LCG [m]	117	117	117
VCG [m]	14.1	14.1	14.1
TCG [m]	13	-13	0

Table 8.6: Additional weight properties for structural integration.

8.1.6 Insight in yaw orientation of wind turbine

Within the current choice of wind turbine positioning, the wind turbine nacelle can make a yaw motion as indicated in figure 8.6. This yaw motion is not limited and can operate the full 360 degrees. The nacelle follows the direction of the wind. To provide insight into the wind turbine's orientation with respect to the FPSO, the offset between the wind direction and FPSO heading is plotted versus its probability of occurrence in figure 8.7. This figure is based on almost 90000 sea-state measurements from 29 years of hindcast data from the Pierce Field, a field located in the UK sector of the central

North Sea [68][6]. The offset shown in the figure is the absolute offset between wind and FPSO, so for both positive and negative rotation. An offset of 0 degrees indicates wind blowing in the negative x-direction of the earlier described coordinate system of figure 8.2. From figure 8.7 it can be observed that at a maximum absolute offset of 30 degrees, almost 80% of the time the wind is aligned within that range compared to the FPSO's orientation.

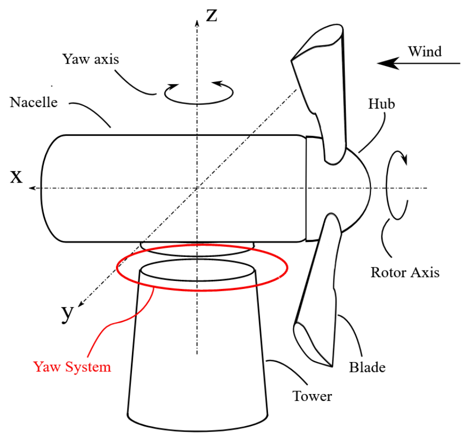


Figure 8.6: Yaw motion of a wind turbine [69].

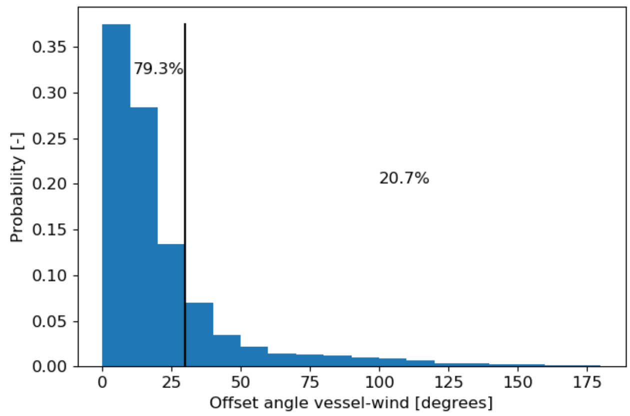


Figure 8.7: Absolute offset between vessel heading and wind direction.

8.2 Vessel loading conditions

The Haewene Brim is exposed to different loading conditions. The pre-defined loading conditions define certain properties of the vessel for specific conditions and should be an accurate representation of several critical situations that occur during the vessel's operations. Two different loading conditions are chosen to represent the in-place weight lightest case, from now on called Ballast, and the heaviest case, from now on called Fully Loaded, of the vessel. The two cases are shown in figure 8.8.

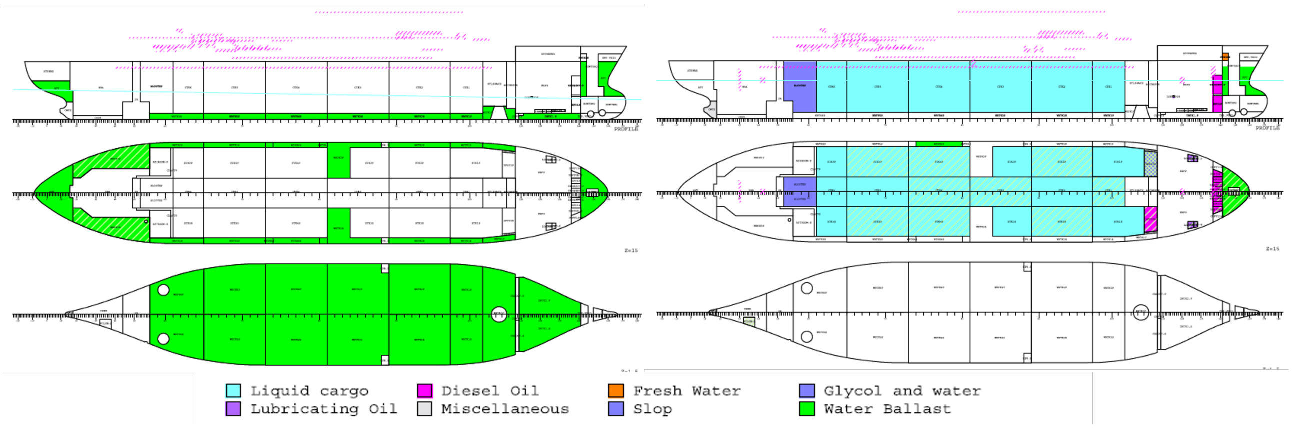


Figure 8.8: Load cases Ballast (left) and Fully Loaded (right).

An overview of the load cases' properties is given in table 8.7. Also, the vessel's lightweight condition is included. The coordinates are given according to the coordinate system established in section 8.1. Both load cases also contain a free surface correction. This correction is made onto the value of the vessel's metacentric height (GM), to represent the free surface effect, which occurs in case a liquid storage tank is not completely filled, offering the liquid the possibility to move around within its storage tank.

[6]Reference coming from Bluewater's Meridian database (not publicly accessible).

Load case	Lightweight	Ballast	Fully Loaded
Displacement [t]	31767.7	81192.0	129370.2
(LCG) [m]	121.81	116.86	120.61
(TCG) [m]	0.32	0.12	0.00
(VCG) [m]	18.95	12.96	14.88
Free surface correction GG0 [m]	0	0.055	0.50

Table 8.7: Reference load cases excluding wind turbine [70][7].

8.3 Final load case combinations

The loading conditions change due to the addition of the turbine on the location as specified in section 8.1. The wind turbine is approached by the tower with a top mass, representing the hub, nacelle, and rotor (RNA). An overview of the turbine's relevant coordinates and mass is shown in table 8.8. The table shows three different transverse coordinates, representing the distinction between the three different design concepts.

Component	RNA	Tower	Added integration
Displacement [t]	350	417.64	250
LCG [m]	117	117	117
VCG [m]	130.6	69.92	14.1
TCG Design 1 [m]	13	13	13
TCG Design 2 [m]	-13	-13	-13
TCG Design 3 [m]	0	0	0

Table 8.8: Coordinates of wind turbine components.

The wind turbine causes a change in overall displacement and coordinates of the center of gravity. This led to a set of final loading combinations which is shown in table 8.9. The new values for the LCG, VCG, and TCG are computed by dividing the mass moment in longitudinal, vertical, and transverse directions respectively, by the total displacement. Similarly, the free surface correction is computed by dividing the free surface moment by the total displacement.

Load case	Ballast			Fully Loaded		
	Design 1	Design 2	Design 3	Design 1	Design 2	Design 3
Displacement [t]	82209.64	82209.64	82209.64	130387.84	130387.84	130387.84
LCG [m]	116.86	116.86	116.86	120.59	120.59	120.59
VCG [m]	13.75	13.75	13.75	15.36	15.36	15.36
TCG [m]	0.284	-0.0379	0.123	0.103	-0.100	0.00111
Free surface correction GG0 [m]	0.054	0.054	0.054	0.50	0.50	0.50

Table 8.9: Reference loading conditions including wind turbine.

An overview of how the weight and properties of the load cases including the wind turbine are built up can be seen in appendix D, section D.1.

[7]Reference coming from Bluewater's Meridian database (not publicly accessible).

9 Technical feasibility

This chapter considers the technical feasibility of placing a wind turbine on an FPSO. First, the methodology for assessing technical feasibility is described. Followed by the assessment or further identification of different topics related to technical feasibility.

9.1 Methodology: SCRUM

From the hazard identification in chapter 6 several technical aspects are identified as potential hazards. These hazards focus on the interaction between the wind turbine and the vessel during normal operations, which are the operations taking place when the FPSO is located at its site. This includes production, storage, offloading, and on-site maintenance. The methodology of assessing technical feasibility is based on SCRUM. SCRUM provides a framework for the management and development of a project. In SCRUM different topics are evaluated in subsequent order, possibly including iterations, usually leading to concrete results. The technical topics from the hazard identification that are assessed or for which further insight is provided in this chapter are shown in the SCRUM diagram in figure 9.1. The topic design configurations is included in the SCRUM diagram to indicate the effect of the previous chapter, where the design concepts are described, on the technical assessment of the topics.

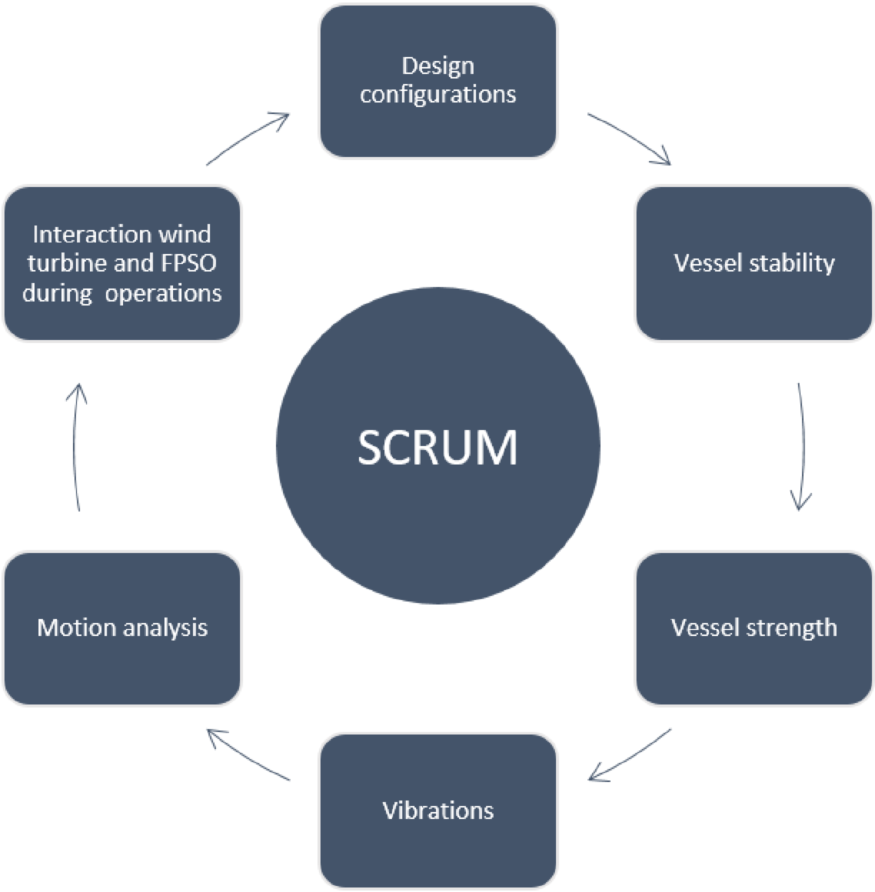


Figure 9.1: SCRUM Diagram

9.2 Stability

Vessel stability can be considered in both statics and dynamics. This section focuses on static vessel stability. Static vessel stability can be described by the assessment of two different angles of the vessel, namely the heel angle and trim angle. As shown in figure 9.2, the heel angle of a vessel is the rotation around its longitudinal axis, and the trim angle is the vessel's rotation about its transverse axis. Several criteria are in place to prevent the vessel from capsizing. These criteria focus mostly on the heel angle, which can be evaluated for different initial values of trim. In this case, trim is defined as the difference in draught between the forward and aft perpendicular of the vessel due to a trim angle.

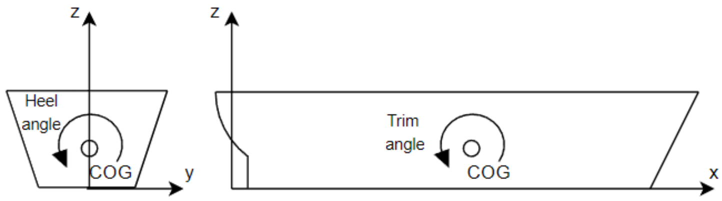


Figure 9.2: Trim and heel of a vessel.

The influence of the wind turbine will be reviewed by comparing the relevant curves, as required by the stability criteria. The results shown in this section are shown for an initial value of trim of 0 meters. The influence of other values of initial trim, ranging between -1 and 4 meters, on the resulting metacentric height (GM) and final vertical distance between keel and center of gravity (KG) is shown in appendix D, section D.3. The extensive results are only shown for an initial value of trim of 0 meters. In appendix D.3 it is shown that for other values of initial trim the criteria are also met.

9.2.1 Vessel stability criteria

The criteria for vessel stability that are evaluated in this thesis originate from:

A Intact criteria from IMO (International Maritime Organisation) A.167 [71]

B Intact criteria including wind from DNV (Det Norske Veritas) [72]

C Intact criteria including wind from HSE (Health and Safety Executive) [73]

The criteria all focus on the vessel being in intact condition. There are also vessel stability criteria for the vessel in damaged condition for which criteria are made by both DNV and HSE for a wind speed of 25.8 m/s. These damage condition criteria consider possible damage to the hull of the vessel which is not evaluated in this thesis but recommended for future research. Nevertheless, the validity of the criteria in the damaged condition is discussed. An overview of the vessel stability criteria is given in table 9.1.

Besides these criteria for the vessel's stability, there is also a summer draught specified for each vessel. This is the maximum allowable draught a vessel can have. From the loading manual of the Haewene Brim, the value for this draught is equal to 15.85 meters [70][8].

[8] Reference coming from Bluewater's Meridian database (not publicly accessible).

A	Intact stability criteria IMO A.167 [71]
1	The area under the GZ-curve up to 30° should not be less than 0.055 meter-radians.
2	The area under the GZ-curve up to θ_f° should not be less than 0.090 meter-radians.
3	The area under the GZ-curve between 30° and θ_f° should not be less than 0.030 meter-radians.
4	The maximum GZ should not occur at an angle that is less than 25°.
5	The maximum GZ should be at least 0.2 meters occurring at an angle equal to or greater than 30°.
6	The initial GM should not be less than 0.15 meters.
θ_f	Angle of flooding: angle of heel at which openings in the hull, superstructures, or deckhouses which cannot be closed weathertight immerse.
B	Intact stability criteria DNV, wind speed = 100 knots (=51.4 m/s) [72]
1	The area under the righting moment curve to the second intercept or the downflooding angle, whichever is less, should be not less than 40% in excess of the area under the wind heeling moment curve to the same limiting angle.
2	The righting moment curve should be positive over the entire range of angles from upright to the second intercept.
C	Intact stability criteria HSE, wind speed = 100 knots (=51.4 m/s) [73]
1	The area under the righting moment curve to the second intercept or the downflooding angle, whichever is less, should be not less than 40% in excess of the area under the wind heeling moment curve to the same limiting angle.
2	The range of positive stability to the second intercept should be at least 30 degrees.
3	The static angle of heel due to the wind should not exceed 15 degrees.
4	The metacentric height should be at least 0.5 m.
D	Damage stability criteria DNV, wind speed = 50 knots (= 25.8 m/s) [72]
1	Then unit should have sufficient reserve stability in a damaged condition to withstand the wind heeling moment based on a wind velocity of 25.8 m/s (50 knots). In this condition the final waterline, after flooding, should be below the lower edge of any downflooding opening.
E	Damage stability criteria HSE, wind speed = 50 knots (= 25.8 m/s) [73]
1	Then unit should have sufficient reserve stability in a damaged condition to withstand the wind heeling moment based on a wind velocity of 25.8 m/s (50 knots). In this condition the final waterline, after flooding, should be below the lower edge of any downflooding opening.
2	The area under the righting moment curve should be at least equal to the area under the 25.8 m/s wind heeling moment curve to an angle not exceeding either the angle of downflooding or the second intercept of the curves, whichever is the lesser. Both areas should be calculated from the static angle of heel without wind.
3	Any unprotected opening should be positioned at least 4 meters above any damaged waterplane, with the unit subject to steady wind heeling.
4	The static angle of heel without wind should not exceed 15 degrees.

Table 9.1: Criteria for assessing vessel stability.

9.2.2 Intact stability IMO A.167

The stability criteria from IMO A.167 describe several criteria that are related to the righting-lever (GZ) curve and the value of the GM of the vessel. Based on several vessel properties the GZ-curve and GM can be determined. With the GZ-curve the transverse static stability of the vessel can be described. Since the transverse stability is determined by properties that are based on the total displacement, longitudinal center of gravity (LCG), and vertical center of gravity (VCG) of the vessel which is the same for each design configuration, there is no distinction in results for the three different design configurations which were earlier described in chapter 8. The cases taken into consideration for this evaluation are therefore load cases Ballast and Fully Loaded including wind turbine (WT), independent of its transverse position. For comparison also results from load case Ballast and Fully Loaded excluding wind turbine are shown. The properties are summarized in table 9.2. GG_0 is the free surface correction due to partially filled storage tanks on board the vessel.

Load case	Ballast		Fully Loaded	
	incl. WT	excl. WT	incl. WT	excl. WT
Displacement [t]	82209.64	81192.0	130387.84	129370.2
LCG [m]	116.86	116.86	120.59	120.61
VCG [m]	13.75	12.96	15.36	14.88
GG_0 [m]	0.054	0.055	0.50	0.50

Table 9.2: Load cases for which stability is evaluated.

Based on the displacement of the vessel and the vessel's initial value of trim, several vessel-specific parameters can be obtained from the Haewene Brim's loading manual [70][9]. These are the transverse metacentric height of the vessel above its baseline (KMT), the vessel's longitudinal center of buoyancy (LCB), the vessel's longitudinal center of flotation (LCF), the moment to change trim (MCT) and the draught of the vessel, either moulded (T) or extreme (Tk).

The values for these parameters described above are shown in appendix D section D.2 tables D.3 and D.4 for load case Ballast and Fully Loaded respectively. Linear interpolation is used between the given displacements to obtain the values for the other parameters for a specific displacement. From the KMT, VCG, and GG_0 it is possible to obtain the metacentric height after free surface correction (GM_c), and the KG. This is shown by formulas 9.1 and 9.2. The values are shown in table 9.3.

$$GM_c = KMT - VCG - GG_0 \tag{9.1}$$

$$KG = KMT - GM_c \tag{9.2}$$

Load case	Ballast		Fully Loaded	
	incl. WT	excl. WT	incl. WT	excl. WT
KMT [m]	18.88	18.97	17.32	17.32
GM_c [m]	5.08	5.95	1.46	1.94
KG [m]	13.80	13.01	15.86	15.38
T [m]	10.49	10.37	15.98	15.85

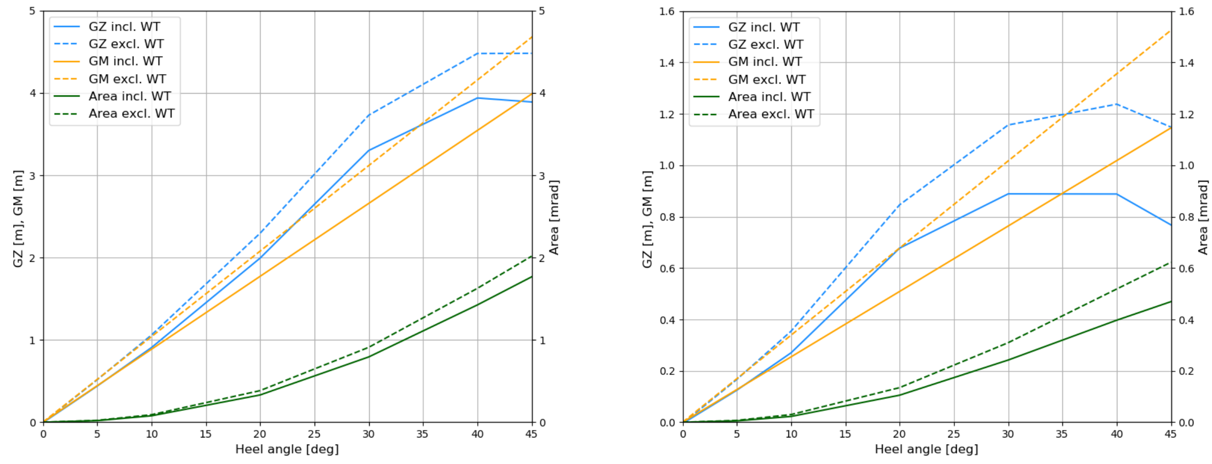
Table 9.3: Stability properties per load case.

Based on the draught of the vessel a value for KN can be obtained. KN is the righting lever measured from the keel. The values of KN for given draughts and heel angles are shown in appendix D section D.2 tables D.5 and D.6 for load case Ballast and Fully Loaded respectively. Linear interpolation is used between the given values of draught to determine the actual values of KN. Having both values for KN and KG, the GZ can be computed for different heel angles. This is done with formula 9.3

$$GZ = KN - KG \cdot sin(\phi) \tag{9.3}$$

With the values of GZ for different angles of heel, the GZ-curve can be plotted. The resulting GZ-curves comparing the Ballast load case including and excluding wind turbine and the Fully Loaded load case including and excluding wind turbine are shown in figures 9.3a and 9.3b respectively. Also, the area under the GZ-curve is plotted, together with the tangent of the GZ-curve indicating GM.

[9]Reference coming from Bluewater's Meridian database (not publicly accessible).

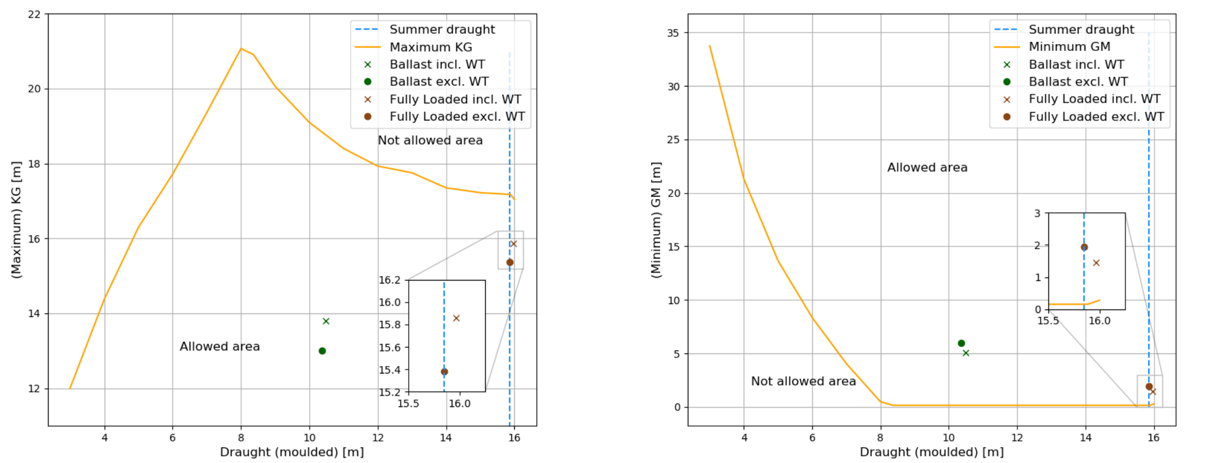


(a) Ballast (b) Fully Loaded

Figure 9.3: GZ-curves vessel including and excluding wind turbine (WT) for different load cases.

From both figures 9.3a and 9.3b is observed that the presence of the wind turbine causes a reduction in the righting-lever arm and a reduction of the value of GM. This indicates an overall decrease in righting moment for different angles of heel.

For the Haewene Brim stability limit curves are defined and available which summarize meeting the stability criteria for IMO A.167 by the use of maximum KG- or minimum GM-curves [74][10]. In case the vessel's load case values lie within the allowed area of the curve, it can be concluded that all the criteria of IMO A.167 regarding intact stability are met. These curves were specifically created for the Haewene Brim vessel and the limit curves are computed to fulfill all of IMO A.167 criteria. Figures 9.4a and 9.4b show the maximum KG-curve and minimum GM-curve respectively, including the position of the different load cases with respect to the curve. It is observed that all cases lie within the allowed areas, indicating that the criteria from IMO A.167 are met.



(a) Maximum KG-curve (b) Minimum GM-curve

Figure 9.4: Limit curves intact stability IMO A.167 criteria and position of different load cases.

For the different load cases, the moulded draught (T) of the vessel is obtained. Both figures 9.4a and 9.4b also indicate the summer draught of the vessel which is equal to 15.85 m. As can be observed the summer draught is exceeded for the load case Fully Loaded including the wind turbine. This means

[10] Reference coming from Bluewater's Meridian database (not publicly accessible).

the vessel's displacement is too large. Fully Loaded excluding wind turbine is already on the limit of the allowable amount of draught. The addition of the wind turbine is enough to go over this limit. A reduction of approximately the weight equal to that of the turbine can solve this issue. This is only 1.04% of the vessel's deadweight in this Fully Loaded condition.

9.2.3 Influence of wind: intact and damage criteria

Vessel stability is also influenced by wind. The existing criteria for vessel stability are not created for a configuration of an FPSO including a wind turbine. The wind speeds that are part of these criteria (51.4 m/s and 25.8 m/s) normally suggest a certain governing situation in either intact or damaged condition. Nevertheless, for a wind turbine, it does not hold that the wind turbine experiences the larger forces for higher wind speeds.

For the comparison of stability criteria including wind, there is looked at the possible worst-case turbine orientation, which is a 90 degrees yaw angle of the turbine relative to the vessel heading as indicated in figure 9.5. The wind direction is constant acting in the transverse direction. In figure 9.5 also the other vessel components that are taken into account are shown. The surface area of the vessel's hull on which the wind acts depends on the draught of the vessel. The wind loading is therefore different for load cases Ballast and Fully Loaded both including and excluding wind turbine.

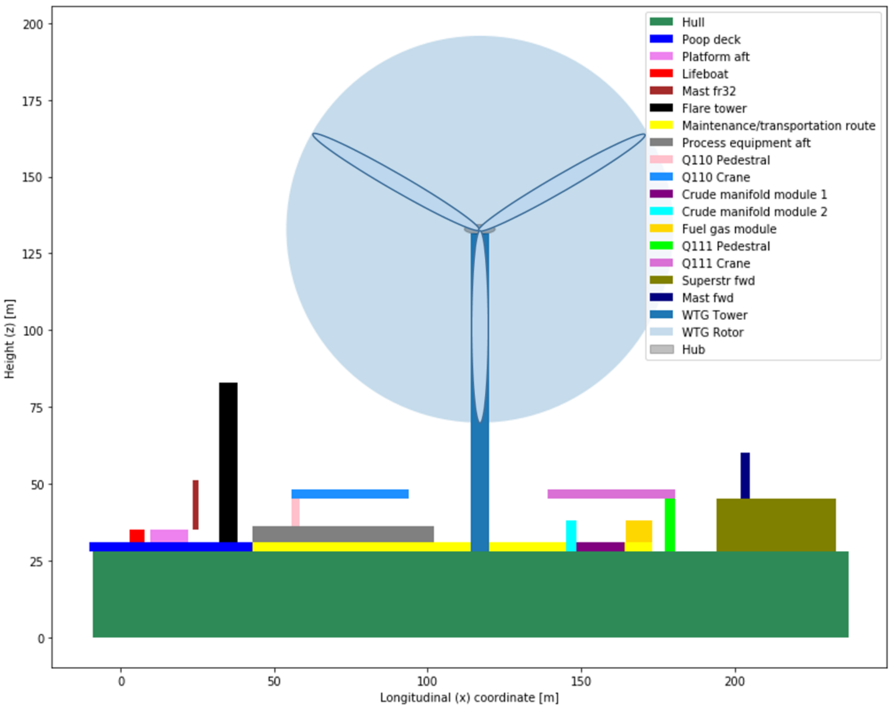


Figure 9.5: Orientation of wind turbine for assessing intact stability criteria including wind.

Validity of criteria

The validity of the criteria including wind is evaluated further in this section. First of all, the forces on a wind turbine are larger when it is in an operating condition compared to a parked condition. Besides that, the thrust force on a wind turbine is larger when the wind speed is at the wind turbine's rated wind speed, which is equal to 11.4 m/s for the NREL 5 MW. This is shown in figure 9.6.

Both the intact and damage criteria by both DNV and HSE consider wind speeds above the NREL 5MW's cut-out wind speed of 25 m/s. It will therefore have to be evaluated under which condition the system of FPSO and wind turbine experiences the largest forces and moments, to find the governing situation. Therefore the heeling moments due to wind speeds of 11.4 m/s, 25.8 m/s, and 51.4 m/s will be determined and compared to the vessel's righting moment curve.

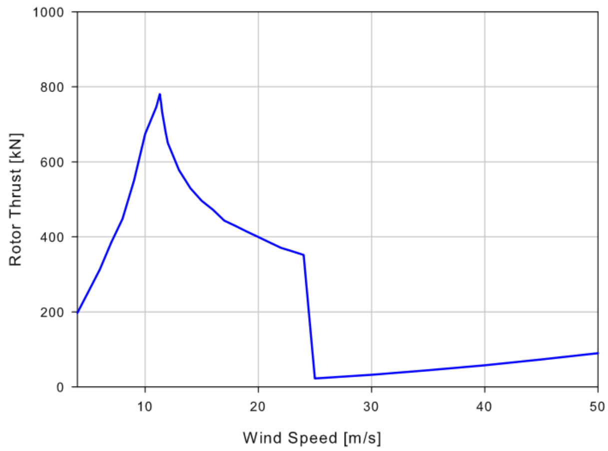


Figure 9.6: Thrust force on NREL 5MW for different wind speeds [75].

Wind heeling moments from FPSO components

In figure 9.5 several vessel components that are taken into account to determine the wind heeling moment are shown. Their properties are shown in table 9.4. The components are approached as rectangles, for which area (A) is calculated. In the case of the flare tower a coefficient of 0.6 (C_{solid} is taken into account since wind can move through part of the frame structure. Coefficient C_s is the shape coefficient and coefficient C_h is a coefficient to take into account the height of the object above sea level. Both coefficients are taken from DNVGL-OS-C301 [72].

Element	X1 [m]	X2 [m]	Z1 [m]	Z2 [m]	C_{solid}	C_s	C_h
Hull below process deck	-9	237	0	27.85	1	1	1
Poop deck	-10	42.8	27.85	31	1	1	1
Platform aft	9.6	22.2	31	34.83	1	1	1.1
Lifeboat	3	8	31	35	1	1	1.1
Mast fr32	23.5	25.3	35	51	1	1.5	1.1
Flare tower	32	38	31	83	0.6	1	1.2
Maintenance/transportation route	43	173	27.85	30.98	1	1	1
Process equipment aft	43	102	30.98	36	1	1.1	1.1
Q110 Pedestal	55.6	58.8	36	45	1	0.5	1.1
Q110 Crane	55.6	94	45	48	1	1.5	1.2
Crude manifold module 1	145	164	30.98	38	1	1	1.1
Crude manifold module 2	145	148.6	38	45	1	1	1.1
Fuel gas module	164.5	173	30.98	38	1	1	1.1
Q111 Pedestal	177.4	180.6	27.85	45	1	0.5	1.1
Q111 Crane	139	180.6	45	48	1	1.5	1.2
Superstr fwd	194	233	27.85	45	1	1	1.1
Mast fwd	202	205	45	60	1	1.5	1.2

Table 9.4: FPSO elements included in the calculation of wind heeling moment.

The wind force on the different components can be determined with equation 9.4, where ρ_{air} is the air density of 1.222 kg/m^3 and V is the wind speed at 10 meters above MSL in m/s. From this, the heeling moment due to the FPSO elements can be determined according to equation 9.5.

$$F_{wind} = \frac{1}{2} \cdot C_{solid} \cdot C_s \cdot C_h \cdot \rho_{air} \cdot A \cdot V^2 \tag{9.4}$$

$$M_{heeling} = F_{wind} \cdot arm \tag{9.5}$$

The arm is taken as the distance between the vertical center of the area and the vertical center of the part of the vessel that is submerged.

Wind heeling moments from wind turbine

The moment on the wind turbine is calculated in two different conditions. Operating in the case of a wind speed of 11.4 m/s and parked in case of wind speeds of 25.8 m/s and 51.4 m/s. In both cases, the moment resulting from the wind force on the wind turbine tower can be calculated the same way. The computed forces are multiplied with a height coefficient C_h taken from DNVGL-OS-C301 to approximate the variability of the wind over the structures height [72]. It should be noted that local wind gusts can in reality generate even larger moments than computed here.

During operation, the thrust force on the rotor can be determined by equation 9.6, which can be derived from momentum theory where the rotor is considered as an actuator disc [76]. The area in this case is the area of the rotor disc, a circle with a diameter of 126 meters. A thrust coefficient of 0.75 is used matching a wind speed of 11.4 m/s [77].

$$T = \frac{1}{2} \cdot C_h \cdot C_T \cdot \rho_{air} \cdot A \cdot V^2 \tag{9.6}$$

For a wind turbine in the parked condition, the thrust force onto the rotor is determined using the blade-element theory. The position of the blades in the parked condition is taken as shown in figure 9.5. Each blade is divided into several different segments. Their properties are taken from [47] and shown in table 9.5.

Segment	Length [m]	Chord (c) [m]	C_D	C_L
1	2.73	3.54	0.5	0
2	2.73	3.85	0.5	0
3	2.73	4.17	0.35	0
4	4.1	4.56	0.0113	0.137
5	4.1	4.65	0.0094	0.196
6	4.1	4.46	0.0094	0.196
7	4.1	4.25	0.0087	0.288
8	4.1	4.01	0.0065	0.444
9	4.1	3.75	0.0065	0.444
10	4.1	3.50	0.0057	0.521
11	4.1	3.26	0.0057	0.521
12	4.1	3.01	0.0052	0.442
13	4.1	2.76	0.0052	0.442
14	4.1	2.52	0.0052	0.442
15	2.73	2.31	0.0052	0.442
16	2.73	2.09	0.0052	0.442
17	2.73	1.42	0.0052	0.442

Table 9.5: Wind turbine blade properties [47].

Since the blades are in parked condition a blade pitch angle of 90 degrees is assumed to obtain the lowest total thrust force on the rotor. This represents the incident angle ϕ. The orientation of the blade relative to the wind is shown in figure 9.7.

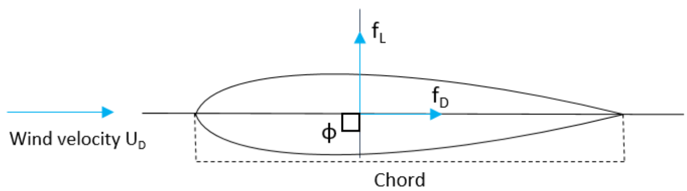


Figure 9.7: Blade orientation relative to the incoming wind in parked condition.

The force for a single blade segment can be determined by its drag and lift force components according to the blade-element theory. The drag force, lift force and total force are determined according to equations 9.7 till 9.9 obtained from [76]. Here c is the chord length in meters, U_D is the wind velocity in meters per second, and W is the incident wind velocity, which is the resultant wind velocity due to the incoming wind velocity U_D and tangential rotational velocity of the blade. Since the turbine is in parked condition this tangential rotational velocity is equal to zero, which equals the incident velocity to the incoming wind velocity. Again a height factor (C_h) is included to take into account the wind variance over the height. Since the incident angle is 90 degrees, the contribution of the lift force in the total force becomes 0.

$$f_D = \frac{1}{2} \cdot \rho_{air} \cdot c \cdot C_D \cdot |U_D| \cdot U_D \tag{9.7}$$

$$f_L = \frac{1}{2} \cdot \rho_{air} \cdot c \cdot C_L \cdot W \cdot |W| \tag{9.8}$$

$$T = C_h \cdot \int_R f_{OP} dr = C_h \cdot (\int_R (f_L cos(\phi) + f_D sin(\phi))dr) \tag{9.9}$$

For the operating condition, the moment due to the thrust force is determined by multiplying the thrust force by the distance between the hub height and the vertical center of the submerged vessel part. For the parked condition, the force acting on the individual blade segments is multiplied by the distance between the vertical coordinate of the segment and the vertical center of the submerged vessel part. The total moment is then determined by summing all individual segment moments.

The wind force onto the tower is computed by dividing the tower into 105 different elements, each with a length of 1 meter. The diameter of each element is determined by linear interpolation over the height of the tower between the top outer diameter of 3.87 meters and the base outer diameter of 6 meters. For each element, the wind force is determined using equation 9.10. A drag coefficient C_D of 1.2 is used which is typical for cylindrical structures. The moment due to the tower is determined by multiplying the force on each element with its vertical distance from the vertical center of the submerged vessel part.

$$F_{tower} = \frac{1}{2} \cdot \rho_{air} \cdot C_h \cdot C_D \cdot A \cdot V^2 \tag{9.10}$$

Evaluation of total moments

The total wind heeling moments are determined by the superposition of the calculated moments from the FPSO elements and the wind turbine components. This way the moments for a heel angle of 0 are obtained. The heeling moments at different heel angles can be determined by multiplying the wind heeling moment at a heel angle (ϕ) of 0 with the cosine of the required heel angle.

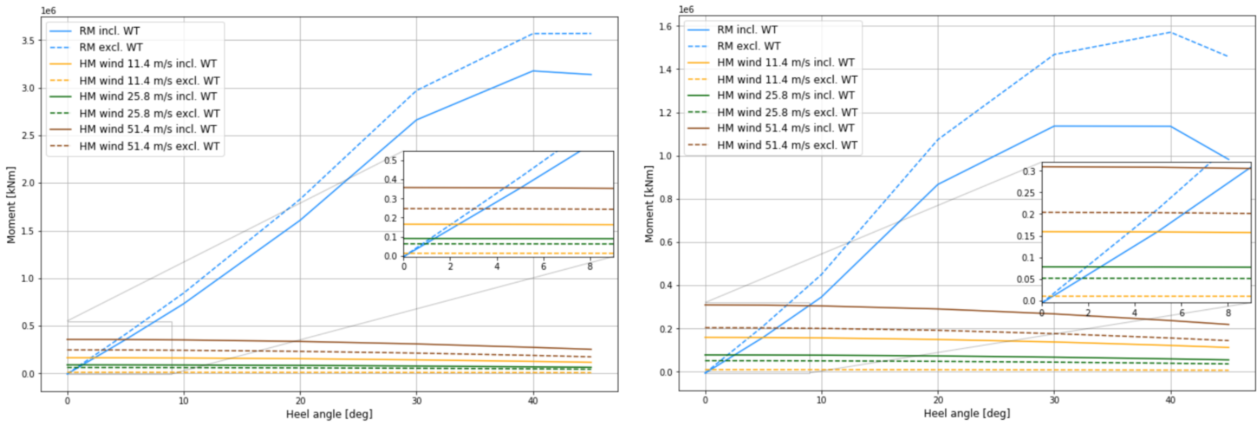
$$M_{windheeling\phi} = M_{windheeling0} \cdot cos(\phi) \tag{9.11}$$

For both load cases, Ballast and Fully Loaded including and excluding wind turbine the righting moment curve is plotted together with the wind heeling moment curves of the different wind speeds. This is shown in figures 9.8a and 9.8b. The righting moment curve is obtained by multiplying the righting lever curve with the total displacement of the load case.

From figures 9.8a and 9.8b it can be observed that in the case of a wind speed of 11.4 m/s, a larger wind heeling moment is generated compared to a wind speed of 25.8 m/s when including the wind turbine. This indicates a different governing situation than is used in the criteria for wind heeling in damaged conditions. This criteria therefore would have to be revised to take into account the addition of a wind turbine and its interaction with the FPSO. Logically, when the wind turbine is excluded, the case of 25.8 m/s stays valid over the 11.4 m/s case.

In the case of wind heeling in intact condition, the criteria stay valid, since a larger wind heeling moment is generated due to wind of 51.4 m/s compared to 11.4 m/s, for both including and excluding the wind turbine's contribution. Because of this, the wind heeling criteria in intact condition can be assessed.

Another observation from figures 9.8a and 9.8b is the increase in static heel angle due to the addition of the wind turbine. Especially for the Fully Loaded case where the extreme case excluding wind turbine for wind equal to 51.4 m/s results in a static heel angle of approximately 5 degrees, this same angle is reached at a wind speed of 11.4 m/s including the wind turbine. This can influence the operations of the FPSO and change the working efficiency of the crew on deck. Nevertheless, it should be noted that this occurs at the worst-case wind turbine alignment for a yaw angle of 90 degrees with respect to the vessel. In chapter 8 figure 8.7 it was shown that this yaw angle has a probability of occurrence of approximately 2% based on 29 years of hindcast data consisting of almost 90000 sea-state measurements. This is low compared to other wind directions with a smaller offset than 90° relative to the vessel heading.



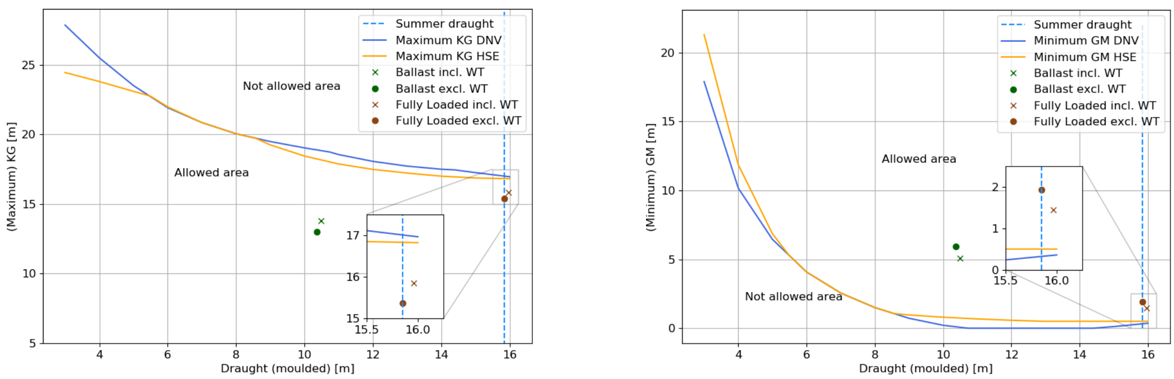
(a) Ballast

(b) Fully Loaded

Figure 9.8: Righting moment (RM) and wind heeling moment (HM) curves for load cases including and excluding wind turbine (WT).

Intact stability criteria including wind: DNV & HSE

Since the intact stability criteria including wind by DNV and HSE are found valid, they can be assessed. For these criteria there is also maximum KG- and minimum GM-curves available. Both DNV and HSE criteria result in specific curves. In figures 9.9a and 9.9b it is shown that for both load cases including and excluding wind turbine the cases are located in the curves allowable areas. Besides the exceeding of the summer draught which is independent of the wind, there are no further issues due to the intact wind stability criteria.



(a) Maximum KG-curve

(b) Minimum GM-curve

Figure 9.9: Limit curves DNV and HSE intact stability and position of the different load cases.

9.3 Vessel strength

The Haewene Brim experiences based on its loading condition a certain amount of bending moment and shear. Including a wind turbine on the vessel results in additional bending moment and shear over the length of the vessel. The amount of effect that the wind turbine has on the bending moment and shear and whether the maximum and minimum allowable values are exceeded is assessed in this section.

9.3.1 Bending moment and shear due to wind turbine

The additional bending moment and shear due to the addition of the wind turbine are calculated for both load cases Ballast and Fully Loaded, which have been earlier described in section 9.2. Since the vessel strength is assessed in the longitudinal direction, there is no difference due to a change in the wind turbine's transverse coordinate, so a distinction between the three different design configurations is not necessary. As shown in figure 9.10, the vessel is represented as a beam, which results in a moment line and shear line as given in the figure. For the total length of the beam, the length between perpendiculars of 233.2 meters is taken. The force acting on the beam represents the gravity force due to the weight of the wind turbine.

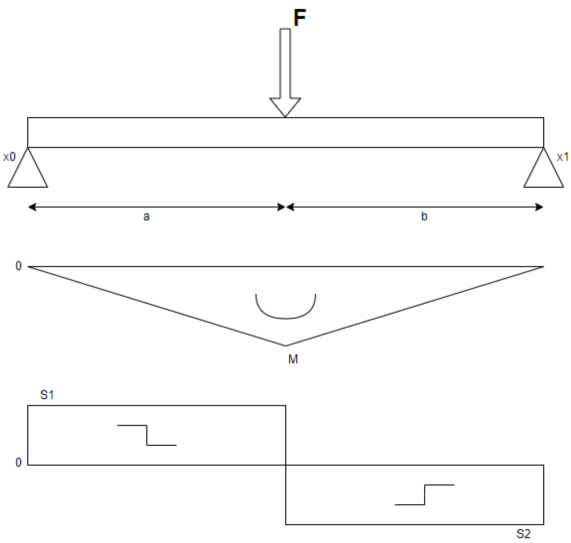


Figure 9.10: Beam representation including moment and shear line.

The force results in two vertical reaction forces in the supports of the beam, S1, and S2. These can be computed by taking the sum of the moments about one of the supports, which has to be equal to 0. The moment M can then be calculated by multiplying one of the reaction forces with the distance to the location of the force F. The resulting parameters are shown in table 9.6.

Parameter	Value	Unit
a	117	m
b	116.2	m
Force F	1011.67	t
Moment M	59879.67	t.m
S1	504.10	t
S2	507.57	t

Table 9.6: Overview of values for moment and shear line.

9.3.2 Original bending moment and shear.

Bending moment and shear on a vessel occur due to the difference in the weight and buoyancy distributions over the length of the vessel. The vessel's weight distribution depends on the vessel's load case. An overview of the weight distribution of the vessel in the lightweight condition is shown in figure 9.11, together with the weight distributions of load cases Ballast and Fully Loaded excluding wind turbine. A typical buoyancy curve is shown in figure 9.12.

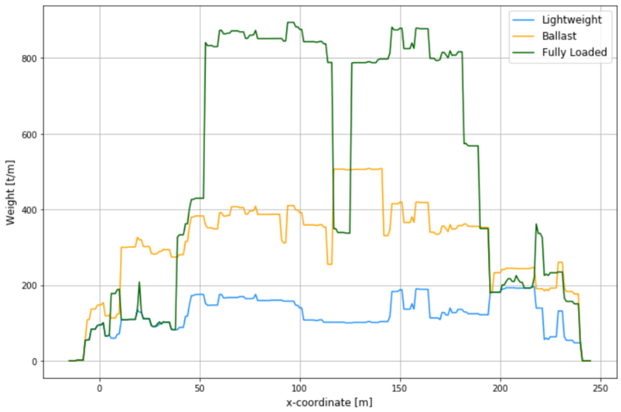


Figure 9.11: Weight distribution for Haewene Brim's different load cases.

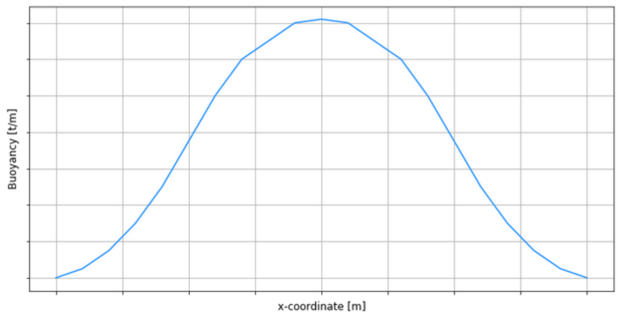


Figure 9.12: Typical buoyancy curve for a vessel.

Load cases Ballast and Fully Loaded both have different bending directions. Figure 9.13 shows that load case Ballast is hogging, and load case Fully Loaded is sagging.

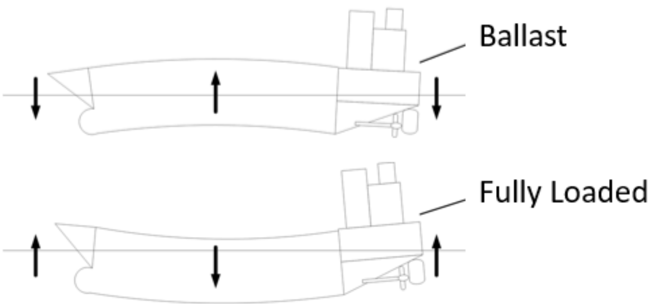


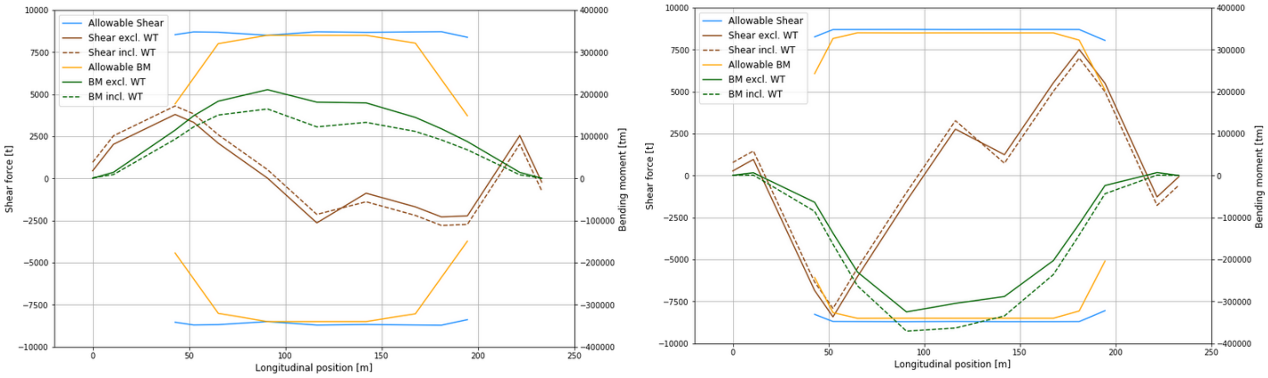
Figure 9.13: Hogging and sagging

9.3.3 Influence of additional bending moment and shear on vessel

Figures 9.14a and 9.14b show the bending moments and shear forces together with the maximum and minimum allowable values for load cases Ballast and Fully Loaded respectively. Both the original bending moment and shear force excluding and including the wind turbine are plotted. The curves excluding the turbine were available from Haewene Brim's loading manual [70][11]. In this manual the bending moment and shear which the vessel experiences due to its loading condition have already been calculated.

The bending moment and shear curves of the vessel including the wind turbine are obtained by superposition of the curves of the vessel excluding the wind turbine and the curves obtained from the wind turbine weight as calculated in 9.3.1. As can be seen from figure 9.14a, for load case Ballast, the plotted curves are not reaching the minimum or maximum allowable values for both shear and bending moment. Figure 9.14b shows for load case Fully Loaded that the bending moment in case the wind turbine is included is exceeding the limit curve, meaning that the vessel's bending resistance is insufficient in this case.

[11]Reference coming from Bluewater's Meridian database (not publicly accessible).



(a) Ballast **(b)** Fully Loaded

Figure 9.14: Influence of wind turbine on the bending moment and shear force of different load cases.

A solution to prevent the exceeding of the vessel's bending resistance for the Fully Loaded case is reducing the ballast liquid cargo. This is the same solution as proposed to solve the stability issue of exceeding the summer draught as described in section 9.2. As explained in section 9.2 it is expected that this reduction is only 1.04% of the vessel's deadweight approximately, for the vessel in its Fully Loaded condition.

9.4 Vibrations

This section provides some insight into the topic of vibrations due to the interaction between the wind turbine and the FPSO or FPSO components.

9.4.1 Wind turbine natural frequency

The natural frequency of a wind turbine depends on the rotational speed of the rotor. Since this speed can vary, ranges of natural frequencies can occur for an operational wind turbine. For a 3-bladed wind turbine, the 1P and 3P frequency ranges are relevant. Here 1P and 3P are the blade-passing frequencies of 1 and 3 blades respectively. These frequencies can be derived from the cut-in and rated rotor speed. For the NREL 5 MW, the cut-in rotor speed is equal to 6.9 rpm. Where the rated rotor speed is equal to 12.1 rpm. These rotor speeds result in a frequency of 0.12 Hz and 0.20 Hz respectively, making up the 1P frequency range. The 3P frequency range is then from 0.35 Hz to 0.61 Hz. The frequency ranges of the NREL 5 MW are shown in figure 9.15.

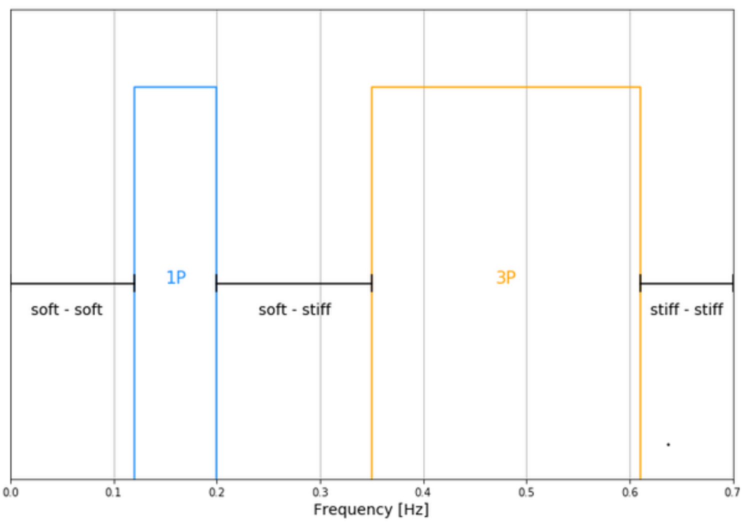


Figure 9.15: Natural frequency ranges of the NREL 5 MW.

Besides the natural frequencies of the rotor, the tower of the wind turbine also has its natural frequencies. Offshore wind turbine towers are often designed to have their natural frequencies fit within the soft-stiff range, which is displayed in figure 9.15. This design choice comes from mainly two different reasons. First of all, to prevent resonance caused by either 1P, 3P, or the environmental loading (waves and wind) in the soft-soft range. Second, to prevent having a very expensive tower when designed in the stiff-stiff range. The exact natural frequencies of the tower depend on its structure. It can be adjusted by altering the diameter or wall thickness of the tower.

9.4.2 FPSO natural frequencies

The FPSO and the equipment on an FPSO have their natural frequencies. In case the natural frequencies of the FPSO or its equipment approach the wind turbine's natural frequencies (1P and 3P), resonance might occur. A distinction can be made between global and local resonance.

The American Bureau of Shipping (ABS) [78] provides insight into the hull girder 2-node vertical vibration. Based on several vessel types and sizes of a vessel ABS provided a table with typical 2-node vertical vibration frequencies. This table is shown in table 9.7. Figure 9.16 shows a typical mode shape of a vessel for this 2-node vertical vibration.

Ship No.	*Type*	*Size (tone)*	*Kumai (Hz)*	*FE Method (Hz)*	*Dev. (%)*
1	Reefer	15000	1.54	1.51	+2
2	Ro-Ro	49000	1.49	1.60	–7
3	Ro-Ro	42000	1.04	0.94	+10
4	Chemical	33000	1.00	0.93	+8
5	Bulk Carrier	73000	0.63	0.64	-2
6	Container Carrier	120900	0.41	0.49	-17.0
7	Large Container Carrier	200000	0.38	0.45	-15
8	VLCC	363000	0.40	0.46	-12.8

Table 9.7: Typical 2-node vertical vibration natural frequencies for different vessel types by ABS [78].

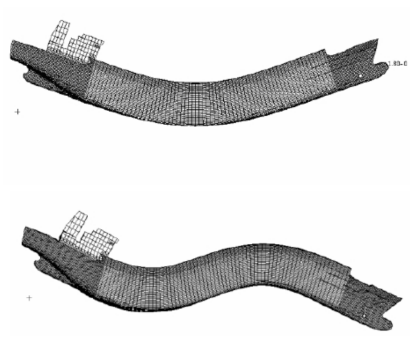


Figure 9.16: Typical first two vertical mode shapes of a vessel [78].

An FPSO such as the Haewene Brim can be compared to a bulk carrier type of vessel as shown in the table. For this type of vessel, the first natural frequency approaches the 3P range of the wind turbine's natural frequencies.

The pieces of equipment on the FPSO also have their own natural frequencies. Local vibrations can therefore also occur, which might lead to local damage to equipment or local vibrations which can be a discomfort for the onboard crew. Future research into both the effect of the wind turbine on the global system vibration, as on the local vibrations, and how this might influence the detailed structural integration of the wind turbine onto the FPSO is recommended. In case the occurrence of significant vibrations is further identified, it should be assessed how this influences both the FPSO and the structural integrity of the wind turbine.

9.5 Motion analysis

This section shows the methodology and results of a motion analysis for a configuration of a wind turbine on top of an FPSO. An overview of the methodology is given after which the different steps are explained in more detail. Finally, the results are described. The goal of the motion analysis is to find an answer to the following two questions:

1. How does the wind turbine influence the FPSO motions?

2. How does the wind turbine operate on the FPSO with respect to its operational limits?

9.5.1 Methodology of motion analysis

The motion analysis consists of two different parts. First, a diffraction analysis is performed in HydroStar where the displacement Response Amplitude Operators (RAOs) and 1^{st} order wave load RAOs are calculated based on potential theory. This is done for the vessel with and without the wind turbine. The wind turbine is modeled as additional mass and inertia, influencing the radii of gyration of the vessel. Later, a comparison of the two is presented.

The RAOs output from HydroStar is used as input for an OrcaFlex model, where the interaction between the wind turbine and vessel is determined in the time domain. The switch to the time domain is made to capture the dynamic behavior of the interaction between the vessel and the wind turbine including the wind turbine's rotation for different environmental conditions. For the dynamic positioning of the vessel, a soft-mooring system is attached to the vessel. The general steps of the modeling process are shown in figure 9.17.

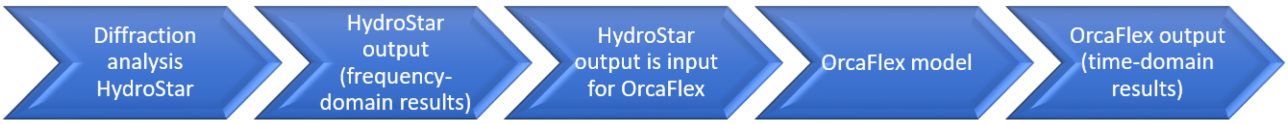


Figure 9.17: General modeling steps within the motion analysis.

The steps are further described in this section. In 9.5.2 an overview is given of the diffraction analysis model. The results of the diffraction analysis are shown in 9.5.3. Section 9.5.4 gives an overview of the model in OrcaFlex. The environmental load cases that are used in the time domain analysis are described in section 9.5.5. Finally, the results of the time domain analysis in OrcaFlex are given and discussed in 9.5.6. For both load cases, Ballast and Fully Loaded this analysis is performed.

The HydroStar output which functions as OrcaFlex input is explained further below. First, a diffraction analysis is performed from which displacement RAOs of the vessel (excluding mooring stiffness) are obtained. These displacement RAOs represent the 6 Degrees of Freedom (DoF) vessel motions at its center of gravity in the frequency domain. From the displacement RAOs, it can be observed what the effect is of the additional mass and inertia of the wind turbine on the vessel's displacement RAOs.

The displacement RAOs can be used as input for an OrcaFlex model where the vessel is coupled to the wind turbine model and mooring system. Nevertheless, to combine the effect of the displacement RAOs and the effect of the wind turbine and mooring in the model, an explicit time domain solver needs to be used, leading to long calculation times, which is also not recommended by Orcina. Therefore an alternative method is used in which from the same diffraction analysis, the 1st order wave load RAOs, added mass, and damping of the vessel is obtained in the frequency domain. This alternative method has the benefit of being able to use the implicit solver, which results in faster computation time.

To check the vessel behavior in the time domain using 1st order wave load RAOs, added mass, and damping this method is compared to using displacement RAOs including mooring stiffness. This is done for a single load case (Ballast) excluding the wind turbine. These displacement RAOs including mooring stiffness are again compared to the displacement RAOs excluding mooring stiffness. The steps of the motion analysis described above are visualized in figure 9.18.

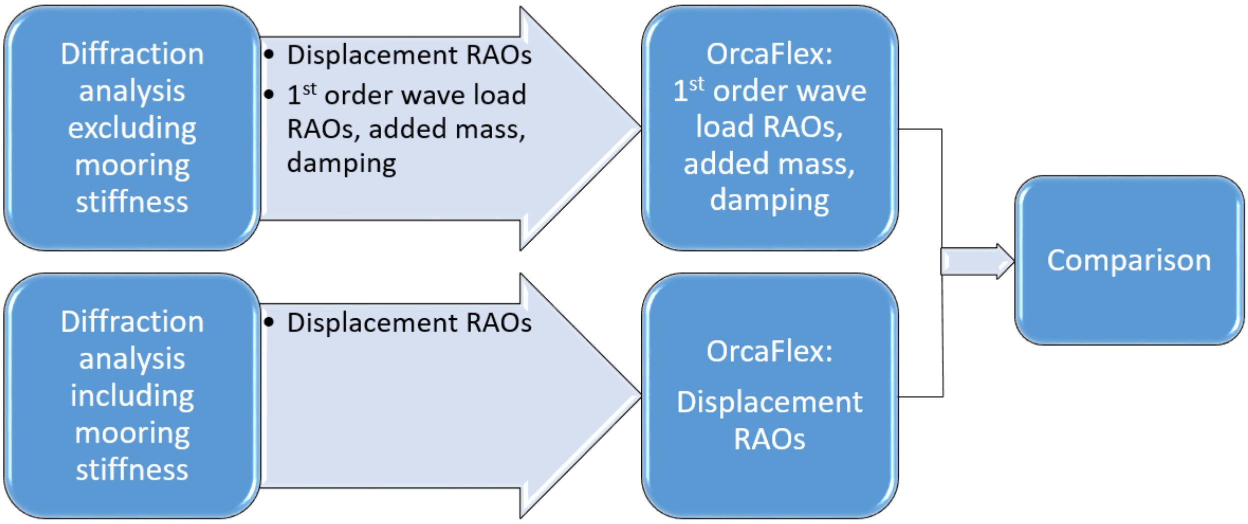


Figure 9.18: Overview of methods for motion analysis.

9.5.2 Diffraction analysis

A diffraction analysis is performed in HydroStar v.8.14. From this diffraction analysis, the FPSOs displacement RAOs for the 6 DoF of the vessel are obtained. From the same analysis, the 1^{st} order wave load RAOs, added mass, and damping of the vessel are obtained. The tool Bluefrac provided by Bluewater is used to generate the input files required for HydroStar. The RAOs of the FPSO including the wind turbine are obtained for the three different design configurations, as shown in figure 8.4, applied to the two different load cases, Ballast and Fully Loaded. These RAOs are compared to the RAOs of the FPSO excluding the addition of a wind turbine. This results in 8 different sets of RAOs.

Methodology

For the Haewene Brim, an existing model of its shape is available in HydroStar. It can be adjusted by changing several of its properties, namely its draft, trim, displacement, center of gravity, and radii of gyrations. For each of the load cases as described in chapter 8 section 8.3, the addition of the wind turbine is included in the diffraction load cases by adjusting these parameters. The analysis is performed for a water depth of 83 meters which approximately occurs at the Pierce Field [79].

The coordinate system that is used is shown in figure 9.19. The z-coordinate is pointing upwards in the positive direction and is equal to 0 at the bottom of the vessel's keel. The headings of the vessel are indicated for several directions. Figure 9.20 indicates the vessel's DoFs.

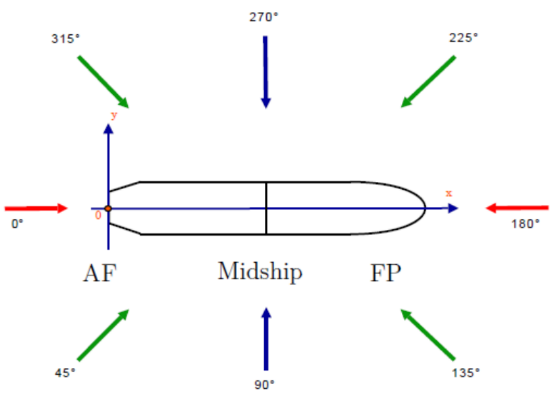


Figure 9.19: Vessel coordinate system and headings for diffraction analysis [80].

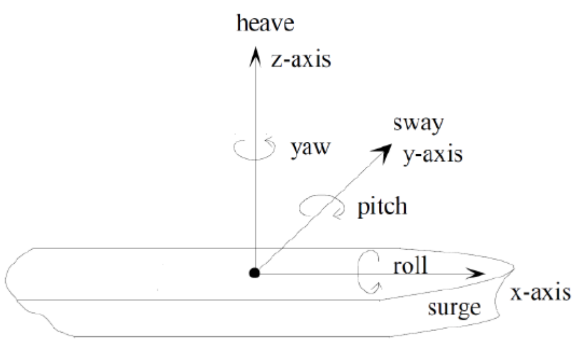


Figure 9.20: Overview of vessel DoFs.

The wind turbine is included in the diffraction analysis by the effects of its mass and inertia on the overall vessel properties. The blades are fixed to the turbine and not rotating. The tower mass is distributed over its height and the RNA is considered a lumped mass. For the inertia both global and local inertia is taken into account, using available values for the RNA's local inertia.

The center of gravity and displacement of the FPSO for the different load cases have already been determined in chapter 8. The required values for draft and trim can be obtained from the FPSO's hydrostatic properties. These hydrostatic properties are already partially determined in section 9.2 and specified in appendix D based on the displacement of the vessel. The trim (TR) is determined with equation 9.12. Equations 9.13 up to 9.15 are used to determine the vessel's draft aft of the vessel (Ta), draft fore of the vessel (Tf), and the vessel's mean draft (Tm).

$$TR = \frac{(LCB - LCG) \cdot Disp}{100 \cdot MCT} \tag{9.12}$$

$$Ta = T + \frac{TR \cdot LCF}{LBP} \tag{9.13}$$

$$Tf = Ta - Tr \tag{9.14}$$

$$Tm = \frac{Ta + Tf}{2} \tag{9.15}$$

The addition of the wind turbine on the vessel influences the vessel's radii of gyration. New radii of gyration are determined including the inertia of the wind turbine's components (RNA, tower, and additional mass for structural integration). For the wind turbine RNA and tower, both local and global inertia is taken into account. Combining the global and local inertia results in the total inertia according to Steiner's theorem. Since the exact shape of the structural integration remains unknown at this point, it is considered a lumped mass of which only its global inertia is added to the total vessel's inertia.

The new radii of gyration of the vessel including the wind turbine are obtained by combining the mass moments of inertia of the components of the entire system. The mass moments of inertia of the vessel excluding the wind turbine are determined from the original radii of gyration. This is done by equation 9.16, where I is the mass moment of inertia, K is the radius of gyration, and m is the displacement mass of the vessel. This is done for the different axis of rotation (xx, yy, zz, xy, xz, yz).

$$I = K^2 \cdot m \tag{9.16}$$

The global inertia of the wind turbine components is obtained by considering the total mass of the component and its COG with respect to the vessel's COG. The distance between the parallel axis through the vessel's COG and the turbine component's COG is determined and multiplied by the mass of the components. This is done for different axis. Equations 9.17 up to 9.22 show the equations used to compute the global inertia of the wind turbine components. Here m_k is the mass of the wind turbine component k, x_k the distance between the component's x-coordinate and the vessel's cog x-coordinate, y_k the distance between the component's y-coordinate and the vessel's cog y-coordinate, and z_k the distance between the component's z-coordinate and the vessel's cog z-coordinate.

$$I_{xx} = \sum_{k=1}^{N} m_k (y_k^2 + z_k^2) \tag{9.17}$$

$$I_{yy} = \sum_{k=1}^{N} m_k (x_k^2 + z_k^2) \tag{9.18}$$

$$I_{zz} = \sum_{k=1}^{N} m_k (x_k^2 + y_k^2) \tag{9.19}$$

$$I_{xy} = -\sum_{k=1}^{N} m_k x_k y_k \tag{9.20}$$

$$I_{xz} = -\sum_{k=1}^{N} m_k x_k z_k \tag{9.21}$$

$$I_{yz} = -\sum_{k=1}^{N} m_k y_k z_k \tag{9.22}$$

The local inertia of the wind turbine is determined for the RNA and the tower. For the RNA existing inertia values are available from Jonkman [81]. These are adjusted to the coordinate system of the vessel and included in the total vessel inertia. The values for the RNA inertia in the vessel's coordinate system are shown in table 9.8. It should be noted that for the RNA inertia the rotor orientation is considered fixed, pointing in the positive x-direction of the vessel's coordinate system.

Ixx	$4.51 \cdot 10^4$ t.m^2
Iyy	$2.49 \cdot 10^4$ t.m^2
Izz	$2.55 \cdot 10^4$ t.m^2
Ixy	$2.01 \cdot 10^{-4}$ t.m^2
Ixz	$-1.45 \cdot 10^3$ t.m^2
Iyz	$-2.88 \cdot 10^{-3}$ t.m^2

Table 9.8: Local inertia of wind turbine's rotor-nacelle-assembly.

For the wind turbine tower, the local inertia is determined by approaching the tower as 105 elements (n) over the tower height with a specific diameter and wall thickness. The inertia can be determined according to equations 9.23 up to 9.25 for the mass moment of inertia of a hollow cylinder.

$$Ixx = \sum_{n=1}^{N} \frac{m_n}{12} \cdot (3 \cdot (R_{n,outer}^2 + R_{n,inner}^2) + h_n^2) \tag{9.23}$$

$$Iyy = \sum_{n=1}^{N} \frac{m_n}{12} \cdot (3 \cdot (R_{n,outer}^2 + R_{n,inner}^2) + h_n^2) \tag{9.24}$$

$$Izz = \sum_{n=1}^{N} \frac{m_n}{2} \cdot (R_{n,outer}^2 + R_{n,inner}^2) \tag{9.25}$$

For each of the inertia axis, the total inertia around that axis can be determined by a summation of all inertia components as indicated in equation 9.26. The final radii of gyration are determined by equation 9.27. For both equations, i and j can be x, y or z.

$$I_{ij_{total}} = I_{ij_{Vessel}} + I_{ij_{RNA,global}} + I_{ij_{RNA,local}} + I_{ij_{Tower,global}} + I_{ij_{Tower,local}} + I_{ij_{Structural,global}} \tag{9.26}$$

$$K_{ij_{total}} = \sqrt{\frac{I_{ij_{total}}}{m_{total}}} \tag{9.27}$$

The final values for the radii of gyration and the other load case-specific input data for the diffraction analysis are shown in table 9.9.

Property	Haewene Brim vessel							
Length overall [m]	253.505							
Length between perpendicular [m]	233							
Breadth [m]	42							
Depth moulded [m]	23.2							
Load case	Ballast	Fully Loaded	Ballast D1	Fully Loaded D1	Ballast D2	Fully Loaded D2	Ballast D3	Fully Loaded D3
Draft mean [m]	10.45	15.87	10.57	15.98	10.57	15.98	10.57	15.98
Draft fore [m]	8.51	15.87	8.63	15.99	8.63	15.99	8.63	15.99
Draft aft [m]	12.38	15.87	12.51	15.97	12.51	15.97	12.51	15.97
Trim by stern [m]	3.87	0.00	3.88	-0.02	3.88	-0.02	3.88	-0.02
Displacement mass [t]	81192.00	129370.40	82209.64	130387.84	82209.64	130387.84	82209.64	130387.84
Displacement volume [m^3]	79211.71	126215.02	80204.53	127207.65	80204.53	127207.65	80204.53	127207.65
LCG (from APP) [m]	116.86	120.61	116.86	120.59	116.86	120.59	116.86	120.59
VCG (w.r.t. base line) (solid) [m]	12.96	14.88	13.75	15.36	13.75	15.36	13.75	15.36
TCG (from CL) [m]	0.12	0.00	0.284	0.103	-0.0379	-0.100	0.123	0.00111
Free surface correction [m]	0.054	0.50	0.054	0.50	0.054	0.50	0.054	0.50
Kxx [m]	17.1	13.51	19.11	15.11	19.11	15.11	19.06	15.07
Kyy [m]	63.1	53.71	63.3	53.92	63.3	53.92	63.3	53.92
Kzz [m]	63.7	54.13	63.28	53.94	63.28	53.94	63.26	53.93
Kxy [m]	1.2	0.73	1.22	0.93	1.26	0.42	1.24	0.72
Kxz [m]	3.7	-1.48	3.63	-0.76	3.63	-0.76	3.63	-0.76
Kyz [m]	1.8	1.44	-2.59	-2.04	3.67	2.88	1.84	1.43

Table 9.9: Input data for different load cases included in diffraction analysis.

The vessel shape is taken from an existing hull file of the Haewene Brim. The mesh size used in the diffraction analysis is 80 panels in the longitudinal direction and 20 panels in height. An example of the resulting hull shape and its meshing is shown in figure 9.21.

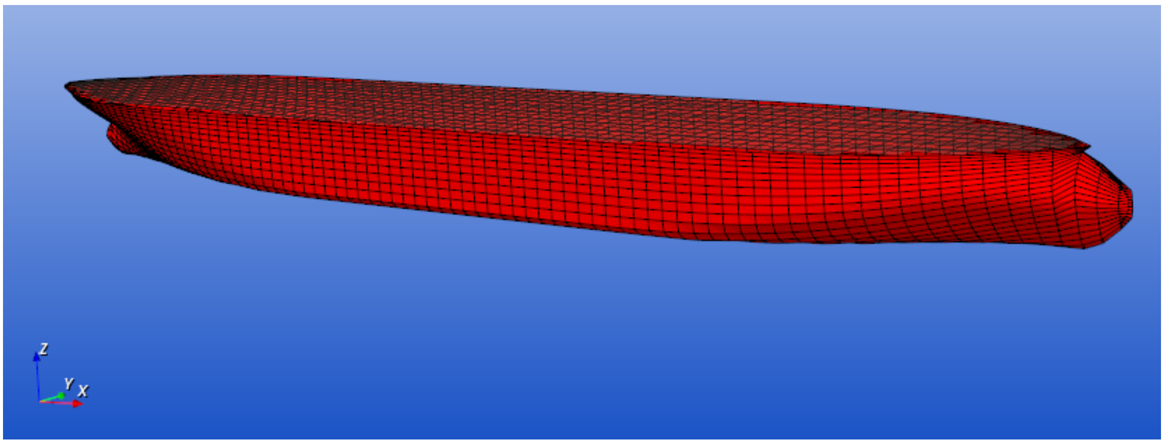


Figure 9.21: Example of vessel shape and its meshing.

The analysis is done for wave heading angles of 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165°, and 180°. The headings are mirrored for the other half of the vessel due to the vessel's symmetry in the xz-plane. This results in a set of 24 displacement RAOs for headings between 0° and 360° with a step of 15°.

The wave frequencies included in the analysis range from 0.05 rad/s to 2.5 rad/s, with steps of 0.05 rad/s. A value of 6% added roll damping is used in the diffraction analysis [82][12]. The governing equations of the 6 DoF dynamic system which are solved in the diffraction analysis in HydroStar can be described with the system's equation of motion shown by equation 9.28. Here ω is the wave frequency, M_i the mass matrix, $A_i(\omega)$ the added mass matrix, $C_i(\omega)$ the damping matrix, K_i the stiffness matrix, x_i the motion of DoF i, and $F_i(\omega)$ the wave force. In the diffraction analysis, the equation of motion is fully linearized.

$$\sum_{i=1}^{6}(M_i + A_i(\omega))\ddot{x}_i + C_i(\omega)\dot{x}_i + K_i x_i = F_i(\omega) \tag{9.28}$$

Assuming $x = X_i(\omega)e^{i\omega t}$ the displacement RAOs can be determined using equation 9.29. Here X_i is the response for DoF i and ζ_a is the wave amplitude.

$$RAO_x = \frac{X_i(\omega)}{\zeta_a} \tag{9.29}$$

Displacement RAOs including mooring stiffness

To compare the final approach in OrcaFlex using 1^{st} order wave load RAOs and frequency-dependent added mass and damping, the displacement RAOs are computed including the OrcaFlex model's mooring stiffness. To include this, the mooring's stiffness matrix is obtained from the OrcaFlex model, for which the mooring and its properties are further described in section 9.5.4. Besides this addition, all other parameters in the diffraction stay the same as explained above. This check is done for a single load case. Since this part focuses on the vessel's behavior, the check is performed for the load case Ballast excluding the wind turbine. The resulting mooring stiffness matrix obtained from OrcaFlex is shown in equation 9.30.

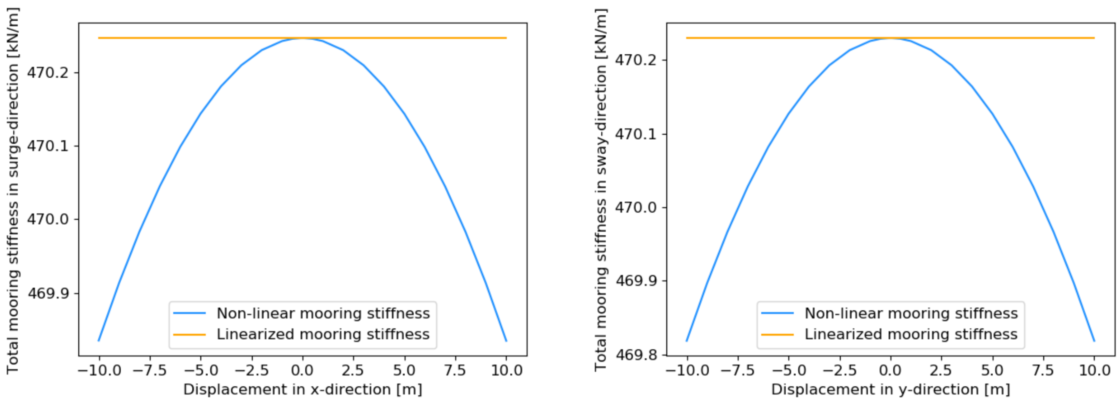
$$K_{mooring} = \begin{bmatrix} 470.25 & -226.04 \cdot 10^{-6} & -4.42 & 0.0024 & 4580.78 & 0.018 \\ -226.04 \cdot 10^{-6} & 470.23 & -0.014 & -4932.71 & -0.99 & -31.53 \cdot 10^{3} \\ -4.42 & -0.014 & 189.74 & 0.15 & 12.11 \cdot 10^{3} & 0.99 \\ 0.0024 & -4932.71 & 0.15 & 30.85 \cdot 10^{3} & 6.37 & 251.61 \cdot 10^{3} \\ 4580.84 & -0.99 & 12.11 \cdot 10^{3} & 10.42 & 6.71 \cdot 10^{6} & 251.48 \\ 0.018 & -31.53 \cdot 10^{3} & 0.99 & 330.98 \cdot 10^{3} & 252.55 & 11.60 \cdot 10^{6} \end{bmatrix} \tag{9.30}$$

The units of the mooring stiffness matrix can be divided into four blocks each with a size of 3x3. The units are shown in 9.31.

$$Units : \begin{bmatrix} kN/m & kN/rad \\ kN.m/m & kN.m/rad \end{bmatrix} \tag{9.31}$$

It should be noted that OrcaFlex has linearized this mooring stiffness matrix in the model's static-state position. An example visualization of this is shown in figure 9.22. Figure 9.22a shows the linearization of the mooring stiffness in the surge direction due to displacement in this same direction. Figure 9.22b shows the same for the sway direction. The influence that the mooring stiffness has on the displacement RAOs is shown in appendix E.2.

[12] Reference coming from Bluewater's Meridian database (not publicly accessible).



(a) Stiffness in surge direction. **(b)** Stiffness in sway direction.

Figure 9.22: Linearization of mooring stiffness by OrcaFlex.

9.5.3 Diffraction Analysis Results

The diffraction analysis provides results in the frequency domain, consisting of displacement RAOs, 1^{st} order wave load RAOs, and frequency-dependent added mass and damping.

Displacement RAOs

The displacement RAOs are obtained for the 8 different load cases as described above. They represent the 6 DoF vessel motions of the vessel's center of gravity (surge, sway, heave, roll, pitch and yaw). The RAOs including wind turbine are compared to the RAOs excluding wind turbine. Figures 9.23 and 9.24 show the RAOs for wave headings of 90° (head waves) and 180° (beam waves) respectively. Variations of the colors blue and red are used to indicate the Ballast and Fully Loaded load cases respectively. The different line types indicate the vessel excluding the wind turbine and the three different design configurations. The 1P and 3P blade passing frequency ranges are also indicated in the figures. Figures of the RAOs for other wave headings are provided in appendix E.1. Verification of the displacement RAOs for load case Ballast is shown in appendix E.5.

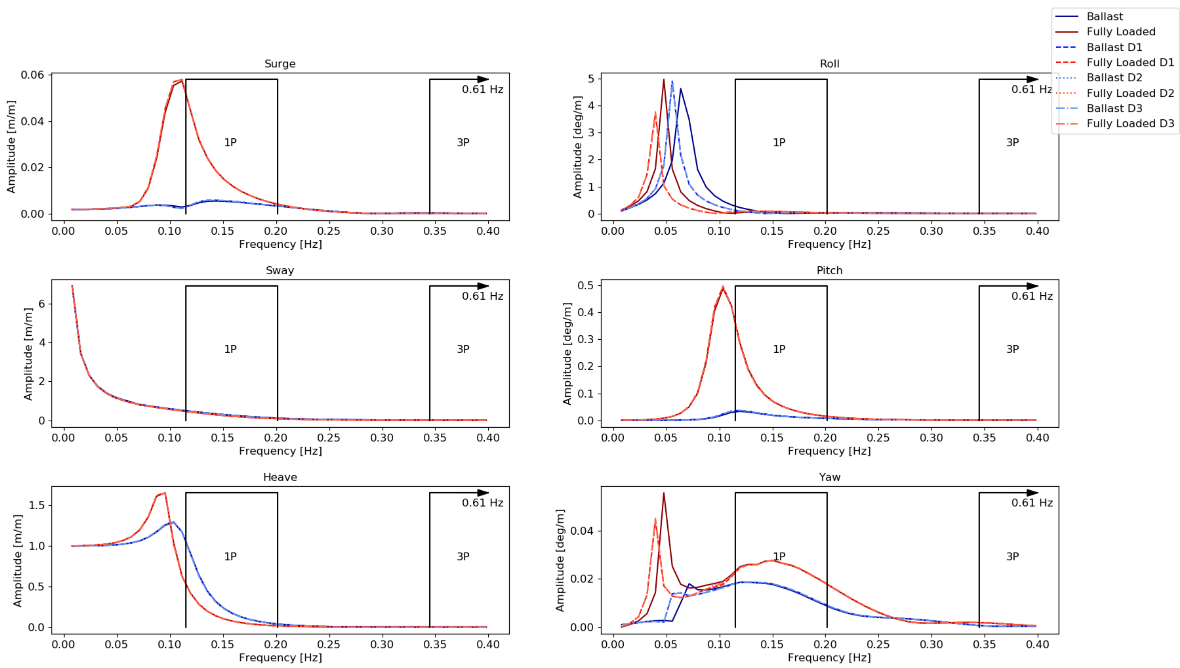


Figure 9.23: Displacement RAOs for 6DoF for a vessel heading of 90°.

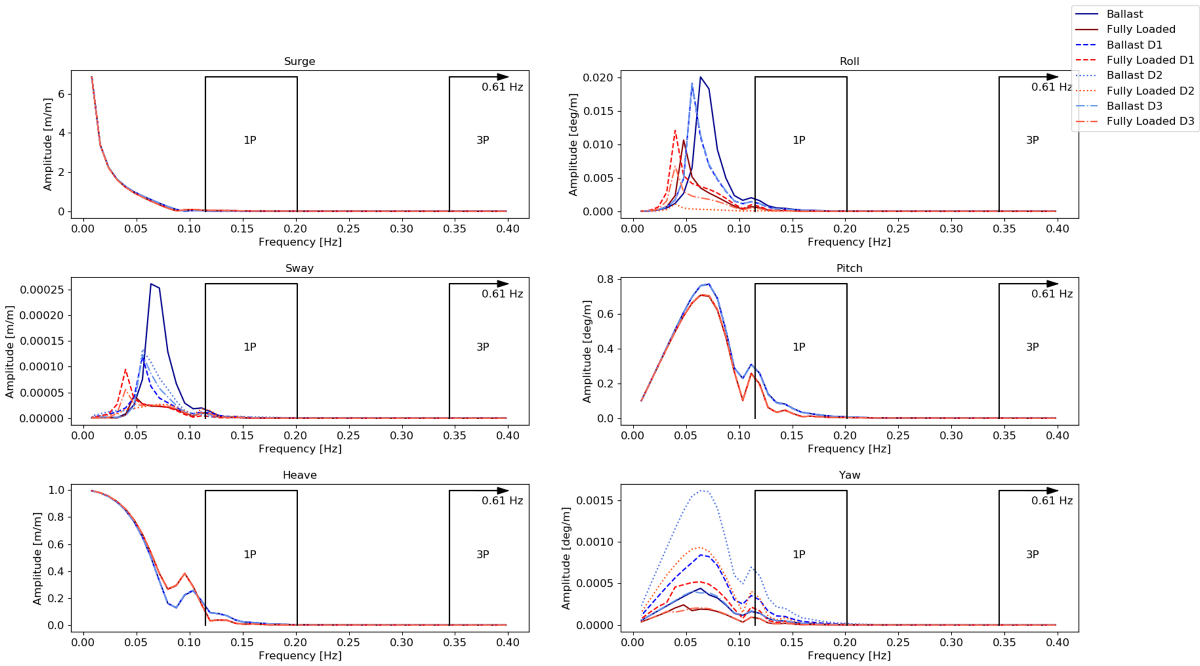


Figure 9.24: Displacement RAOs for 6DoF for a vessel heading of 180°.

The wind turbine affects the vessel's displacement RAOs. The following observations are made from the displacement RAOs:

- For both vessel load cases the vessel's surge RAO is hardly affected by the presence of the wind turbine. Only for a wave heading of 90° a negligible difference is observed. No difference is observed between the three design concepts.
- Similar to surge, the sway RAO is only affected by the wind turbine's presence for wave headings perpendicular to its motion direction (0° and 180°). The wind turbine causes the peak frequencies to shift towards a lower frequency for these directions. The different design concepts have different amplitudes around the peak. Nevertheless, the amplitudes for all cases are small.
- For both load cases the vessel's heave RAO is not affected by the presence of the wind turbine. This is observed for all wave headings. That the heave is hardly affected is in line with the only small increase of draught due to the wind turbine, after which the vessel's contact area for heave is more or less equal to that of the vessel without wind turbine.
- The roll RAO of the vessel is affected for all the different wave headings by the wind turbine's presence. For all the wave headings the peak frequency shifts to a lower frequency. The peak frequencies of the roll RAOs are the same, independent of the wave heading. For wave headings of 0° and 180° a difference in roll amplitude can be observed for the three different design configurations. For the other wave headings, the different design implementations have no difference in roll RAO.
- For both load cases the vessel's pitch RAO is not affected by the presence of the wind turbine. This is observed for all wave headings. This is an expected result since the longitudinal coordinate of the vessel's COG changed by only a negligibly small amount, due to the chosen position of the wind turbine placement very close to the original vessel's COG. The weight of the turbine, therefore, generates barely any additional pitch for the vessel.
- For the yaw RAO several observations are made. For wave headings of 0° and 180° there is a change in the amplitude of the RAO. There is also a difference between the different designs, where wind turbine placement on the vessel's center line has the least effect on the RAO. In

all design cases, the amplitudes in the RAO remain small. For a wave heading of 90° the peak frequency of the RAO shifts to a lower frequency, but no differences are observed due to different wind turbine placements. For the other wave headings, little impact of the wind turbine is observed in the yaw RAO.

- All of the displacement RAOs do not interfere with the 3P blade passing frequency of the wind turbine. However, the 1P blade passing frequency does collide with some of the displacement RAOs. Nevertheless, the RAOs in general contain most energy below the 1P frequency.

From the observations, it can be concluded that the roll of the vessel is most influenced by the wind turbine's presence. The changes occur at the most significant amplitudes, whereas a change for any of the other RAOs occurs only at small amplitudes, with small amplitude deviations.

Besides, there is no significant difference in RAOs for the three different design configurations, and when there are differences observed the amplitudes of the RAOs are small. Due to this little difference in RAOs for the three design concepts, the part of the motion analysis in the time domain is only performed for a single wind turbine placement. The chosen configuration is here design 3, where the wind turbine is placed on the center line of the vessel.

1^{st} order wave load RAOs

The 1^{st} order wave load RAOs are obtained from the diffraction analysis and are input for the OrcaFlex model. Due to the little differences observed in the displacement RAOs for the different wind turbine configurations, the wave load RAOs, added mass, and damping are only shown for the selected placement of the wind turbine on the vessel's center line (design 3). Figures 9.25 and 9.26 show the 1^{st} order wave load RAOs for wave hadings of 90° and 180°.The other wave headings are shown in appendix E.3. For the 1^{st} order wave load RAOs it is observed that the same DoF are affected due to the presence of the wind turbine as was observed for the displacement RAOs.

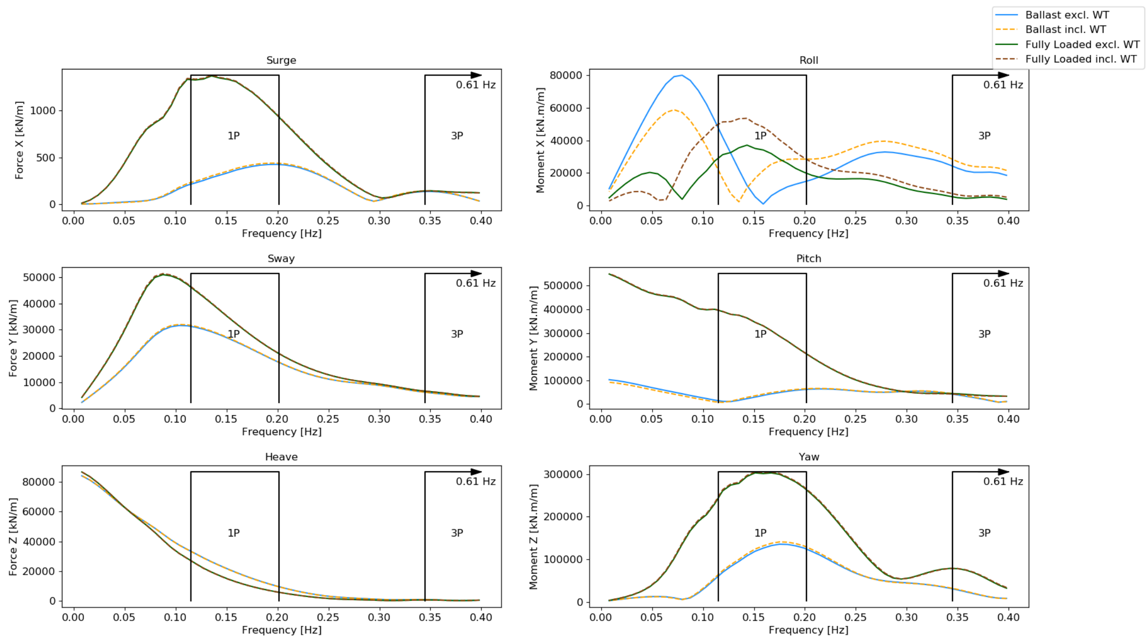


Figure 9.25: 1^{st} order wave load RAOs for a vessel heading of 90°.

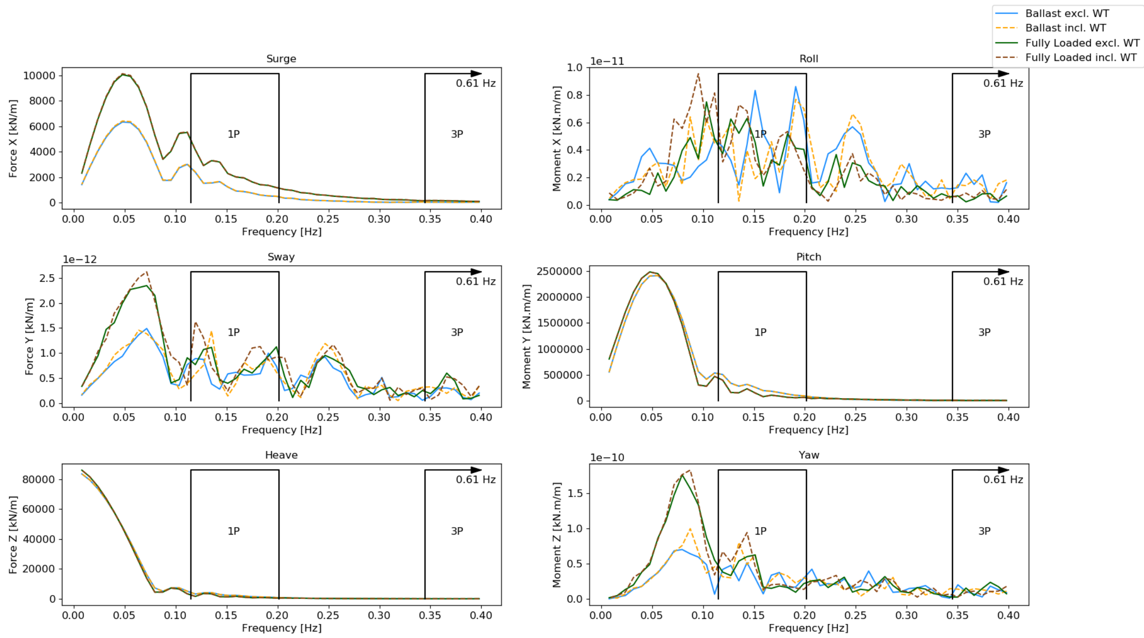


Figure 9.26: 1^{st} order wave load RAOs for a vessel heading of 180°.

Added mass and damping

From the diffraction analysis, frequency-dependent added mass and damping are obtained. The results show surge-heave-pitch coupling and sway-roll-yaw coupling. The added mass matrix, therefore, has the following coefficients:

$$\begin{bmatrix} a_{11} & 0 & a_{13} & 0 & a_{15} & 0 \\ 0 & a_{22} & 0 & a_{24} & 0 & a_{26} \\ a_{31} & 0 & a_{33} & 0 & a_{35} & 0 \\ 0 & a_{42} & 0 & a_{44} & 0 & a_{46} \\ a_{51} & 0 & a_{53} & 0 & a_{55} & 0 \\ 0 & a_{62} & 0 & a_{64} & 0 & a_{66} \end{bmatrix}$$

The damping matrix is of the same shape as the added mass matrix:

$$\begin{bmatrix} c_{11} & 0 & c_{13} & 0 & c_{15} & 0 \\ 0 & c_{22} & 0 & c_{24} & 0 & c_{26} \\ c_{31} & 0 & c_{33} & 0 & c_{35} & 0 \\ 0 & c_{42} & 0 & c_{44} & 0 & c_{46} \\ c_{51} & 0 & c_{53} & 0 & c_{55} & 0 \\ 0 & c_{62} & 0 & c_{64} & 0 & c_{66} \end{bmatrix}$$

Figures of the frequency-dependent added mass and damping coefficients are shown in appendix E.4.

9.5.4 OrcaFlex model description

The 1^{st} order wave load RAOs and frequency-dependent added mass and damping obtained from HydroStar are input for an OrcaFlex model. The OrcaFlex model can simulate the interaction between the wind turbine and FPSO in the time domain. This is done to evaluate the impact of the wind force acting on the wind turbine and how this again impacts the motions of the FPSO. Also, it is used to evaluate the impact of the FPSO on the wind turbine's motions. For the dynamic positioning of the vessel, a soft-mooring system is attached to the vessel. The system is modeled in OrcaFlex version 11.2c. For comparison purposes, for load case Ballast the vessel is also modeled with displacement RAOs which contain the effect of the mooring stiffness. In section 9.5.6 the comparison of the two cases is shown.

Model overview

The model in OrcaFlex consists of several components, namely the vessel, the wind turbine, and a soft-mooring system. The components of the system are further explained in the following subsections. A visualization of the model is shown in figure 9.27. For comparison purposes with the original vessel behavior, the same model is used from which the wind turbine is removed.

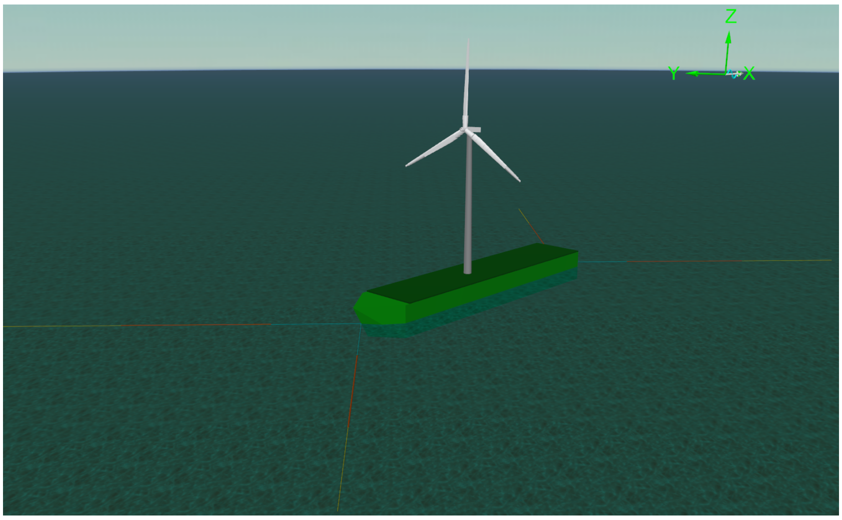


Figure 9.27: Visualization of the OrcaFlex model.

FPSO

The FPSO is modeled as a vessel object in OrcaFlex. The vessel object is assigned a specific vessel type representing the Haewene Brim. The vessel type consists of different draughts. The draughts are implemented for the chosen load cases, Ballast and Fully Loaded including wind turbine design configuration 3, and the original vessel cases Ballast and Fully Loaded excluding wind turbine. An expectation of what would happen in case of intermediate load cases is given in appendix E.6. For each draught, the diffraction analysis output is used as input for the vessel object in OrcaFlex. Other vessel properties such as mass, displaced water volume, COG, inertia, and hydrostatic stiffness matrix are assigned. From these properties, the hydrostatic stiffness matrix needs to be computed.

In OrcaFlex the hydrostatic stiffness matrix needs to be specified for heave, roll, and pitch. This results in the following hydrostatic stiffness matrix:

Heave	Roll	Pitch
c_{33}	c_{34}	c_{35}
c_{43}	c_{44}	c_{45}
c_{53}	c_{54}	c_{55}

The components of the hydrostatic stiffness matrix can be determined with equations 9.32 up to 9.35. An assumption is made that there is no heave-roll or roll-pitch coupling as was observed in the added mass and damping matrices.

$$c_{33} = \rho \cdot g \cdot A_{wl} \tag{9.32}$$

$$c_{44} = \rho \cdot g \cdot \nabla \cdot GM_T \tag{9.33}$$

$$c_{55} = \rho \cdot g \cdot \nabla \cdot GM_L \tag{9.34}$$

$$c_{35} = c_{53} = -\Delta x \cdot c_{33} \tag{9.35}$$

The parameters used to determine the hydrostatic stiffness matrix are shown in table 9.10. The value for the waterplane area is taken from the diffraction analysis output. For the value of the longitudinal metacentric height (GM_L), it is assumed that it is 110 times the value of the transverse metacentric height (GM_T) [83], which has already been determined in section 9.2 on vessel stability. The resulting hydrostatic stiffness coefficients are shown in table 9.11.

Load case	Ballast	Ballast D3	Fully Loaded	Fully Loaded D3
Displacement mass [t]	81192.00	82209.64	129370.40	130387.84
Waterplane area, A_{wl} [m^2]	8475.0	8488.0	8743.8	8748.3
Displaced water volume, ∇ [m^3]	79211.71	80204.53	126215.02	127207.65
GM_T [m]	5.95	5.08	1.94	1.46
GM_L [m]	654.9	558.4	213.6	160.4
LCF [m]	120.25	120.09	114.14	114.07
LCG [m]	116.86	116.86	120.61	120.59
Δx (LCF-LCG)	3.39	3.23	-6.47	-6.51

Table 9.10: System properties used to determine hydrostatic stiffness.

Load case	Ballast	Ballast D3	Fully Loaded	Fully Loaded D3
c_{33} [kN/m]	$8.52 \cdot 10^4$	$8.54 \cdot 10^4$	$8.79 \cdot 10^4$	$8.80 \cdot 10^4$
c_{44} [kNm/rad]	$4.74 \cdot 10^6$	$4.09 \cdot 10^6$	$2.46 \cdot 10^6$	$1.87 \cdot 10^6$
c_{55} [kNm/rad]	$5.22 \cdot 10^8$	$4.50 \cdot 10^8$	$2.71 \cdot 10^8$	$2.05 \cdot 10^8$
c_{34} [kN/rad] = c_{43} [kNm/m]	0	0	0	0
c_{35} [kN/rad] = c_{53} [kNm/m]	$-2.89 \cdot 10^5$	$-2.76 \cdot 10^5$	$5.69 \cdot 10^5$	$5.73 \cdot 10^5$
c_{45} [kNm/rad] = c_{54} [kNm/rad]	0	0	0	0

Table 9.11: Hydrostatic stiffness coefficients.

The motions of the vessel are based on the included effects. An overview of the effects that are included in the OrcaFlex model that influence the vessel motions is shown in figure 9.28. It should be noted that in OrcaFlex the vessel is assumed to be rigid, neglecting the vessel's bending flexibility. Inertia compensation is applied to the vessel in OrcaFlex, to prevent double counting the weight and inertia of the wind turbine in both the diffraction results and in the OrcaFlex model.

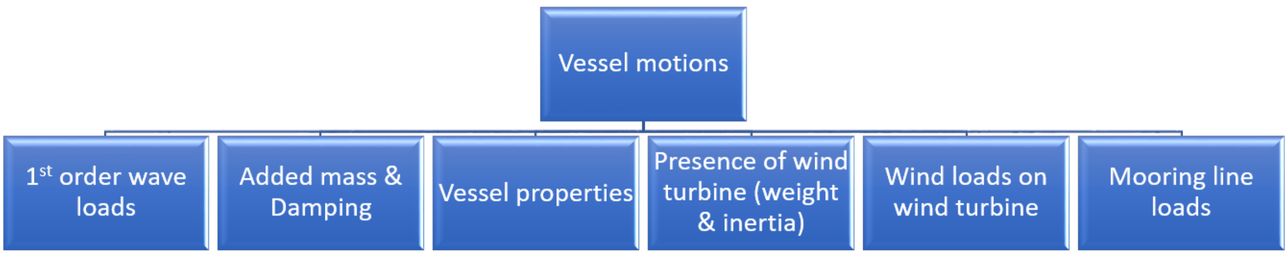


Figure 9.28: Effects influencing the vessel motions.

Wind turbine

The wind turbine model that is used in OrcaFlex is extracted from an available model called 'K01 5MW spar FOWT' in OrcaFlex provided by Orcina. This model consists of the NREL 5MW baseline model which is placed on top of the OC3 Hywind spar. The wind turbine model is validated as a land-based system by Orcina against the NREL 5MW baseline model modeled in FAST as described by Jonkman in [47]. This validation is documented by Orcina in [84]. An explanation of the wind turbine properties and a reproduction of the land-based system validation by Orcina in [84] is given in appendix F.

A few changes between the land-based model as described in appendix F and the wind turbine model used for the motion analysis are made. Some of these changes are a result of modeling restrictions/limitations in FAST. These are:

- The land-based model does not take into account wind loading on the wind turbine tower to show consistency compared to the NREL 5MW as modeled in FAST [84]. In the motion analysis, wind loading on the tower is included.
- The blades of the wind turbine in the land-based system are given a very high value to both its torsional and axial stiffness properties to align its results with the results from FAST in which the torsional and axial degrees of freedom of the blades were not modeled [84]. In the motion analysis, the torsional and axial degrees of freedom of the blades are taken into account.

Another change in the model is due to the change of tower height in the design of the wind turbine necessary to fulfill the design requirements as described in chapter 8. The changes made to the tower design as described in 8.1.4 are applied to the tower in the OrcaFlex model to increase the tower height from 87.6 meters to 105 meters.

The wind turbine model contains a blade pitch and generator torque controller. For the yaw of the wind turbine, no existing controller is available. Therefore, the yaw of the wind turbine is manually adjusted based on the wind direction input by rotating the wind turbine tower and nacelle in that direction. The wind turbine tower is rigidly connected to the vessel at the position of design configuration 3, the center line of the vessel.

Soft-mooring system

A soft-mooring system is attached to the vessel for station keeping. The soft-mooring system is used due to the limitation of an available yaw control mechanism for the wind turbine. This is to prevent large offsets between the wind turbine and wind alignment in case of weathervaning of the FPSO in a single-point mooring configuration. A soft-mooring system is typically used for seakeeping tests. The properties of the soft-mooring are adapted from a model test performed for one of the FPSO projects within Bluewater [85][13].

The soft-mooring system consists of 4 mooring lines. The lines are connected to the vessel with an angle of 45° from the vessel's center line, 2 lines at the bow, and 2 lines at the stern of the vessel. This is visualized in figure 9.29. The lines are connected to the vessel at the height of the MWL when the vessel is in its equilibrium position.

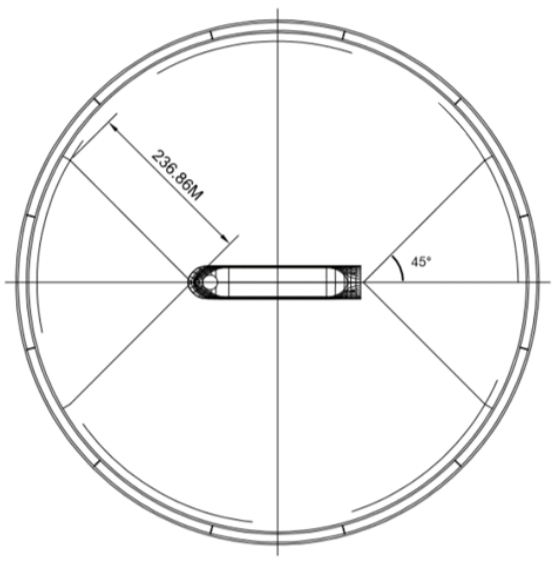


Figure 9.29: Soft-mooring system orientation.

[13]Reference coming from Bluewater's Meridian database (not publicly accessible).

For the mooring lines, the individual line properties are known. These are shown in table 9.12.

Mass	157.2	t
Submerged weight	137.3	t
Line stiffness, K_{eq}	189.8	kN/m
Stretched line length in equilibrium position	236.8	m
Line pretension	10929	kN

Table 9.12: Individual mooring line properties.

The mooring line consists of three different parts. From fairlead until the anchor point the mooring line is made from steel wire 1, spring, and finally steel wire 2. The spring stiffness of the total line, steel wire 1, and steel wire 2 was known. With equation 9.36 the spring stiffness of the spring (K_2) is determined.

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} \tag{9.36}$$

The length of steel wire 1 and spring were given. The length of steel wire 2 is determined by adjusting the length and axial stiffness of this wire until the pretension of the line was reached. The final properties of the mooring line components are shown in table 9.13. The end-connection stiffness of the mooring lines is set to infinity at the anchor points.

	Steel wire 1 (i=1)	Spring (i=2)	Steel wire 2 (i=3)
Mass [t]	1.11	153.4	2.88
Submerged weight [t]	0.89	133.7	2.21
Axial stiffness (EA/L) [kN/m]	$7.24 \cdot 10^4$	190.8	$7.24 \cdot 10^4$
Length [m]	45.5	75.0	58.9
Cross-sectional axial stiffness (EA) [kN]	$3.29 \cdot 10^6$	$14.31 \cdot 10^3$	$4.26 \cdot 10^6$

Table 9.13: Individual mooring line composition.

The overall linearized stiffness characteristics of the 4 lines combined mooring system in surge and sway are given for Bluewater's reference soft-mooring project [85][14]. A negligible difference is observed between the stiffness values of the reference project and the computed linearized stiffness values by OrcaFlex, for which the linearization is shown in figure 9.22. The values are shown in table 9.14.

Coefficient	Given stiffness	OrcaFlex stiffness	Difference
K_{surge}	472 kN/m	470.25 kN/m	0.37%
K_{sway}	472 kN/m	470.23 kN/m	0.38%

Table 9.14: Stiffness of the mooring system in surge and sway direction.

Time domain simulation

The simulations are run in the time domain. The time for the simulation is set to 3 hours excluding a build-up phase of 30 minutes. The solution method is the implicit time domain.

9.5.5 Environmental loading conditions

The Haewene Brim is located at the Pierce field, a field located in the UK sector of the central North Sea where the water depth is approximately 83 meters. The model is evaluated under different environmental loading conditions. The loading conditions are determined from 29 years of hindcast data containing 87662 sea-states of 3 hours for which the magnitudes and directions of current, wind,

[14] Reference coming from Bluewater's Meridian database (not publicly accessible).

and waves are measured, as are the wave periods [68][15]. These measurements have been performed at the Pierce field. The data contains a distinction between wind-waves and swell. For selecting the wave conditions for the environmental load cases the influence of wind-waves and swell is combined.

The combination of wind-waves and swell is performed based on characteristics from a JONSWAP wave spectrum. Average values for a JONSWAP spectrum of the North Sea are $\gamma = 3.3$, $\sigma_a = 0.07$, and $\sigma_b = 0.09$ [86]. The combined significant wave height can be obtained with equation 9.37.

$$H_{s_{total}} = \sqrt{H^2_{s_{wind-waves}} + H^2_{s_{swell}}} \tag{9.37}$$

The measurement data contained only the peak periods of the sea states. Equation 9.38 shows the ratio between the peak period T_p and the mean zero-up-crossing period T_z. In the case of a JONSWAP spectrum with a γ of 3.3, the expression can be simplified to equation 9.39.

$$\frac{T_z}{T_p} = 0.6673 + 0.05037\gamma - 0.006230\gamma^2 + 0.0003341\gamma^3 \tag{9.38}$$

$$T_z = \frac{T_p}{1.2859} \tag{9.39}$$

For wind-waves and swell the spectral moments, M_0 and M_2 can be determined with equations 9.40 and 9.41 respectively. The combined spectrum M_0 can also be determined using formula 9.40 with the combined significant wave height. The spectral moment M_2 for the combined wind-waves and swell can be determined by adding the individual spectral moments M_2 as shown in equation 9.42. Eventually, equation 9.41 can be used with the combined M_0 and M_2 to compute the combined T_z.

$$M_0 = \frac{1}{16} \cdot H_s^2 \tag{9.40}$$

$$M_2 = \frac{M_0}{(\frac{T_z}{2*\pi})^2} \tag{9.41}$$

$$M_{2_{total}} = M_{2_{wave}} + M_{2_{swell}} \tag{9.42}$$

The environmental loading conditions are determined by obtaining a range of significant wave heights that occur at two different particular wind speeds, namely the wind turbine's rated and cut-out wind speeds which are valid at hub height. The measured wind speeds from the data are the wind speeds at 10 meters above Mean Sea Level (MSL). Therefore, the measured wind speed data is converted to hub height. This is done using formulas 9.43 and 9.44 which are both obtained from the Pierce field metocean reference document [79][16].

$$U_{w,1h}(z) = U_{w0} \cdot [1 + C \cdot ln(z/z_r)] \tag{9.43}$$

$$C = 0.0573\sqrt{1 + 0.15 \cdot U_{w0}} \tag{9.44}$$

Here $U_{w,1h}$(z) is the hourly mean wind speed at height z (hub-height) above MSL, and U_{w0} is the hourly mean wind speed at reference height zr (10m) above MSL. The hub-height z is equal to 117.33 meters above MSL. The average is taken of the mean draughts of load cases Ballast and Fully Loaded, from which the distance to hub height is determined. The factored wind speeds are plotted versus the combined wind-waves and swell significant wave height. This is shown in figure 9.30. For the wind turbine's rated and cut-out wind speed three different values of significant wave height are selected that cover the range of the scatter plot. This is also indicated by the marked spots in figure 9.30.

[15]Reference coming from Bluewater's Meridian database (not publicly accessible).
[16]Reference coming from Bluewater's Meridian database (not publicly accessible).

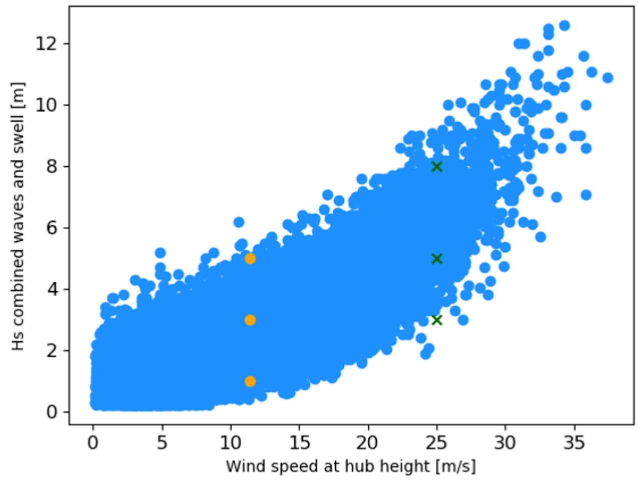


Figure 9.30: Wind speed at hub height vs Hs combined wind-waves and swell.

The mean zero-up-crossing period is selected from the scatter table shown in figure 9.31. For each significant wave height that has been selected, a period is selected which occurs the most at that specific wave height. This means that for wave heights 1, 3, 5, and 8 meters, the mean zero-up-crossing periods are selected as 4.5, 6, 7.5, and 9 seconds respectively.

		Tz [s]															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Hs [m]	1	0	46	2887	11550	10452	4168	1924	1104	455	189	70	44	14	6	4	32913
	2	0	0	1	1161	10094	9524	2875	1699	945	243	72	30	5	0	0	26649
	3	0	0	0	2	942	7270	4277	1052	634	292	59	23	9	1	0	14561
	4	0	0	0	0	5	881	4903	1276	295	128	69	9	1	1	0	7568
	5	0	0	0	0	0	10	1447	1663	321	63	37	18	3	0	0	3562
	6	0	0	0	0	0	0	78	912	372	74	19	5	5	0	0	1465
	7	0	0	0	0	0	0	0	140	324	74	13	5	3	0	0	559
	8	0	0	0	0	0	0	0	2	80	55	14	0	0	0	0	151
	9	0	0	0	0	0	0	0	0	25	31	14	5	0	0	0	75
	10	0	0	0	0	0	0	0	0	1	11	13	3	0	0	0	28
	11	0	0	0	0	0	0	0	0	0	9	6	2	0	0	0	17
	12	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	6
	13	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2
	Total	0	46	2888	12713	21493	21853	15504	7848	3452	1169	387	150	41	8	4	87556

Figure 9.31: Wave scatter table: Tz vs Hs combined wind-waves and swell.

For the directions for the wind and waves, three different combinations are used. DNV describes two different combinations for moored weathervaning vessels, namely a collinear and a non-collinear environment [65]. In a collinear environment, the wind and waves act in the same direction with the vessel heading pointing towards the environment (angle of 0°). In the non-collinear environment, there is a 30° offset between the wave and wind direction, with the vessel heading pointing toward the waves. Besides these combinations, an expected worst-case scenario for the vessel's roll of beam waves and wind with a 90° offset to the vessel's heading is assessed. However, this combination is unlikely to occur, especially for higher wind speeds, which can be seen in figure 9.32 based on Haewene Brim's vessel heading analysis [68][17]. Nevertheless, it is included, since if the motion criteria are fulfilled in this expected worst-case scenario, it also provides a reason to further evaluate intermediate cases in a later stage. The three directional cases are visualized in figure 9.33.

For each of the chosen wind speeds, chosen wave height, and wave period the three directions are applied. This results in a set of 18 different environmental loading combinations. These combinations represent several operational environmental conditions. Added to this is an omni-directional extreme environment load case with a 100-year return period. In this case, a wind speed of 35.2 m/s at 10 meters above MSL, a significant wave height of 13 meters, and a mean zero-up-crossing period of 11.5 seconds are given [79][18]. The same three directions are applied to the extreme case. An overview of all the combinations and their component values is shown in table 9.15. It should be noted that the current is neglected in the motion analysis.

[17]Reference coming from Bluewater's Meridian database (not publicly accessible).
[18]Reference coming from Bluewater's Meridian database (not publicly accessible).

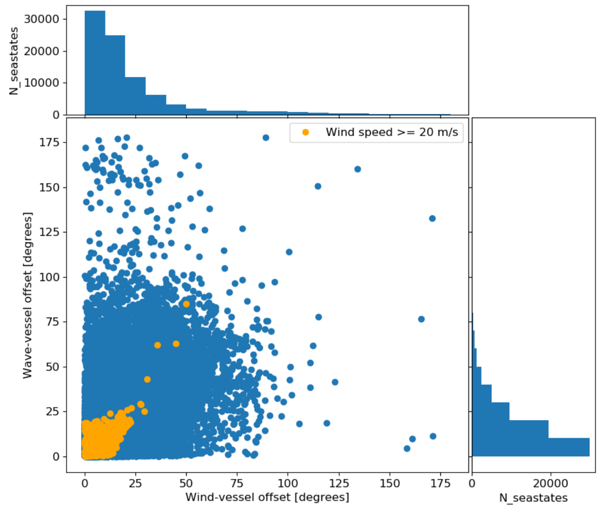


Figure 9.32: Vessel offset wind vs waves.

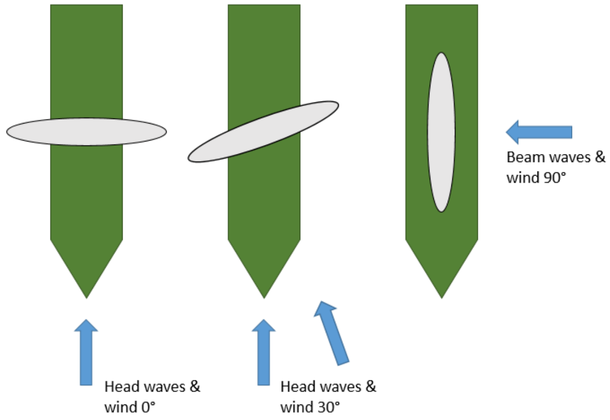


Figure 9.33: Environmental loading directional combinations.

Case	Wind speed MSL +10 m [m/s]	Wind speed at hub height [m/s]	Wind direction [deg]	Hs [m]	Tz [s]	Wave direction [deg]
1.1	9.35	11.4	0	1	4.5	0
1.2	9.35	11.4	30	1	4.5	0
1.3	9.35	11.4	90	1	4.5	90
2.1	9.35	11.4	0	3	6	0
2.2	9.35	11.4	30	3	6	0
2.3	9.35	11.4	90	3	6	90
3.1	9.35	11.4	0	5	7.5	0
3.2	9.35	11.4	30	5	7.5	0
3.3	9.35	11.4	90	5	7.5	90
4.1	19.55	25	0	3	6	0
4.2	19.55	25	30	3	6	0
4.3	19.55	25	90	3	6	90
5.1	19.55	25	0	5	7.5	0
5.2	19.55	25	30	5	7.5	0
5.3	19.55	25	90	5	7.5	90
6.1	19.55	25	0	8	9	0
6.2	19.55	25	30	8	9	0
6.3	19.55	25	90	8	9	90
7.1	35.2	47.7	0	13	11.5	0
7.2	35.2	47.7	30	13	11.5	0
7.3	35.2	47.7	90	13	11.5	90

Table 9.15: Environmental loading combinations.

The JONSWAP spectrum for the different wave conditions is shown in figure 9.34. A single wave seed, with seed number 12345, containing 200 components is used for all the different simulations. Most of the wave energy lies in the low-frequency region, below the 1P frequency of the wind turbine. Because of the choice for the most occurring periods, the peak of the wave spectrum lies within the 1P range for wave heights of 1 and 3 meters.

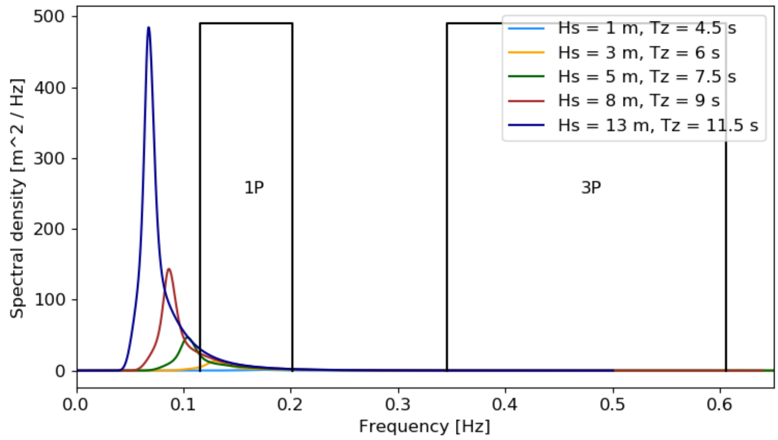
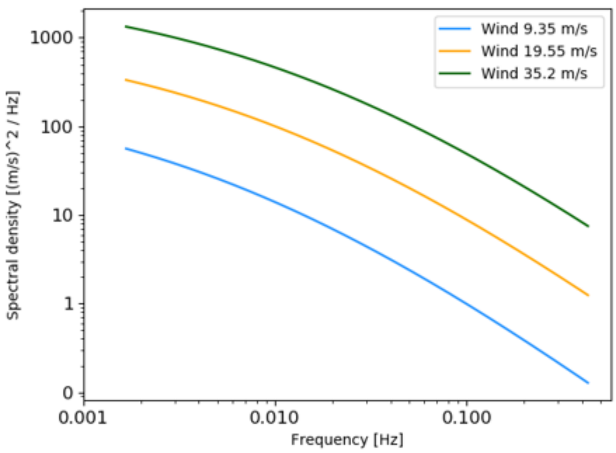
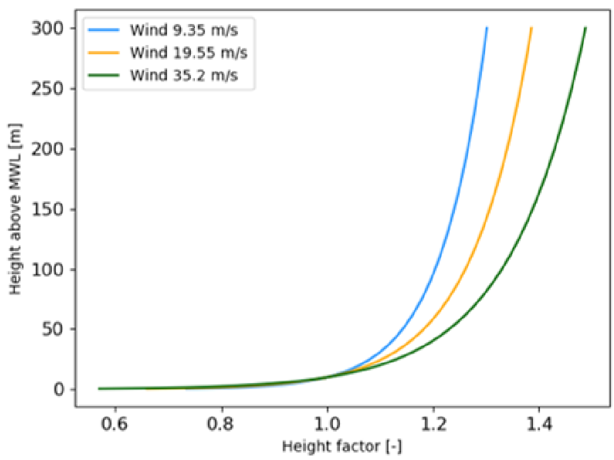


Figure 9.34: JONSWAP spectrum for different significant wave heights.

The wind is modeled by an NPD wind spectrum [87]. A height factor is applied to the wind speed to take into account the variance of the wind speed over the height. These factors are determined according to formulas 9.43 and 9.44. The NPD-spectrum and the height factors for the three different wind speeds are shown in figure 9.35. Some general environmental properties in the OrcaFlex model are indicated in table 9.16.



(a) NPD wind spectrum.



(b) Height factor for wind speed over the height above MWL.

Figure 9.35: Wind characteristics for time domain simulations.

Sea kinematic viscosity	$1.35 \cdot 10^{-6}$	m^2/s
Sea temperature	10.0	°C
Water density	1.025	t/m^3
Air kinematic viscosity	$15 \cdot 10^{-6}$	m^2/s
Air density	0.00122	t/m^3

Table 9.16: OrcaFlex simulation general environmental properties.

9.5.6 Time Domain Analysis Results

The results in the time domain are split into several parts. First, the method that used 1^{st} order wave loads and frequency-dependent added mass and damping to describe the vessel motions is compared to the method where displacement RAOs including mooring stiffness is used. Second, the impact of the wind turbine on the vessel motions is described. Third, it is explained how damping influences the transient response observed in the time-series results. Fourth, the effect that the wind turbine has on the mooring system, and how this can be related to the catenary mooring of the Haewene Brim is explained. Finally, several limiting benchmarks are described and evaluated that relate to the operability of both vessel and wind turbine. The different parts are visualized in figure 9.36. Due to the limitation of the unavailability of a wind turbine model including a yaw-control system, the focus lies on the in-place vessel motions. The impact of the wind turbine on the vessel heading is recommended for future research, for which the assessment requires a wind turbine yaw-control system in its model.

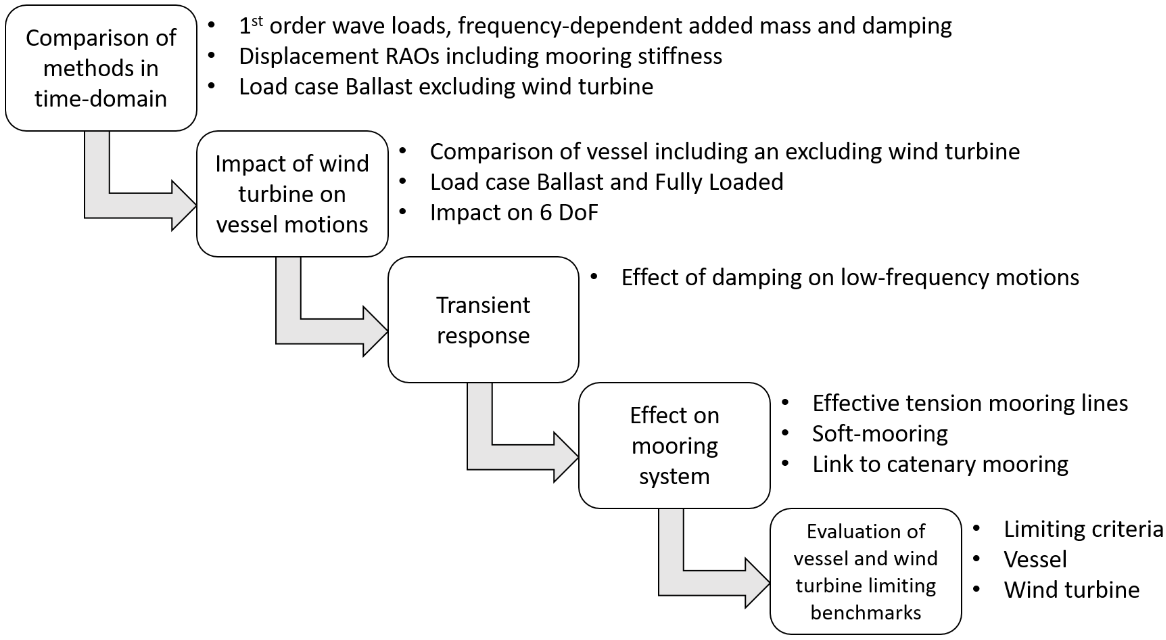


Figure 9.36: Overview of results.

The vessel position is described in the global axis coordinate system in OrcaFlex. The directional orientation of this system is indicated in figure 9.37. The z-coordinate is pointing upwards in the positive direction.

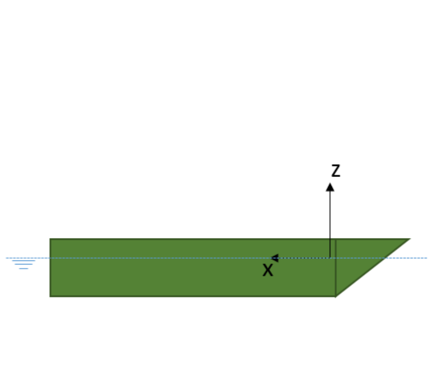


Figure 9.37: OrcaFlex global coordinate system.

Comparison of methods in time domain

A comparison is made in the time domain between the displacement RAOs in which the mooring stiffness is included and the method of using 1^{st} order wave loads, and frequency-dependent added mass and damping. This comparison is done for load case Ballast excluding wind turbine. A single environmental case is evaluated, namely for a JONSWAP spectrum with a significant wave height of 3 meters, and a mean zero-up-crossing period of 6 seconds. For this wave condition, the energy of the JONSWAP spectrum lies completely in the frequency range for which no difference is observed between the displacement RAOs including and excluding mooring stiffness as can be seen in appendix E.2. Because of this, the expectation is that the comparison between the method of displacement RAOs and 1^{st} order wave loads, frequency-dependent added mass and damping (which are a result of the same diffraction as the displacement RAOs excluding mooring stiffness) will show similar results. Three different wave directions are applied, which are head waves, 30° waves, and beam waves. A piece of the time series with a duration of 600 seconds is shown for the different wave directions in figures 9.38 up to 9.40.

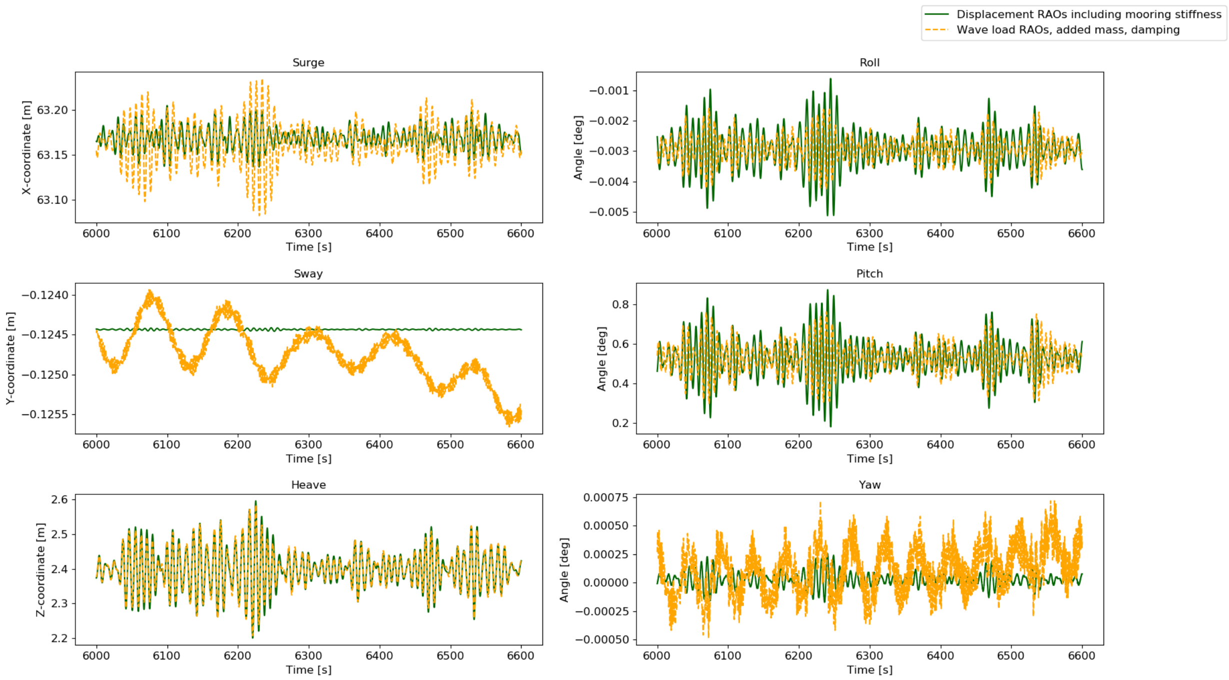


Figure 9.38: Comparison of methods for head waves.

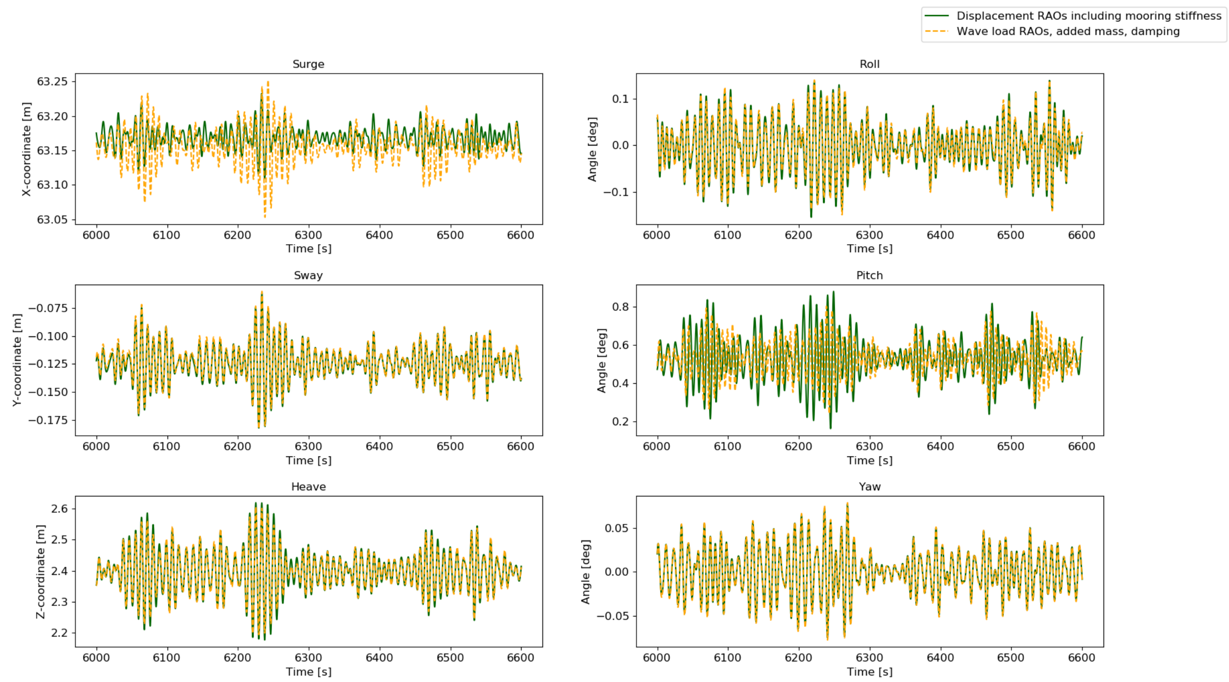


Figure 9.39: Comparison of methods for 30° waves.

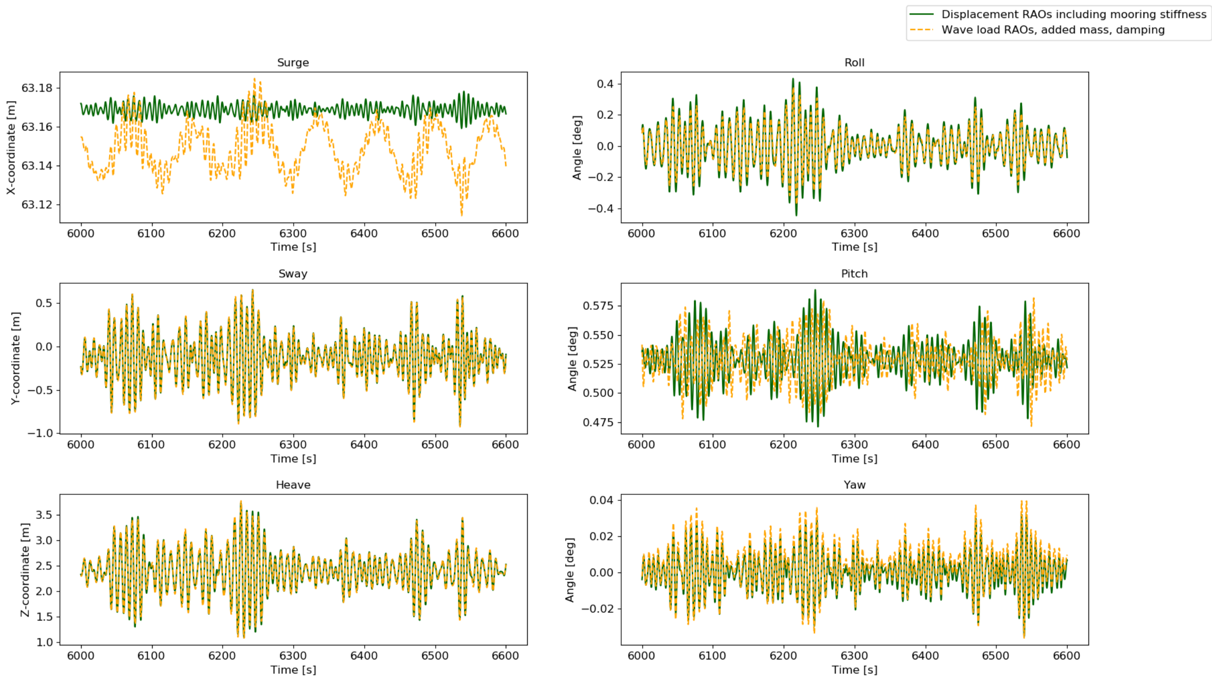


Figure 9.40: Comparison of methods for beam waves.

Contrary to expectations, depending on the wave direction, several differences can be observed from figures 9.38 up to 9.40. For head waves, a difference is observed in the surge, sway, roll, pitch, and yaw. For sway and yaw a low-frequency motion occurs, from which the amplitude is small. For the surge, roll, and pitch the motion amplitudes are different. For 30° waves, a difference is observed in the surge and pitch of the vessel. Similar to the case of head waves, the amplitudes of these motions differ. For beam waves, the surge shows the most significant difference, where a similar low-frequency motion occurs as for sway in head waves.

The main difference between the two methods is the inclusion of the mooring stiffness. For the method using the displacement RAOs, the mooring stiffness matrix is fully linearized as part of the diffraction analysis, as explained in section 9.5.2. For the method using 1^{st} order wave loads and frequency-dependent added mass and damping, the mooring line stiffness matrix is non-linear in time. The expectation is that the observed difference in results between the two methods is caused by this.

Because the observed differences are small, the decision is made to use the method with 1^{st} order wave loads and frequency-dependent added mass and damping. This is to prevent the need for the explicit solver in OrcaFlex and to be able to use the implicit solver, which saves a significant amount of computational time. Besides, this method can capture the non-linear effects of the mooring system.

Impact of wind turbine on vessel motions

In this subsection, the impact of the wind turbine on the vessel motions is analyzed. The impact of the wind turbine consists of a contribution due to its weight, inertia, and wind loads acting on the (in operation rotating) RNA and wind turbine tower. A comparison is made between the vessel excluding and including wind turbine, for different wind speeds as described in section 9.5.5. First, a statistical overview is given of the vessel's behavior under all environmental loading combinations for each of its 6 DoF. Second, the impact of the wind turbine on the vessel's 6 DoF is discussed. Third, a part of the time series is shown for a particular load case (Hs = 3m, Tz = 6 s) under different directional loading to describe the general vessel behavior.

Figures 9.41, 9.42, and 9.43 show the means and standard deviations of the vessel's COG motions in Ballast condition for the environmental cases in head waves and wind, head waves and 30° wind, and beam waves and wind respectively. The figures show results of the vessel excluding wind turbine, and including wind turbine for different wind speeds, and combinations of significant wave height and mean zero-up-crossing period as shown in table 9.15. Figures 9.44, 9.45, and 9.46 show the results for the Fully Loaded vessel condition. The rotations are shown as the absolute angle of rotation about the x-, y- and z-axis for roll, pitch, and yaw respectively.

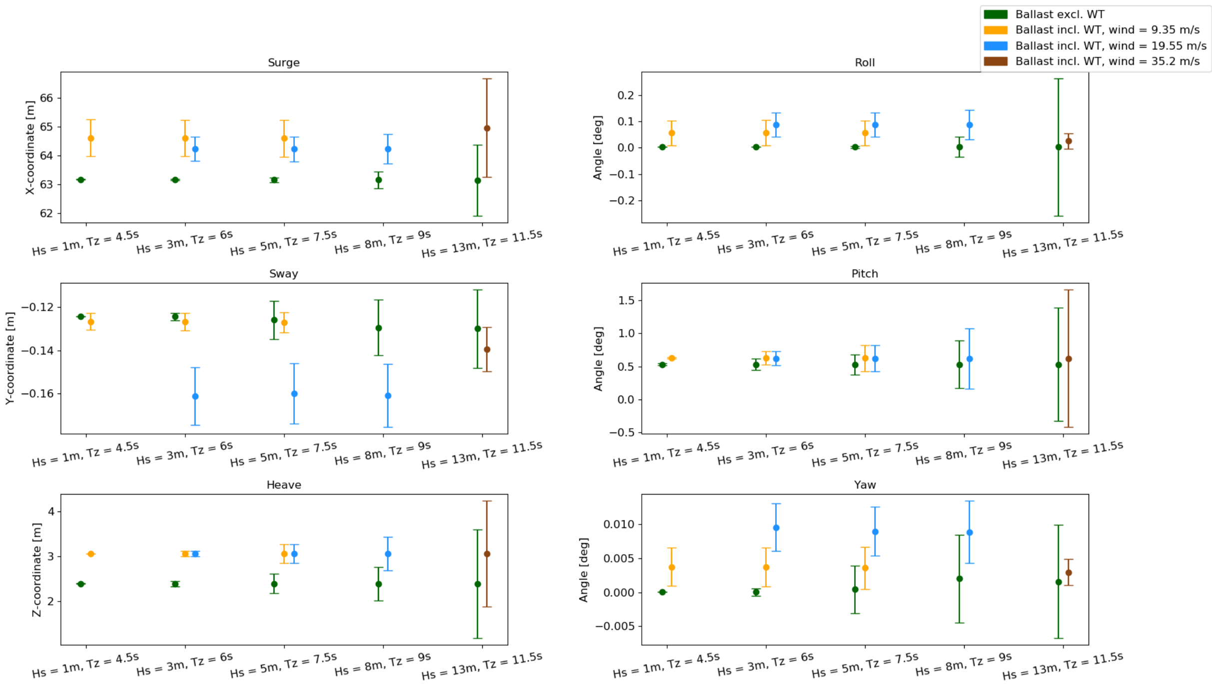


Figure 9.41: Mean and standard deviation of 6 DoF in head waves and wind under different conditions: Ballast.

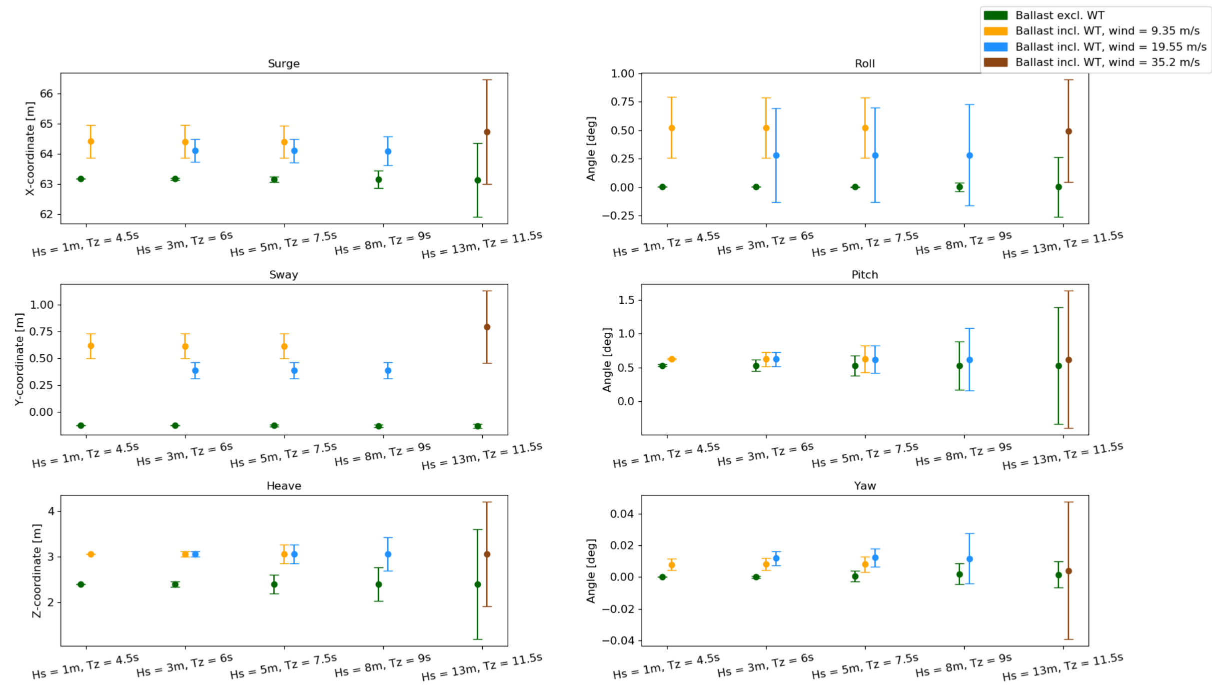


Figure 9.42: Mean and standard deviation of 6 DoF in head waves and 30° wind under different conditions: Ballast.

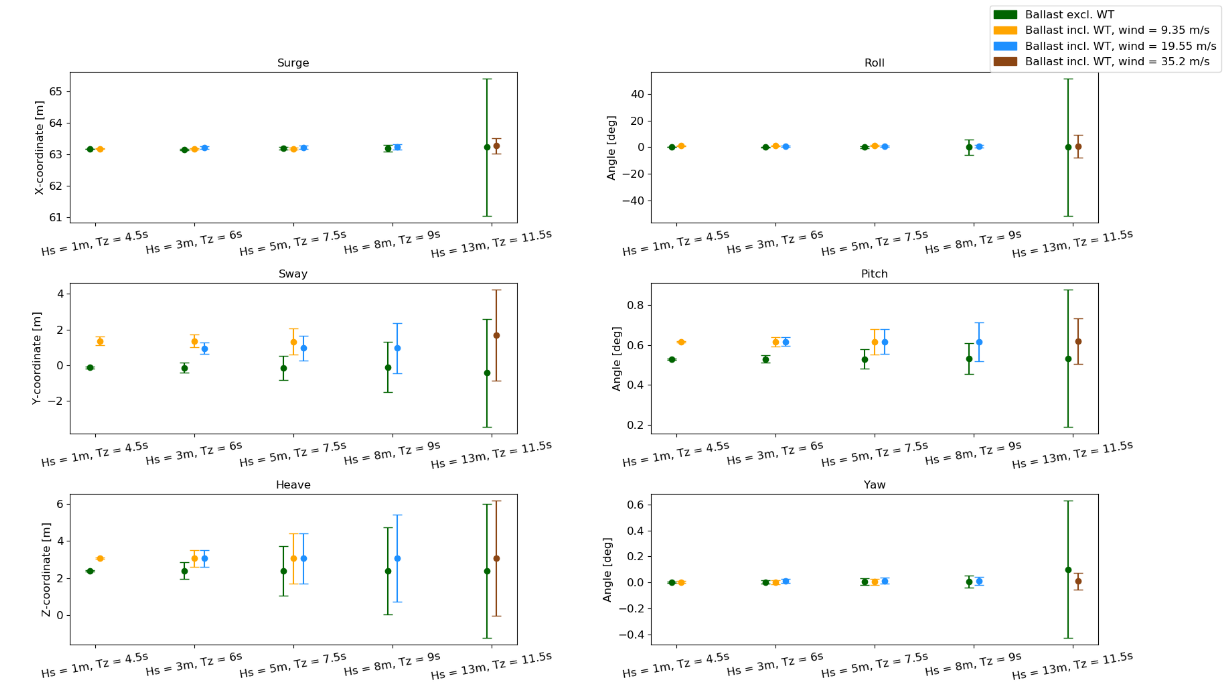


Figure 9.43: Mean and standard deviation of 6 DoF in beam waves and wind under different conditions: Ballast.

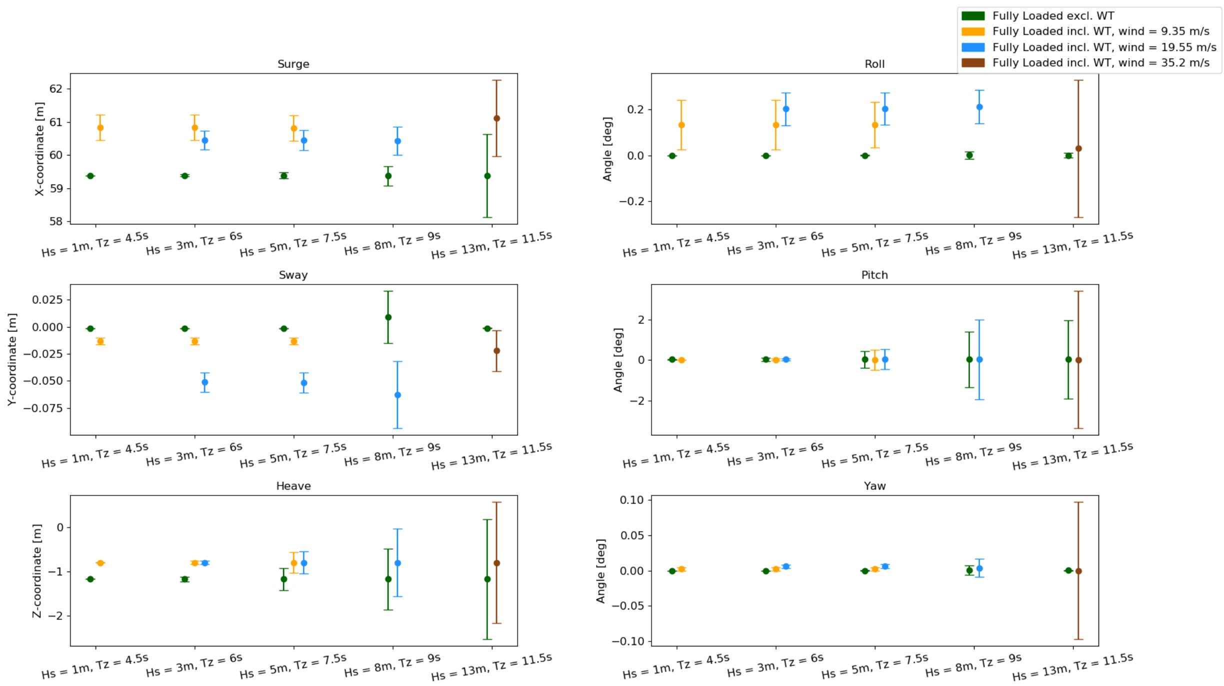


Figure 9.44: Mean and standard deviation of 6 DoF in head waves and wind under different conditions: Fully Loaded.

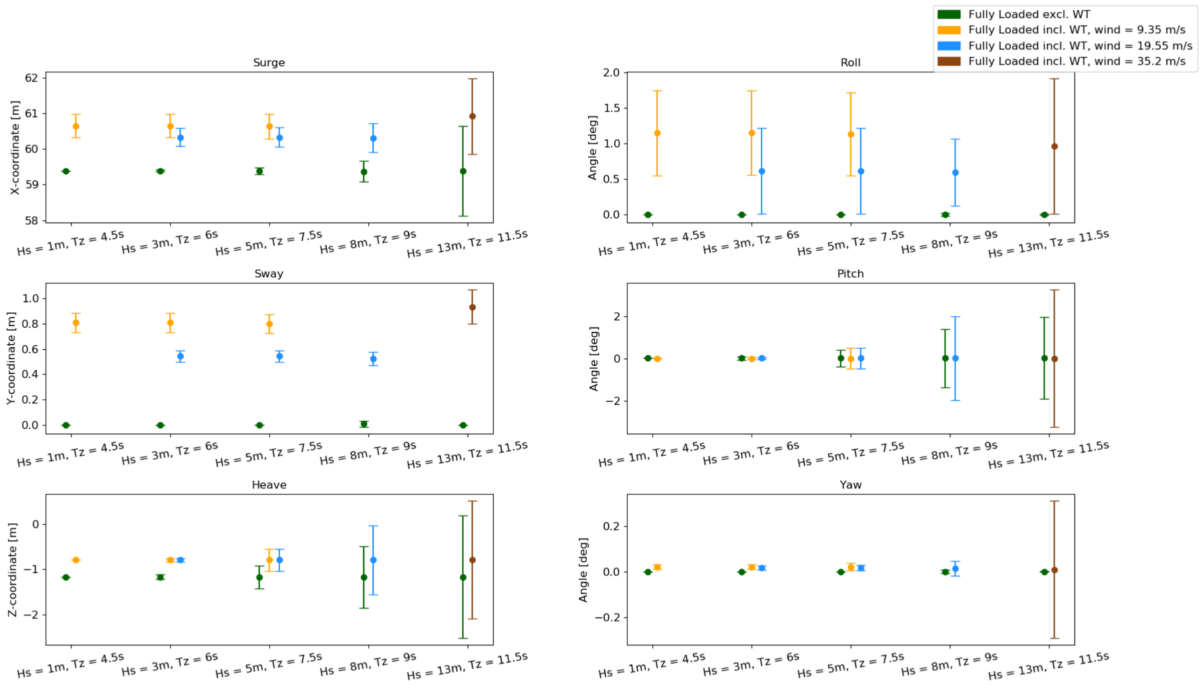


Figure 9.45: Mean and standard deviation of 6 DoF in head waves and 30° wind under different conditions: Fully Loaded.

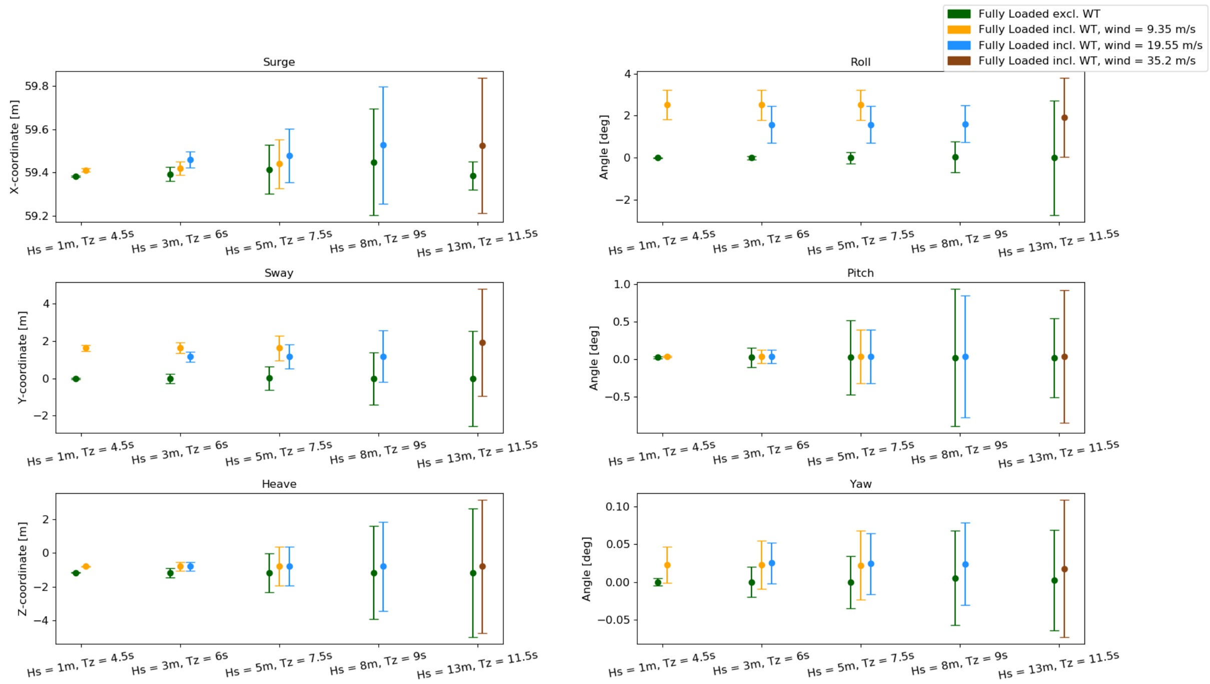


Figure 9.46: Mean and standard deviation of 6 DoF in beam waves and wind under different conditions: Fully Loaded.

Several general trends are observed from the means and standard deviations of the vessel's COG motions as shown in figures 9.41 up to 9.46. To support the observed trends, two different environmental load cases (2.1 and 2.3) are evaluated in more detail, which is shown in tables 9.17 and 9.18. These tables show the contribution of the wind and waves to the vessel's COG motions separately, for the vessel in Ballast condition under head waves and wind and beam waves and wind respectively. The observations from figures 9.41 up to 9.46 are described and discussed further below.

Case 2.1		Ballast excl. WT	Ballast incl. WT waves only	Ballast incl. WT wind only	Ballast incl. WT wind & waves
Surge [m]	Mean	63.16	63.18	64.60	64.60
	St. Dev.	0.025	0.023	0.64	0.64
Sway [m]	Mean	-0.12	-0.12	-0.13	-0.13
	St. Dev.	0.002	$3.00e^{-6}$	0.004	0.004
Heave [m]	Mean	2.40	3.06	3.06	3.06
	St. Dev.	0.060	0.060	$307e^{-6}$	0.060
Roll [deg]	Mean	0.003	0.003	0.056	0.056
	St. Dev.	$486e^{-6}$	$489e^{-6}$	0.047	0.048
Pitch [deg]	Mean	0.53	0.61	0.63	0.63
	St. Dev.	0.084	0.10	0.003	0.10
Yaw [deg]	Mean	0.00	0.00	0.004	0.004
	St. Dev.	$549e^{-6}$	$75.3e^{-6}$	0.003	0.003

Table 9.17: Evaluation of contribution head waves and wind to vessel's COG motions.

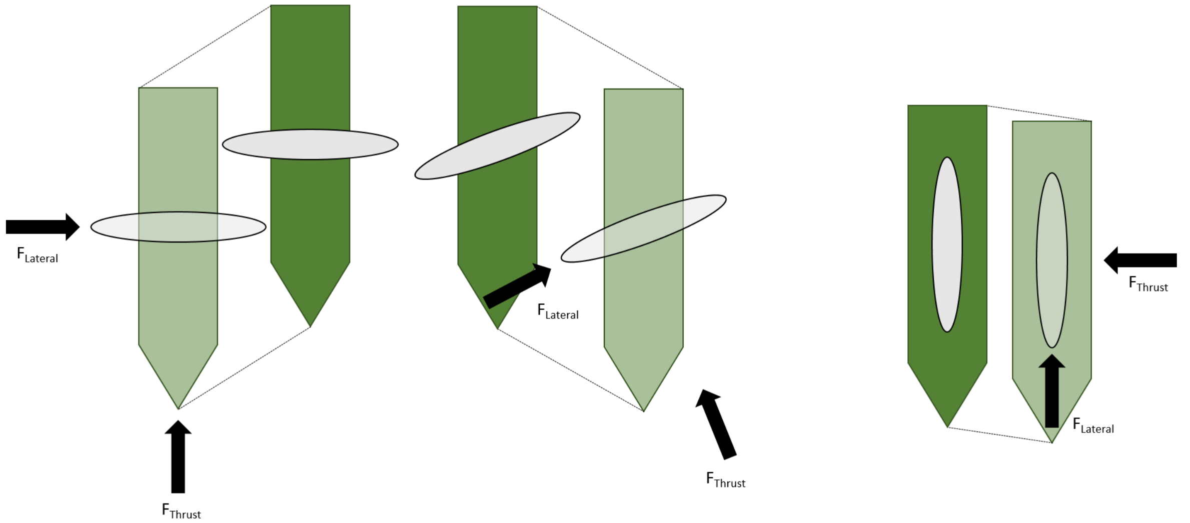
Case 2.3		Ballast excl. WT	Ballast incl. WT waves only	Ballast incl. WT wind only	Ballast incl. WT wind & waves
Surge [m]	Mean	63.15	63.17	63.18	63.17
	St. Dev.	0.017	0.011	0.009	0.016
Sway [m]	Mean	-0.13	-0.12	1.36	1.36
	St. Dev.	0.28	0.28	0.23	0.36
Heave [m]	Mean	2.40	3.06	3.06	3.06
	St. Dev.	0.44	0.44	$202e^{-6}$	0.44
Roll [deg]	Mean	0.003	0.015	1.14	1.14
	St. Dev.	0.12	0.047	0.33	0.33
Pitch [deg]	Mean	0.53	0.61	0.62	0.62
	St. Dev.	0.018	0.022	$263e^{-6}$	0.022
Yaw [deg]	Mean	0.002	0.0004	0.003	0.002
	St. Dev.	0.014	0.014	0.008	0.016

Table 9.18: Evaluation of contribution beam waves and wind to vessel's COG motions.

Surge and sway

For surge and sway, a change is observed in the mean position of the vessel. The direction of the shift of the vessel's mean position for the different combinations of directional loading is shown in figure 9.47. Figure 9.48 shows an example of the connection forces at the bottom of the wind turbine tower. The connection forces result from the wind force acting on the RNA and the wind turbine tower. The larger mean connection forces cause a larger change in the vessel's mean surge and sway positions.

That the wind plays a large role in the results of surge and sway can also be observed in tables 9.17 and 9.18, in which the mean and standard deviation of both surge and sway significantly increase in the cases for which wind is included. An increase in the mean is expected due to the additional wind forces acting on the system. The increase in standard deviation is expected to be a result of the wind loading from which low-frequency motions occurred which are further explained later in this section.



(a) Head waves and wind. **(b)** Head waves and 30° wind. **(c)** Beam waves and wind.

Figure 9.47: Vessel offset under different directional loading.

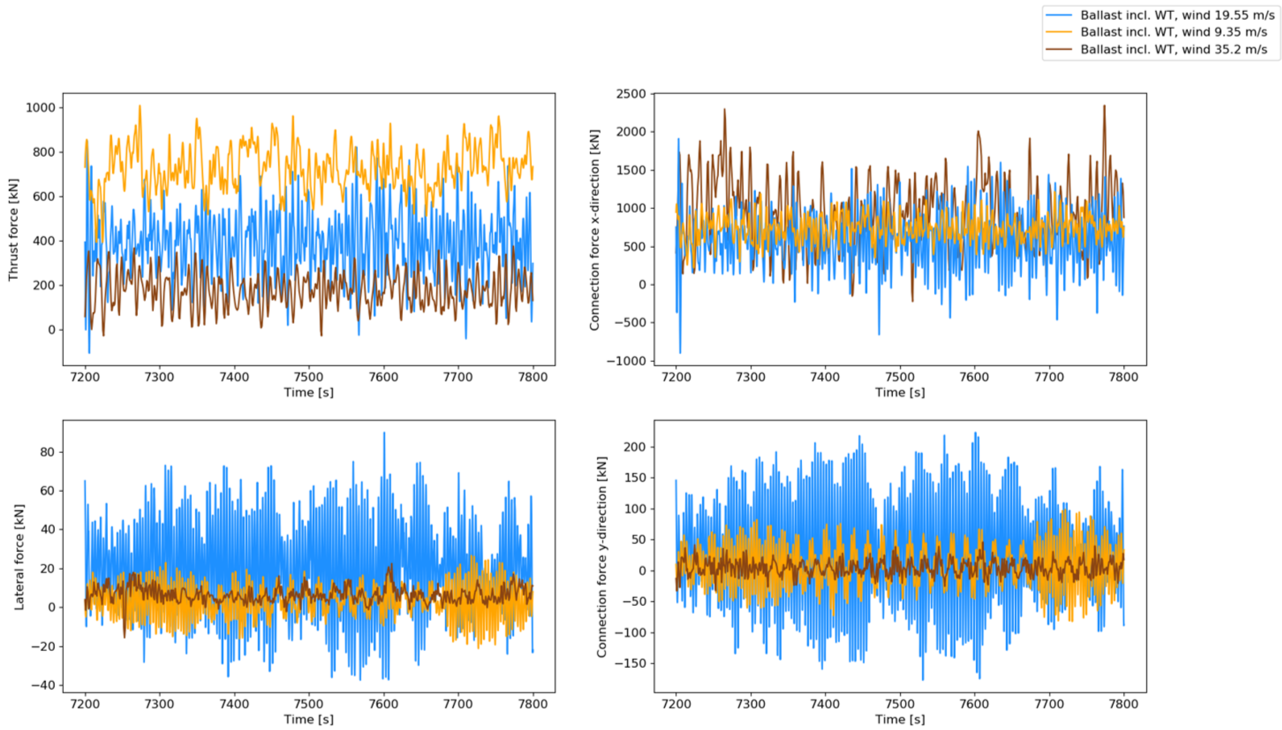


Figure 9.48: Example of forces acting on the wind turbine, left on RNA, right at the connection between WT and vessel.

Heave

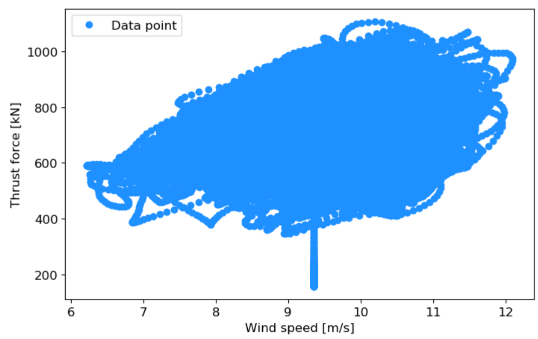
For heave, it is observed that the vessel's COG shifts upwards to a new mean position as a result of the addition of the wind turbine. This is a result of the upwards shift of the vessel's COG, which is larger than the additional draught of the vessel, so in the global coordinate system this upwards shift is visible. The heave motion itself is barely affected by the wind turbine, which is indicated by the negligible difference in standard deviations. That the wind has hardly any effect on the heave can also be observed in tables 9.17 and 9.18.

Roll

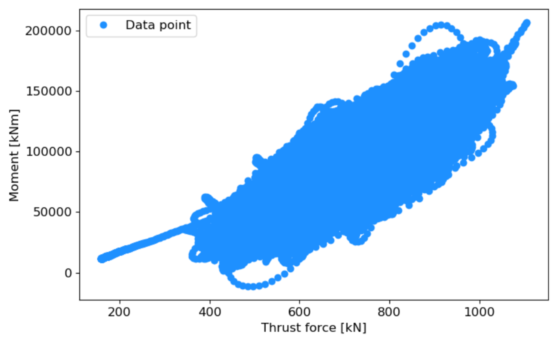
The roll generally increases comparing the vessel excluding wind turbine and including wind turbine. The amount of increase highly depends on the thrust and lateral forces acting on the RNA of the wind turbine, for which an example is shown in figure 9.48 for the different wind speeds. In the case of head waves and wind the roll is largest for the largest lateral force (at 19.55 m/s). For beam waves and wind the roll is largest for the highest thrust force (at 9.35 m/s). At head waves and 30° wind, the roll depends on the balance of forces between thrust and lateral force.

Based on the observations in the displacement RAOs for roll, where the addition of the wind turbine caused the natural roll frequency (peak of RAO) to shift to lower frequencies, away from the peak of the wave spectrum, the observed increase in the roll's standard deviation results was not expected. Because of this, the contribution of the wind is further evaluated. From both tables 9.17 and 9.18 can be observed that the effect of the wind on the roll is significant. Also can be observed, that in the case of waves only, the roll's standard deviation decreases, following the expectation described above. It is therefore further evaluated if the effect of the wind resulting in the changes in roll is correct. This is shown for the load case Ballast including wind turbine, in beam waves and wind, for a Hs of 3 meters, a Tz of 6 seconds, and a mean wind speed of 9.35 meters per second at 10 meters above MSL (environmental load case 2.3 for which results are shown in table 9.18).

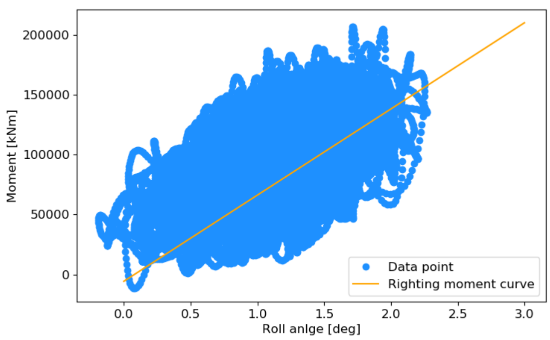
Figure 9.49 shows for this case the correlation between wind speed, thrust force, the moment in roll direction (resulting from both wind and wind turbine weight and inertia), and finally the roll angle. From figure 9.49 can be observed that both the wind speed and the resulting thrust force show sufficient variation to generate a range of different moments affecting the dynamic behavior of the vessel's roll motion, increasing the standard deviation which is observed in the motion analysis results. From figure 9.49c can be seen that the correlation between the moment and the roll angle, shows a similar slope as was determined for the vessel's righting moment curve in section 9.2 on the vessel's stability. The Fully Loaded load case with the wind turbine therefore also generally experiences a larger roll angle, since the slope of its righting moment curve is less steep compared to that of the Ballast case with the wind turbine.



(a) Wind speed and thrust force.



(b) Thrust force and moment.



(c) Moment and roll angle.

Figure 9.49: Correlation between parameters.

For head waves and wind, the standard deviation of the roll also increases, but in that case, it is the fluctuating lateral force acting on the nacelle which causes this. Since the lateral force is significantly smaller compared to the thrust force, the effect remains small. Because the magnitude of the thrust force and lateral force is determined by the wind turbine's generator torque and blade pitch control systems, and the observed fluctuations of the thrust force are covering a broad range of force amplitudes, a recommendation is to perform a model test evaluating whether the observed fluctuating thrust force would also occur in measurement data from a model test.

Pitch
For pitch, it is observed that for the higher sea-states the difference between the vessel excluding wind turbine and including wind turbine becomes larger, especially for head waves. This is because for head waves the peak of the JONSWAP spectrum lies closer to the peak of the vessel's pitch RAO. The variation of the wind also plays a role but has less influence on the pitch behavior compared to the roll.

Yaw
Overall an increase in yaw is observed. Nevertheless, the yaw amplitudes stay small for all the different environmental combinations.

System's modes
In the case of the Ballast load case, for beam waves and wind, the vessel excluding the wind turbine shows high standard deviations for all 6 DoFs, for Hs = 13 m and Tz = 11.5 s, after which the vessel including wind turbine reduces the standard deviation. This can be explained by the modes and their associated natural frequency of the system. The first 6 modes of the system in its different conditions are shown in table 9.19. The fourth mode of the Ballast load case excluding the wind turbine has a natural roll frequency of 0.071 Hz, which is close to the associated peak of the JONSWAP curve for this wave conditions as shown in 9.34. As shown in table 9.19, including the turbine reduces the frequency of this mode, moving it away from the peak of the JONSWAP spectrum, resulting in fewer, but still considerable motions. This reduction is also observed in the roll of figure 9.41, head waves, and wind for the same wave height and period.

	Mode	1	2	3	4	5	6
	DoF	Sway	Surge	Yaw	Roll	Heave & pitch	Pitch
Ballast	Frequency [Hz]	0.012	0.012	0.027	0.071	0.162	0.199
excl. WT	Period [s]	82.73	82.66	37.11	14.14	6.16	5.03
Ballast	Frequency [Hz]	0.012	0.012	0.027	0.057	0.161	0.182
incl. WT	Period [s]	83.28	83.18	37.13	17.40	6.20	5.49
Fully Loaded	Frequency [Hz]	0.010	0.010	0.025	0.051	0.125	0.141
excl. WT	Period [s]	104.68	104.31	39.78	19.53	7.99	7.08
Fully Loaded	Frequency [Hz]	0.010	0.010	0.025	0.039	0.134*	0.113*
incl. WT	Period [s]	105.86	105.03	39.79	25.53	7.44*	8.85*

*In this case the natural frequency of heave & pitch is higher than for pitch, so the order of modes swaps.

Table 9.19: First 6 system modes: natural frequencies and periods.

Low-frequency motions in time-series

Figures 9.50 up to 9.52 show a comparison of the time series of the vessel's COG motions including and excluding wind turbine for the vessel's Ballast condition under different directional loading. A duration of 1000 seconds from the total time series is shown for which the significant wave height is equal to 3 meters and the mean zero-up-crossing period is 6 seconds. The vessel excluding wind turbine is compared to the vessel including wind turbine for wind speeds of 9.35 m/s and 19.55 m/s.

Besides the general trends that are visible in the time series, it can be observed in figures 9.50 up to 9.52 that for the DoFs surge, sway, and yaw a low-frequency motion is visible. This was also shown in the comparison of the two different methods. Depending on the directional loading the amplitude of this motion is large or small. In the cases including wind turbine, the amplitudes of these low-frequency motions become larger. The larger wind force acting on the wind turbine causes larger amplitudes, which is also something that would occur in a mass-spring system with equal mass and stiffness. The increase in the surge and sway standard deviations which were observed earlier is also in line with this. The period of these motions is close to the periods for surge, sway, and yaw of the first 3 modes of the system shown in table 9.19. The periods of these modes are typical in the case of using a soft-mooring system [85].

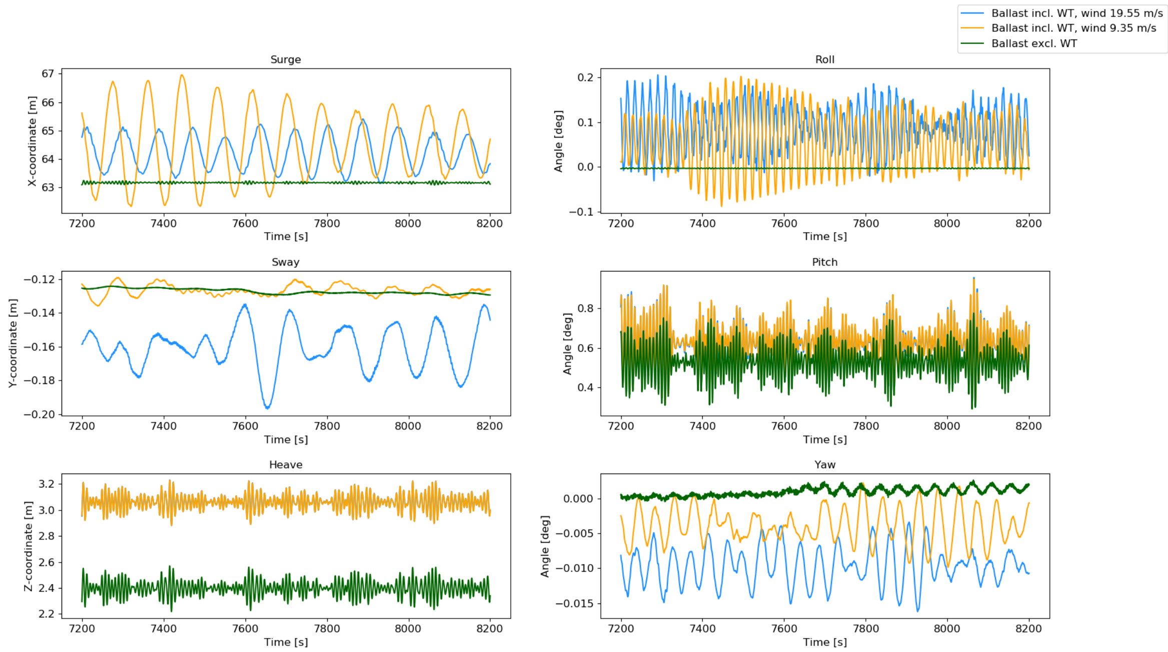


Figure 9.50: Vessel COG 6 DoF in time domain for Hs = 3 m, Tz = 6 s, head waves, and wind.

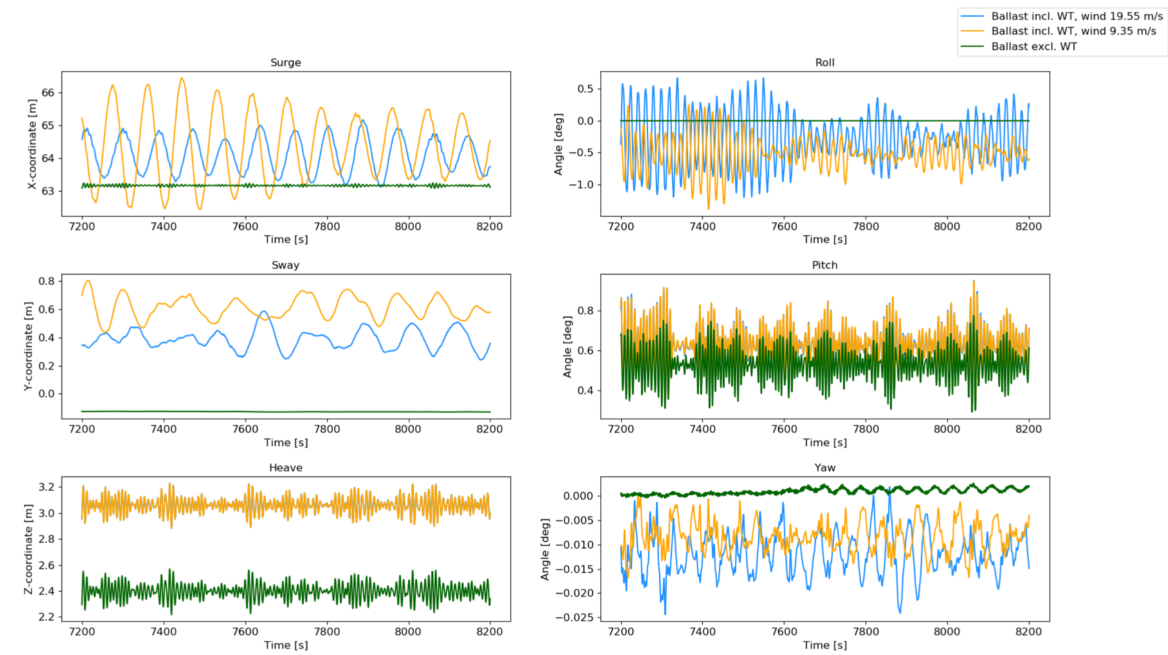


Figure 9.51: Vessel COG 6 DoF in time domain for Hs = 3 m, Tz = 6 s, head waves and 30° wind.

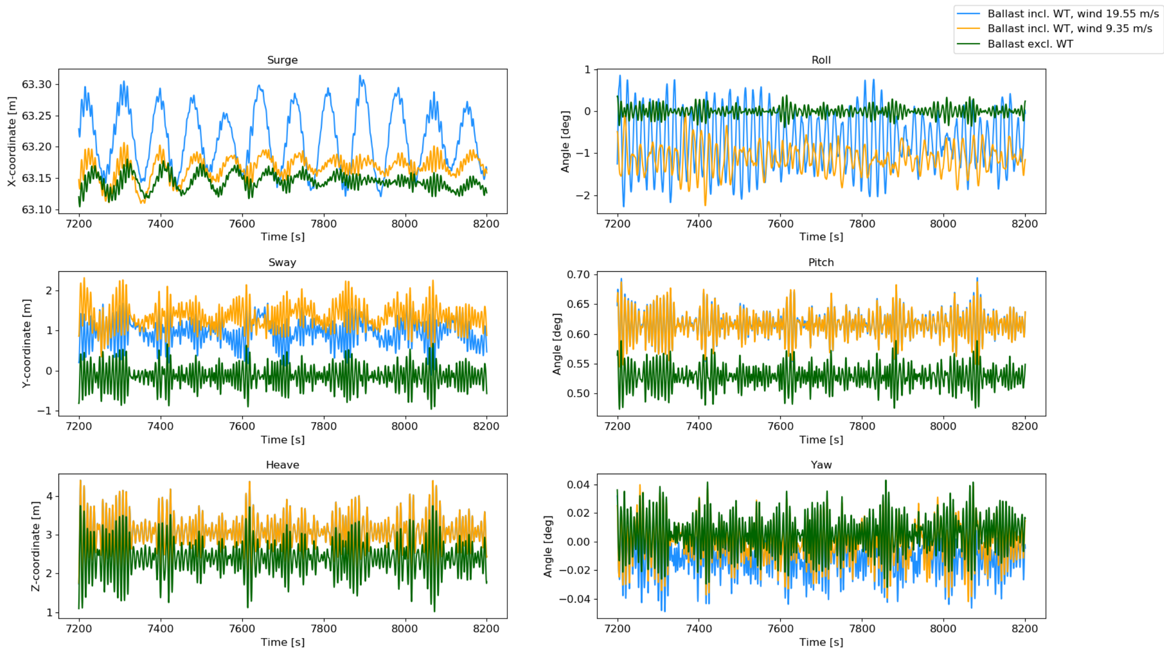


Figure 9.52: Vessel COG 6 DoF in time domain for Hs = 3 m, Tz = 6 s, beam waves, and wind.

Transient Response

From the time series shown in figures 9.50 up to 9.52 a low-frequency motion is observed for surge, sway, and in case of head waves for yaw. A possibility is that these motions represent a transient response. A transient response is a response that occurs due to instant load changes. To evaluate whether this observed low-frequency motion is a transient response due to the wind forces acting on the vessel, a simulation is performed in which damping is added to the model. This additional damping is added in both the surge and sway direction of the vessel, for which the values are shown in table 9.20.

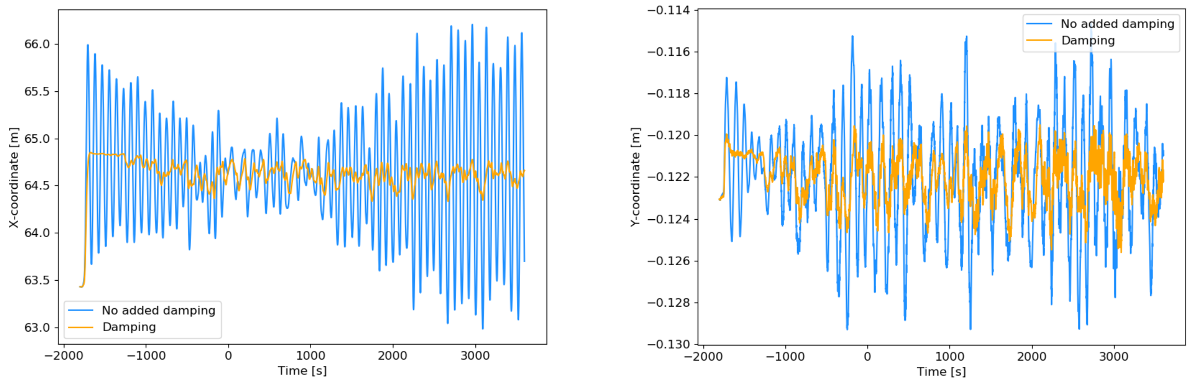
DoF	Surge	Sway
Added damping [kN/(m/s)]	10000	10000

Table 9.20: Additional damping added to the model.

The motions are evaluated for the vessel in an NPD wind spectrum, similar to the wind loading used in the earlier explained simulations, for a wind speed of 11.4 m/s, only without using a height factor. Also, the same is done for a constant wind only of 11.4 m/s with a linear built-up phase starting from 0 m/s of 1800 seconds. In both cases, the wind is coming from the front of the vessel. The response for surge and sway using the NPD wind spectrum is shown in figure 9.53 for both the case excluding and including the added damping. The response for surge and sway under a constant wind is shown in figure 9.54 for both cases excluding and including the added damping.

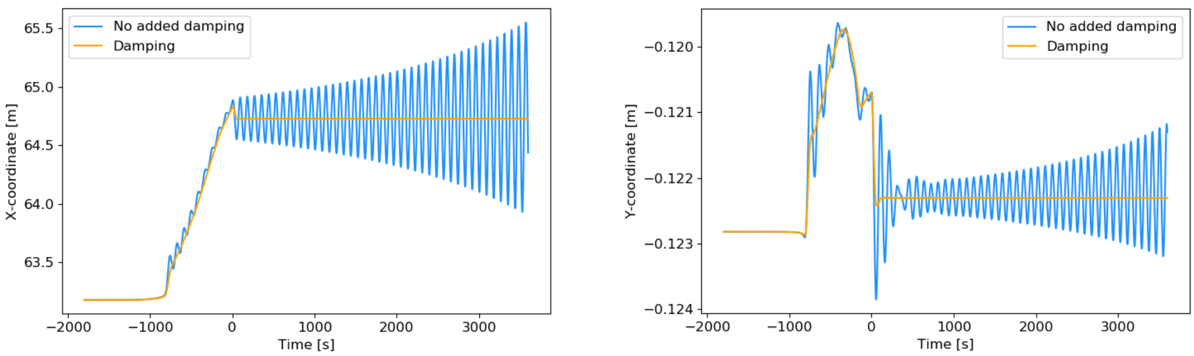
From figures 9.53a and 9.53b it is observed that for the case using an NPD wind spectrum, in case damping is added the motion amplitudes for surge and sway significantly reduce. From figures 9.54a and 9.54b it is observed that for constant wind the low-frequency motion disappears in case the damping is added. This indicates that the response is an underdamped transient response.

In the case of constant wind, the low-frequency response is therefore likely to be a result of modeling, and not a result due to a physical phenomenon. However, for the case using NPD wind loading, variations in surge and sway remain where the dynamic variation in the wind speed likely causes this. That the wind speed varies significantly in time using an NPD spectrum, is shown in figure 9.55, where a piece of the time-series of the three different wind speeds used in the environmental load cases is shown, together with their statistical properties.



(a) Surge **(b)** Sway

Figure 9.53: Effect of damping on surge and sway response, NPD spectrum wind loading.



(a) Surge **(b)** Sway

Figure 9.54: Effect of damping on surge and sway response, constant wind loading.

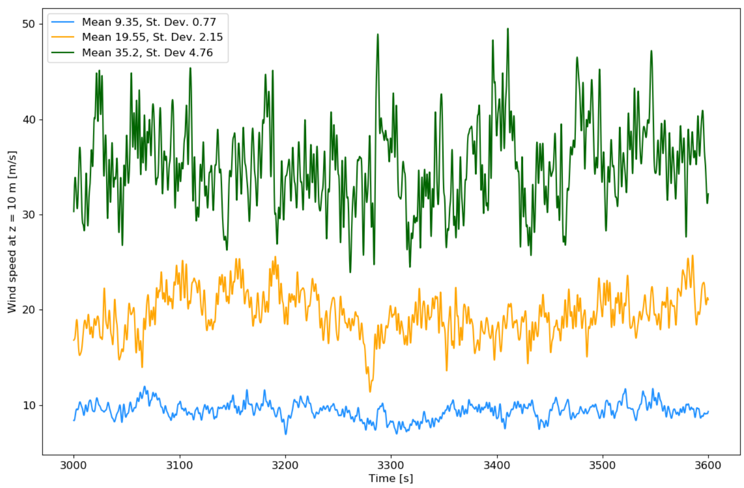


Figure 9.55: Variation of wind speed in time for different wind speeds.

Effect on mooring system

Since the wind turbine causes a difference in the motions of the vessel, it also affects the mooring system. Table 9.21 shows the maximum observed mooring line effective tensions for all the different cases, and the percentage increase of this tension in case the wind turbine is included. These results do not consist of the additional damping as explained above. For the operational cases, the maximum increase is almost 5%. For the extreme case, the largest increase is 9.83%. Because for intact dynamic conditions the American Petroleum Institute prescribes a safety factor of 1.67 (67%) [88], in general, the lines should be able to withstand the load.

Case	Ballast Excl. WT	Ballast Incl. WT	Increase [%]	Fully Loaded Excl. WT	Fully Loaded Incl. WT	Increase [%]
1.1	10936.66	11440.23	4.60	10931.19	11267.24	3.07
1.2	10936.66	11476.86	4.94	10931.19	11324.98	3.60
1.3	10952.49	11223.92	2.48	10948.16	11199.43	2.30
2.1	11295.01	11466.34	1.52	10941.09	11267.83	2.99
2.2	11295.01	11515.62	1.95	10941.09	11325.77	3.52
2.3	11570.36	11432.55	-1.19	11052.05	11265.58	1.93
3.1	12069.95	11526.66	-4.50	10985.87	11289.13	2.76
3.2	12069.95	11525.79	-4.51	10985.87	11350.77	3.32
3.3	13045.65	11679.94	-10.47	11377.64	11471.43	0.82
4.1	11295.01	11275.00	-0.18	10941.09	11190.81	2.28
4.2	11295.01	11340.32	0.40	10941.09	11254.64	2.87
4.3	11570.36	11343.01	-1.96	11052.05	11224.78	1.56
5.1	12069.95	11381.40	-5.70	10985.87	11207.45	2.02
5.2	12069.95	11450.10	-5.14	10985.87	11262.13	2.51
5.3	13045.65	11681.20	-10.46	11377.64	11419.59	0.37
6.1	12375.91	11438.49	-7.57	13074.63	11928.19	-8.77
6.2	12375.91	11545.21	-6.71	13074.63	11946.79	-8.63
6.3	13550.40	11909.64	-12.11	13781.31	11821.1	-14.22
7.1	13400.12	11967.79	-10.69	12120.17	13311.55	9.83
7.2	13400.12	12395.52	-7.50	12120.17	12535.24	3.42
7.3	19615.14	12285.05	-37.37	12301.32	12682.98	3.10

Table 9.21: Maximum observed mooring line effective tension [kN].

Table 9.21 also shows several decreases in the observed maximum effective line tension. Especially for case 7.3 of load case Ballast, a large decrease is observed. However, this is in line with the vessel's motion behavior, where in this case the vessel's motions were significantly reduced due to the addition of the wind turbine, as was earlier explained in the subsection on the system's modes.

It should be noted that the soft-mooring system used in the analysis is not the actual mooring system used at the site. For the Haewene Brim, a catenary mooring system is used to dynamically position the vessel. A catenary mooring is less stiff compared to a soft-mooring system.

For the catenary mooring, low-frequency motions are an already existing issue due to drift forces caused by the current. It is recommended to further research the combined effect of the low-frequency motions observed and those caused by the current. This will influence the extreme and fatigue loads on the mooring system. The increase in the amplitude of the low-frequency motion can also cause the vessel to go over its excursion limit. Especially when the wind load on the vessel would also be included, a larger offset for surge and sway of the vessel will be likely to occur. The current excursion envelope of Haewene Brim based on its ultimate limit state (ULS) is shown in figure 9.56 [89][19]. Too much additional excursion can cause the excursion envelope to exceed the excursion limit. Therefore it is recommended for future research to further evaluate the combined effects of wind and current.

[19]Reference coming from Bluewater's Meridian database (not publicly accessible).

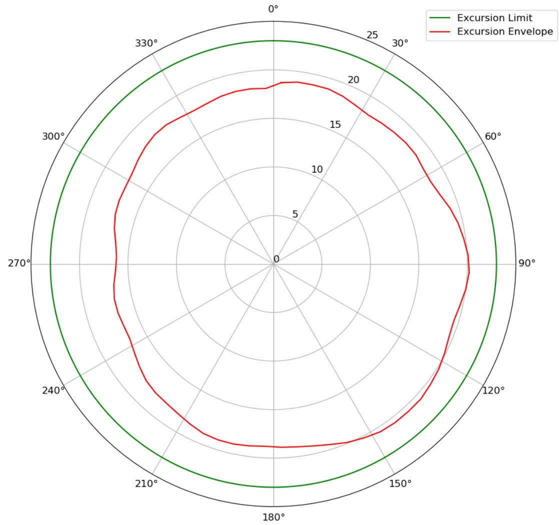


Figure 9.56: Existing excursion envelope of Haewene Brim in ULS [89].

Evaluation of vessel and wind turbine limiting benchmarks

The motions of the FPSO and wind turbine can be evaluated against several criteria. For the vessel, there are criteria for its acceleration (vertical relative to gravity (g) and horizontal) and angle from the vertical, in case of 1/1 year and 1/10000 year conditions [90][20]. For these criteria, the limiting benchmark values are shown in table 9.22.

Condition	Vertical acceleration (rel. g) [m/s^2]	Horizontal acceleration [m/s^2]	Max angle from vertical [°]
Operational 1/1 year condition (FLS)	9.81 ± 3	3.5	9
Operational 1/10000 year condition (ULS)	9.81 ± 4.1	5.6	19

Table 9.22: FPSO standard maximum vessel motions and accelerations limiting benchmarks [90][19].

The criteria for wind turbines are usually provided by a wind turbine manufacturer. For each specific wind turbine model, these criteria can slightly differ. Corewind [91] provides several criteria for a floating wind turbine system. Nevertheless, not all criteria are related to the turbine. Some criteria are limits for the power cable, or for the floating platform itself, which are not relevant to the configuration of a wind turbine on an FPSO. Therefore only one criterion is used as a reference limiting benchmark which is the nacelle acceleration. This criterion is directly related to the functioning of the wind turbine itself. The limiting values are shown in table 9.23.

Condition	Nacelle acceleration [m/s^2]
Operational	2.8
Survival	3.5

Table 9.23: Wind turbine nacelle acceleration limits [91].

The results from the time domain analysis are compared to the limiting benchmark values. Tables 9.25 and 9.26 show the values obtained from the time domain analysis for load case Ballast, for its operational and extreme case results respectively. Tables 9.27 and 9.28 show the same for the Fully Loaded case. A green value indicates that the obtained maximum value is not exceeding the limiting

[20]Reference coming from Bluewater's Meridian database (not publicly accessible).

benchmark. A red value indicates that the limiting value is exceeded. The results are split based on the directional environmental loading. The number of the cases are matching the environmental loading properties as shown in table 9.24.

Case	Wind speed [m/s]	Hs [m]	Tz [s]
1	9.35	1	4.5
2	9.35	3	6
3	9.35	5	7.5
4	19.55	3	6
5	19.55	5	7.5
6	19.55	8	9
7	35.2	13	11.5

Table 9.24: Overview of cases.

From tables 9.25 up to 9.28 is observed that in general, the limiting factor is the nacelle acceleration. Overall the vessel is meeting its criteria, where the nacelle acceleration is exceeded in the cases where a higher wind speed is present. For the case of beam waves and wind in ballast condition, the criteria for cases 6 and 7 are exceeded for the vessel excluding the wind turbine. This has to do with the natural frequency for the roll of the vessel being close to the peak of the JONSWAP spectrum as explained earlier in section 9.5.6. For the same cases including wind turbine, a similar effect is observed, only with less amplitude since the roll natural frequency is further from the JONSWAP peak compared to the vessel excluding wind turbine.

			Head waves and wind		Head waves, 30°wind		Beam waves and wind	
	Parameter	Case	Excl. WT	Incl. WT	Excl. WT	Incl. WT	Excl. WT	Incl. WT
Vessel operational 1/1 year condition	Max vertical acceleration (m/s^2)	1	9.79-9.82	9.79-9.82	9.79-9.82	9.79-9.82	9.69-9.92	9.68-9.92
		2	9.69-9.93	9.69-9.93	9.69-9.93	9.69-9.93	8.82-10.77	8.82-10.77
		3	9.49-10.11	9.49-10.11	9.49-10.11	9.49-10.11	7.72-11.82	7.73-11.82
		4	9.69-9.93	9.69-9.93	9.69-9.93	9.69-9.93	8.82-10.77	8.82-10.77
		5	9.49-10.11	9.49-10.11	9.49-10.11	9.49-10.11	7.72-11.82	7.73-11.83
		6	9.32-10.22	9.32-10.23	9.32-10.22	9.32-10.23	6.84-12.95	6.92-12.93
	Max horizontal acceleration (m/s^2)	1	0.10	0.13	0.10	0.26	0 24	0.54
		2	0.13	0.16	0.13	0.27	0.73	0.91
		3	0.17	0.18	0.17	0.28	1.57	1.46
		4	0.13	0.16	0.13	0.30	0.73	0.90
		5	0.17	0.18	0.17	0.31	1.57	1.49
		6	0.20	0.23	0.20	0.32	4.78	2.07
	Max angle from the vertical (°)	1	0.58	0.68	0.58	1.54	0.74	2.33
		2	0.85	1.01	0.85	1.59	0.74	2.35
		3	1.11	1.40	1.11	1.60	2.78	2.55
		4	0.85	1.01	0.85	1.84	0.74	2.70
		5	1.11	1.40	1.11	1.99	2.78	3.01
		6	1.92	2.38	1.92	2.41	19.98	4.38
Wind turbine operational condition	Max nacelle acceleration (m/s^2)	1	n/a	0.86	n/a	0.88	n/a	0.86
		2		1.18		1.20		1.70
		3		1.38		1.33		2.77
		4		3.06		2.96		2.91
		5		3.02		3.02		3.78
		6		3.19		3.07		5.39

Table 9.25: Comparison to limiting benchmarks: Ballast operational cases

			Head waves and wind		Head waves, 30°wind		Beam waves and wind	
	Parameter	Case	Excl. WT	Incl. WT	Excl. WT	Incl. WT	Excl. WT	Incl. WT
Vessel operational 1/10000 year condition	Max vertical acceleration (m/s^2)	7	8.84-10.58	8.79-10.69	8.84-10.58	8.84-10.57	-7.24-13.15	6.55-13.03
	Max horizontal acceleration (m/s^2)	7	0.32	0.28	0.32	0.49	13.18	6.15
	Max angle from the vertical (°)	7	3.53	4.43	3.53	4.34	90	31.20
Wind turbine survival condition	Max nacelle acceleration (m/s^2)	7	n/a	2.16	n/a	2.92	n/a	12.45

Table 9.26: Comparison to limiting benchmarks: Ballast extreme case.

			Head waves and wind		Head waves, 30°wind		Beam waves and wind	
	Parameter	Case	Excl. WT	Incl. WT	Excl. WT	Incl. WT	Excl. WT	Incl. WT
Vessel operational 1/1 year condition	Max vertical acceleration (m/s^2)	1	9.80 - 9.81	9.80-9.81	9.80-9.81	9.79-9.81	9.76-9.86	9.73-9.86
		2	9.73-9.89	9.74-9.88	9.73-9.89	9.73-9.87	9.27-10.33	9.23-10.35
		3	9.49-10.11	9.50-10.11	9.49-10.11	9.50-10.11	8.27-11.25	8.14-11.38
		4	9.37-9.89	9.74-9.87	9.37-9.89	9.73-9.87	9.27-10.33	9.26-10.35
		5	9.49-10.11	9.50-10.11	9.49-10.11	9.50-10.11	8.27-11.25	8.20-11.37
		6	9.11-10.45	9.06-10.43	9.11-10.45	9.06-10.43	7.01-12.80	7.05-12.73
	Max horizontal acceleration (m/s^2)	1	0.02	0.08	0.02	0.52	0 16	0.83
		2	0.10	0.09	0.10	0.52	0.54	1.11
		3	0.31	0.36	0.31	0.52	1.13	1.55
		4	0.10	0.11	0.10	0.40	0.54	0.97
		5	0.31	0.37	0.31	0.44	1.13	1.29
		6	0.82	1.20	0.82	1.22	1.90	1.99
	Max angle from the vertical (°)	1	0.03	0.48	0.03	3.02	1.92	4.54
		2	0.27	0.48	0.27	3.01	0.57	4.57
		3	1.55	1.90	1.55	2.99	1.92	4.71
		4	0.27	0.43	0.27	2.34	0.57	4.96
		5	1.55	1.94	1.55	2.50	1.92	4.87
		6	5.41	7.31	5.41	7.30	3.69	4.79
Wind turbine operational condition	Max nacelle acceleration (m/s^2)	1	n/a	0.84	n/a	0.90	n/a	0.89
		2		0.87		0.88		1.23
		3		1.54		1.49		2.29
		4		2.94		2.91		2.78
		5		3.44		3.31		2.80
		6		5.91		5.37		3.96

Table 9.27: Comparison to limiting benchmarks: Fully Loaded operational cases.

			Head waves and wind		Head waves, 30°wind		Beam waves and wind	
	Parameter	Case	Excl. WT	Incl. WT	Excl. WT	Incl. WT	Excl. WT	Incl. WT
Vessel operational 1/10000 year condition	Max vertical acceleration (m/s^2)	7	8.74-10.94	8.72-10.74	8.74-10.94	8.72-10.63	6.05-13.04	5.95-13.22
	Max horizontal acceleration (m/s^2)	7	0.73	1.86	0.73	1.80	3.45	3.20
	Max angle from the vertical (°)	7	6.81	13.6	6.81	12.09	10.05	9.16
Wind turbine survival condition	Max nacelle acceleration (m/s^2)	7	n/a	6.08	n/a	5.46	n/a	4.51

Table 9.28: Comparison to limiting benchmarks: Fully Loaded extreme case.

In case the same sea state is considered with a different wind speed, the higher wind speed causes an exceedance of the limits, indicating that the wind is a limiting factor. Figure 9.57 provides insight into the probability of occurrence of wind speed, based on almost 90000 sea-state measurements from 29 years of hindcast data [68][21]. As is shown mostly lower wind speeds occur over higher wind speeds.

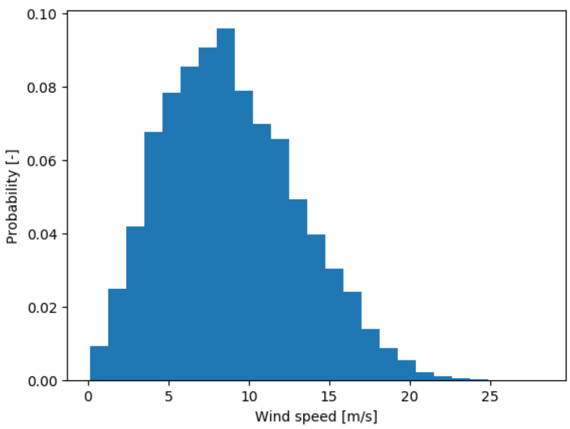


Figure 9.57: Probability of occurrence of wind speeds.

From the nacelle acceleration results stands out the large increase in nacelle acceleration in case of cut-out wind speed compared to rated wind speed, for example, case 2 and 4 for head waves in table 9.25. These 2 cases both have the same wave conditions. For these 2 cases, it can also be observed in figure 9.41 that the vessel's COG motions are in the same order of magnitude. Therefore the large difference in nacelle acceleration stands out even further. This indicates the wind plays a large role in the determination of this acceleration. Therefore the contribution of tower bending to the nacelle's acceleration is further evaluated.

The OrcaFlex model allows the wind turbine tower to bend. The bending stiffness of the tower is determined by Young's Modulus (E) multiplied by the tower's cross-sectional inertia (I). The tower bends because of the wind load on both the tower and RNA. To further evaluate the contribution of tower bending to the nacelle's acceleration, several cases are selected for which the simulation is run using a rigid tower. The tower is made rigid in OrcaFlex by setting the Young's Modulus (E) to infinity. This way, the weight of the tower is not affected, which would again influence the overall system's properties.

[21] Reference coming from Bluewater's Meridian database (not publicly accessible).

Table 9.29 shows the comparison in the mean, standard deviation, and maximum acceleration at the bottom of the tower and the nacelle between the use of a flexible or rigid wind turbine tower for three different cases in head waves and wind. From the table can be seen that for Ballast cases 2 and 4 in head waves and wind, the acceleration at the bottom of the tower is approximately equal between the two cases, for both flexible and rigid towers. This is expected since the vessel motions are similar. The table also shows a significant reduction in nacelle acceleration, in the case of a rigid tower. Again for cases 2 and 4 of Ballast, in the case of a rigid tower, the nacelle acceleration is almost the same, which is to be expected since the nacelle's acceleration is in this case dominated by the vessel behavior, and no longer by the wind and flexibility of the tower itself. In figure 9.55 it was shown that the higher wind speed has a larger standard deviation, which explains larger variation in wind speed and therefore larger fluctuations in the wind loading on both tower and RNA, explaining the large difference in the two cases nacelle acceleration for a flexible tower. For the extreme case (7) for the vessel in Fully Loaded condition, a rigid tower also significantly reduces the nacelle acceleration. However, its value lies still above the allowable survival limit.

		Ballast case 2 head waves and wind		Ballast case 4 head waves and wind		Fully Loaded case 7 head waves and wind	
		Flexible tower	Rigid tower	Flexible tower	Rigid tower	Flexible tower	Rigid tower
Acceleration bottom tower (m/s^2)	Mean	0.03	0.03	0.029	0.029	0.18	0.18
	St. Dev.	0.019	0.019	0.018	0.019	0.17	0.17
	Max.	0.13	0.13	0.12	0.13	0.94	0.93
Nacelle Acceleration (m/s^2)	Mean	0.25	0.11	0.63	0.11	1.08	0.87
	St. Dev.	0.17	0.07	0.42	0.07	1.14	0.90
	Max.	1.18	0.48	3.06	0.49	6.08	4.60

Table 9.29: Influence of tower rigidity on nacelle acceleration.

Besides increasing the tower's bending stiffness, there are other options for reducing the nacelle's acceleration. For the chosen design configuration, a possible solution for reducing the nacelle acceleration in operational conditions can be to shut down the wind turbine earlier than its cut-out wind speed. This reduces the wind loads acting on the nacelle, which will reduce its acceleration. This is observed in the results of the extreme case of the Ballast condition. Nevertheless, this can possibly only solve the operational cases, since in the evaluation of the extreme case the wind turbine was already in its parked condition. The largest concern from the results is that in the extreme loading condition, the Fully Loaded load case does not have a configuration that meets the nacelle acceleration criteria, whereas for the ballast load case there are possibilities to stay within the limits for this type of environmental loading. This is a result of the combined roll and pitch of the vessel, where the main difference between the two is that for the Fully Loaded case, the maximum angle from the vertical of the vessel is significantly larger compared to the Ballast load case, causing more movement to the turbine's nacelle, which can be observed by the higher nacelle acceleration. Increasing the bending stiffness of the tower is also not sufficient to reduce the value below its allowable limit.

Another option is therefore to reduce the wind turbine's tower height. However, this causes more challenges, since the wind turbine will operate in the same area as the cranes. This solution, therefore, requires limits on the operational areas of the different interfering components, and clear coordination on these components and when they are allowed to operate. Besides, the evaluation of the system's behavior is performed for the Haewene Brim at its specific location, which is the Pierce Field in the UK sector of the central North Sea. The North Sea is generally known to be a harsh environment to operate in [92]. A possible mitigation for the exceedance of the nacelle acceleration survival limits is to apply it only at a different location in the world, where the extreme conditions are less rough compared to the rough conditions of the North Sea. The above findings can be used as input for future research. It is recommended to further improve the design by increasing the tower's bending stiffness, which can be done by increasing the wall thickness of the tower, reducing the tower's height, evaluating the wind turbine's operability window, and identification of a suitable location with less rough conditions.

9.6 Wind turbine and FPSO interaction during operations

One of the technical challenges is the interaction of an FPSO with the wind turbine during day-to-day operations. This section provides an overview of the significant events occurring on an FPSO, and what the effect of these events will be for both wind turbine and FPSO.

9.6.1 Large events during FPSO operations

There are several large events taking place during FPSO operations. These events are identified in the hazard identification of chapter 6 as events that could lead to hazards during the operations of both wind turbine and FPSO. These main events are:

- FPSO offloading
- Helicopter operations
- Flaring
- Lifting operations

The locations of these events are shown in figure 9.58.

Figure 9.58: FPSO overview of components during large events in operations.

FPSO offloading

During offloading of an FPSO an additional shuttle tanker locates itself near the FPSO. During this time cargo (oil) is transported from the FPSO to the shuttle tanker through a hose. An offloading operation usually takes place once every ten days, of which the operation itself takes approximately two days. During these two days, the FPSO shuttle tanker is located near the FPSO continuously. Often it is positioned at the stern of the vessel. Normally the shuttle tanker only approaches the FPSO when the 48-hour weather forecast predicts suitable conditions for offloading.

From the motion analysis in section 9.5 it is observed that the presence of the wind turbine influences the motions of the FPSO. This might influence the operational weather window for the offloading operation, due to larger FPSO motions under normally suitable weather conditions due to the presence of the wind turbine. Since offloading of the FPSO is a necessity to keep the FPSO running, the wind turbine may be required to shut down during offloading to reduce FPSO motions, to safely perform the offloading operation. The exact operability window for this configuration during offloading operations will have to be determined in more detail. However, this operation can likely take place in calm weather conditions, so offloading is not considered to be a showstopper for the project's feasibility.

Helicopter operations

Helicopter operations typically take place twice a week on the Haewene Brim. Here crew and goods are transported towards and from the FPSO.

The location of the helideck requires an approach and off-take area of 210° without any obstruction. A 1000 meters away from this area no objects are allowed to occur at a height higher than the helideck itself [66]. With the chosen turbine placement, the described available area for helicopter operations is always present. This implies that helicopter operations are possible, also when the wind turbine would be present on the FPSO.

Nevertheless, it is very important to perform helicopter operations safely. Landing and take-off of the helicopter are ideally taking place on a stable platform. Similar to offloading, it was observed that the wind turbine presence influences the FPSO motions and also its stability. The wind turbine's presence will likely affect the operability weather window for helicopter operations. Since again processes on the FPSO are primary over the secondary wind turbine, it can again be required that the wind turbine shuts down during helicopter landings and off-takes.

Flaring

The flare tower is one of the large components present on the FPSO. Flaring is the process of getting rid of excess gas in the FPSO system, by first burning it after which it is released into the air. This process causes a flare flame to occur at the top of the tower. The amount of flaring that is performed is decreasing more and more. More incentives occur to use the gas for other processes, to reduce the FPSO's emissions. Many FPSO operators only make use of the flare tower in case of emergencies, resulting in emergency flaring.

In the chosen configuration the wind turbine is placed in the middle of the vessel, in front of the flare tower. With this configuration, the system is often aligned with the wind such that the flare flame is blown in the direction opposite to the wind turbine's location. By doing this the flare flame is not able to damage the wind turbine.

However, a possible issue might be the resulting turbulent wind behind the wind turbine while operating, influencing the spreading of the flare flame in the downwind direction. This is visualized in figure 9.59.

The exact spreading of the flare flame in the wake created by the wind turbine is something that needs to be evaluated further. A possible preventive measure can be to shut down the turbine in case flaring occurs.

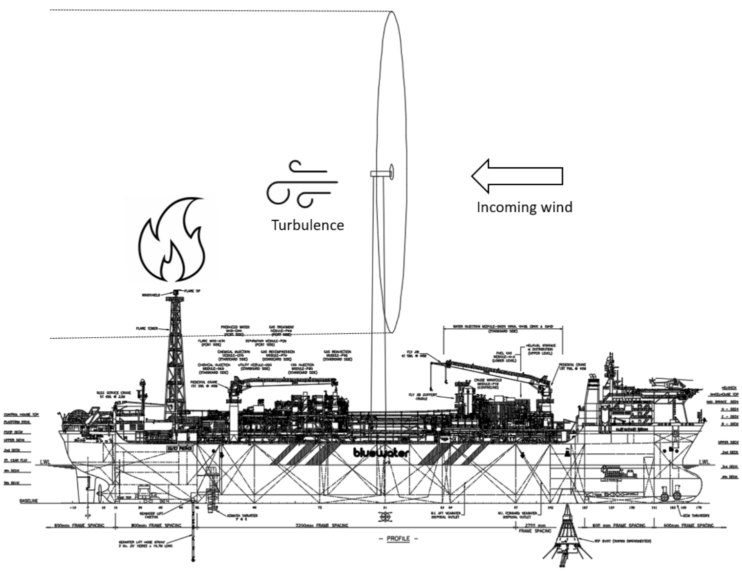


Figure 9.59: Possible effect of wind turbine wake on spreading flare flame.

Lifting operations

Lifting operations on an FPSO take place on an irregular basis. Each lifting operation is assessed individually, to prevent hazards from occurring and to ensure a safe lifting operation. With the chosen wind turbine placement, the wind turbine and cranes on the FPSO have the clearance between them to not collide with each other.

Important for lifting is the FPSO's stability. Again this is influenced by the presence of the wind turbine. In case the lifting operations cannot take place the first solution would again be to shut down the wind turbine. Depending on the importance of the lifting operation it can be determined if a wind turbine shutdown is a necessity or whether it can be postponed to an operational weather window that allows for the wind turbine to operate.

9.6.2 Wind turbine frequent start/stops

Normally, wind turbine design is focused on optimal structural design, which is cost and time efficient, to maximize power production and the lifetime of the wind turbine. Almost every decision that is made in this process is based on the wind turbine's performance, which is the primary focus.

In the suggested configuration of a wind turbine on top of an FPSO, the wind turbine is an integrated item on the FPSO. In this case, it is not the main focus to obtain optimal performance of the wind turbine, but to keep all operations on the FPSO running as much as possible. The wind turbine becomes a secondary component whereas the FPSO is the primary component in this configuration.

This order of importance means that the wind turbine needs to adapt to events occurring on the FPSO. In several cases, this has resulted in the need of shutting down the wind turbine whenever a specific event takes place on the FPSO, or when certain environmental conditions occur.

Whether a turbine is operational is normally defined by a wind turbine's power curve, see figure 9.60. The wind turbine is only non-operational whenever the wind is below the cut-in wind speed (region I), or above the cut-out wind speed (above 25 m/s).

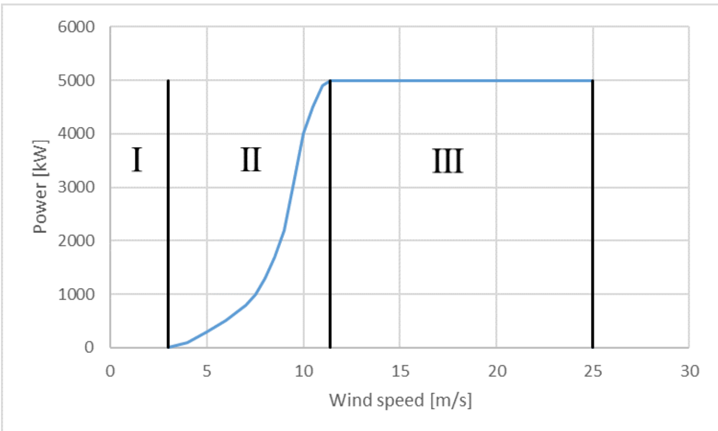


Figure 9.60: Power curve NREL 5 MW wind turbine.

The FPSO requires in certain cases the wind turbine to shut down. These situations are not always directly linked to the environmental conditions, which might result in the need for the turbine to shut down at different wind speeds, possibly in regions II and III between cut-in and cut-out wind speed, compared to how it would normally operate. This requires active monitoring of the wind turbine's operational behavior.

The need for these additional wind turbine shutdowns, therefore, changes the way of operation of the wind turbine. This results in more frequent start/stops of the wind turbine. It is recommended for future research what the impact is of these more frequent starts/stops of the wind turbine under these unusual conditions. Possibly it is required to perform more maintenance to the wind turbine compared to other wind turbine applications, due to earlier occurring damage. This can also impact the wind turbine's overall lifetime.

10 Non-technical project aspects

This chapter addresses the topic of non-technical aspects concerning project realization. Besides the fact that projects can fail due to technical limitations, there are also many different sources of non-technical project risks that can lead to the failure of a project. Part of these non-technical topics are HSE-related risks and the financials of the project. These two aspects were earlier in chapter 7 identified as the fundamentals for feasibility and are evaluated in chapter 11 and 12 respectively. This chapter addresses the role of several other common non-technical project-related risks.

10.1 Categories of non-technical risk

Many different types of risks can be classified as non-technical risks. These risks can be categorized based on their different sources. Ite [93] describes six categories of non-technical project risks. These categories are visualized in figure 10.1.

For the management of these non-technical risk categories, Ite [93] mentions three critical factors that can lead to either project success or project failure. These factors are risk management, stakeholder management, and organizational issues.

Figure 10.1: Categories for sources of non-technical risk [93].

From the stakeholder management, the acceptability of the project by the different stakeholders becomes important. Besides, alternative solutions for reducing emissions by changing the power source of an FPSO can play a role in the project's realization. The relevance of these non-technical aspects is described further in the following sections.

10.2 Risk management

Risk management is a tool to deal with both technical and non-technical risks. Sometimes, risk can be avoided by choosing a particular technical solution. Nevertheless, not all risks can be avoided. Risk management is therefore important to create awareness of the different risks that can occur and to not get rid of the risks. This awareness will benefit the process of decision-making during the project's lifetime.

In the end, this decision-making is a human effort. Bakker et al. [94] describe: "Different people will judge the danger of risks (or potential of opportunities) in different ways". In relation to this, how there is dealt with risk and opportunities can therefore also depend on the question: are the right people, in the right place, at the right time? This can be transferred to the overall project's realization.

10.3 Stakeholder management

One of the non-technical reasons for project failure has to do with the role of stakeholders in a project. Adekoya et al. [95] refer to non-technical risks as: 'all risks and opportunities that arise from the interactions of a business with its broad range of external stakeholders.' Possible stakeholders for the further development of placing a wind turbine on top of an FPSO are:

- National/Local governments
- Legislative bodies
- Policy/design code makers
- Wind turbine manufacturer
- Wind turbine installer
- FPSO operator (Bluewater)
- FPSO Off-loader
- Client
- Personnel on the FPSO
- Insurance company
- Helicopter operator
- Environmental organizations, for example, Greenpeace or WWF
- Social organizations, for example, Amnesty International

Depending on the stakeholder's influence and interest it is required to maintain a good relationship with the stakeholders. Stakeholders with high interest and a lot of influence should be closely cooperated with during the project's realization. Stakeholders with less interest and influence require only little interaction. In the end, the (important) stakeholders need to agree on the project plans to eventually achieve successful execution of the project.

10.4 Acceptability

Acceptability is beside the suitability and feasibility part of the SAF-model described by Johnson et al. [96]. Acceptability brings together both risk- and stakeholder management. It is from this perspective critical for a project's realization that the expected risks and returns are accepted by the different relevant stakeholders. Each stakeholder is likely to assess this acceptability according to their selection of relevant criteria.

For personnel on the FPSO, acceptability will be an important factor for the feasibility of the project. In the end, the on-site personnel needs to be able to work and live on the FPSO, under the impressive presence of a large wind turbine. The situation can be found completely safe and accepted to all relevant rules and standards, but it remains very important that the personnel on the FPSO feels safe as well.

So far, working and living near an (almost continuously) operating wind turbine is an experience that is new for the industry. Normally wind turbines are placed at larger distances, away from people. Social acceptance is therefore something that should not be taken lightly. Surveys among employees should be conducted, together with tests where people can feel and experience the situation. Several adjustments might need to be made on an FPSO so that people start to feel safer. For example, it already feels more safe walking underneath the turbine with a roof over your head, compared to being in the open air, even while this roof is not protecting but only taking away the visual aspect in that matter.

10.5 Alternative solutions

In project realization, it is common to make a comparison between different solutions that can achieve the same or similar goals. Therefore, the realization of this project depends not only on the feasibility of the project itself but also on how it relates to other alternatives. The interesting alternatives, in this case, are the ones that intend to reduce the emissions of an FPSO, focusing on changing the FPSO power source. Alternative solutions that can be considered for this application are:

- Floating wind turbine:
  A floating wind turbine can be placed near an FPSO's location, delivering power to the FPSO utilizing a power cable connecting the wind turbine to the FPSO.

- (Floating) solar
  Solar panels can be placed on the FPSO itself. Besides, with developments in floating solar, it can be possible to place floating solar near the FPSO location.

- Connection of FPSO to the (green) electricity grid
  The FPSO can be connected to an existing electricity grid. Preferably this grid is part of a renewable energy production plant, such as a wind farm. Depending on the FPSO's location this existing grid can be located offshore or onshore. It requires a power cable between the grid and the FPSO to transfer the electricity.

A comparison between the different alternatives is out of the scope of this thesis report. It is recommended to perform research on the alternatives and to compare the different options. In the end, the project that will be realized will be the one that is financially most attractive, reduces risk as low as reasonably practicable (ALARP), is favored by stakeholders, and is technically feasible.

11 Health, Safety and Environmental analysis

From the hazard identification in chapter 6 health, safety, and environmental related hazards are identified. Some of the identified hazards are already further assessed in chapter 9 on technical feasibility. In this chapter, the other important identified HSE-related hazards are analyzed. First, the different identified hazards are further described. Second, the hazards are evaluated using a qualitative risk assessment method. Here the focus lies on the additional hazards that occur due to the interaction between the wind turbine and FPSO. Sometimes this overlaps with existing FPSO hazards.

11.1 Health hazards

In the hazard identification, only three direct health-related hazards are identified, which are noise, stroboscopic effects, and mental health.

11.1.1 Noise

A wind turbine can produce a significant amount of noise which might lead to health issues for people working or living nearby a wind turbine. According to Maizi et al. [97] the noise that is generated by a wind turbine can be either mechanical, as a result of the wind turbine part such as the gearbox and generator, or aerodynamic as a result of the wind flow around the wind turbine blades. The amount of noise that is experienced by people surrounding the wind turbine depends on several factors. First of all the size of the wind turbine, its height, and the distance from the wind turbine.

Since the wind turbine is placed on top of the FPSO, the distance between the working and living space, and the wind turbine is much less compared to other wind turbine applications. Close to the wind turbine's rotor, modern wind turbines have a maximum sound between 100 and 110 dB(A), resulting in a maximum of 55 dB(A) at a distance of 100 meters away from the wind turbine at ground level [98]. Wind turbine noise occurs continuously during wind turbine operations.

Next to this, many other sources that generate noise are already present on an FPSO. The experienced noise in the FPSO environment will be based on the combined noise levels of the present equipment and the distance of an individual to the different types of noise emitters. FPSO equipment that generates noise exceeding 100 dB(A) is common.

Based on the location on an FPSO there are criteria for the allowable noise levels. Overall it holds that during a 12-hour work day an employee's maximum exposure to noise should be no more than an average of 83 dB (A), with peaks of a maximum of 130 dB (A). For non-working areas, such as living quarters, the allowable noise levels are much lower about 50 dB(A) [99][22]. Too much noise can cause health implications or sleep problems.

Employees working on an FPSO are because of the already existing noise levels used to deal with noise. The already present use of adequate hearing protection and sound-proof isolated living quarters can reduce the amount of experienced noise. Measurements should be performed to check that the allowable limits are not exceeded.

11.1.2 Stroboscopic effects

The stroboscopic effect, also known as shadow flicker, is the recurring movement of the shadow that occurs from the wind turbine's rotation of the blades due to its position in sunlight. The stroboscopic effect is considered a health issue related to wind turbines throughout the industry. People with

[22] Reference coming from Bluewater's Meridian database (not publicly accessible).

photosensitive epilepsy are sensitive to visual disturbances. For these people the concern of getting seizures induced from the observation of the shadow flicker of the wind turbine is the largest health-related issue connected to the stroboscopic effect [100].

Besides this serious health risk, it can be imagined that this frequent shadow flicker due to the wind turbine blade's rotation can become annoying in case of exposure for longer periods. The occurrence of the stroboscopic effect depends on the presence of sunlight and whether the turbine is in operation. An increase in sunlight intensity can increase the intensity of the visual effect of the shadow flickering.

11.1.3 Mental health

The health effects people experience from being near a wind turbine have been studied broadly. Often, findings are related to noise and stroboscopic effects. According to the Dutch National Institute for Public Health and the Environment (RIVM), no direct relationship has been found between mental health and living near a wind turbine [101]. However, the distance between people and wind turbines is normally larger than the configuration on top of an FPSO. People on the FPSO are constantly close to the turbine, without the possibility of easily getting away. This possibly causes new insights in the research field of mental health effects due to wind turbines, which is something that is recommended for future research. The risk is therefore evaluated as uncertain.

11.2 Safety hazards

Multiple safety hazards have been identified in the hazard identification. The ones that are not mitigated by design are further discussed in this section.

11.2.1 Dropped objects

The results of the HAZID have shown that a major hazard that has been identified concerning placing a wind turbine on an FPSO is related to the potential of having dropped objects (wind turbine parts). These dropped objects can either drop onto the FPSO or into the sea, depending on their trajectory. This possibly damages the FPSO, its equipment, or any sub-sea equipment, risers, or mooring lines.

Wind turbine failures

Several wind turbine failures can result in the hazard of a dropped object scenario. These are a blade throw, a tower collapse, or a dropped rotor. According to Bakhshi et al. [102], wind turbine failures are not always registered in publicly available databases, which makes it difficult to determine the exact failure rates. Nevertheless, the RIVM conducted a study in which the failure probability of these events is determined for onshore wind turbines between 1 and 5MW, with a 95% reliability percentile [103]. The results are shown in table 11.1.

Event	Failure probability 95% reliability percentile
Blade throw	$8.4 \cdot 10^{-4}$
Tower collapse	$1.3 \cdot 10^{-4}$
Dropped rotor	$4.0 \cdot 10^{-5}$

Table 11.1: 1-5MW wind turbine events failure probabilities per turbine per year [103].

Since these probabilities are determined for onshore wind turbines, it can also give some insight into bottom-founded offshore wind turbines. Nevertheless, it is more difficult to transfer this to suitable numbers for offshore floating wind turbines, where the turbine experiences more motions compared to onshore or bottom-founded. However, it does provide some insight into the reliability of wind turbines in general.

In the case of a wind turbine on an FPSO, the above probabilities do not provide the full picture of events resulting in wind turbine parts dropping onto or near the FPSO. These are namely the probabilities for the wind turbine on itself. On an FPSO, there can also occur other events, such as a helicopter collision, with their probability of occurrence, resulting in damage to the wind turbine, which again results in dropped wind turbine parts. This makes it difficult to estimate the exact failure probabilities for dropped objects in this new configuration. However, it can be assumed that the failure probabilities will be somewhat higher than the values from table 11.1, due to the influence of the other factors present on an FPSO.

To prevent these failures from occurring, structural health monitoring can be applied. This can be done both by visual inspection and by installing sensors onto the wind turbine. This is to make sure that any issue is found and action can be undertaken in the form of maintenance or replacements before any large failure event occurs.

Dropped objects: accidental limit state

The scenario of dropped objects classically belongs to the category of accidental limit states. Most dropped objects until now have been assessed according to this limit state. On FPSOs this limit state usually contains the risk of having dropped objects during crane operations, which are accidents. According to DNV [104] the load created by dropped objects is characterized by the kinetic energy of the dropped object, where the mass and velocity of the object are the governing parameters.

The kinetic energy can be described with formula 11.1:

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 \tag{11.1}$$

, where m is the mass of the dropped object and v is the velocity at the moment of impact, which can also be described by formula 11.2 for objects falling straight down in the air:

$$v = \sqrt{2 \cdot g \cdot h} \tag{11.2}$$

, where g is the gravitational constant of 9.81 m/s^2 and h is the height from which the object is dropped. Together this can be rewritten to formula 11.3:

$$E = m \cdot g \cdot h \tag{11.3}$$

In the case of dropped objects into the sea, the hydrodynamic added mass of the considered motion of the object has to be added to the mass of the object. Furthermore, the formulas are the same. With this method of impact assessment the details in shape, volume, and material properties of an object are not taken into consideration.

It should be noted that the evaluation method using the impact energy is part of the accidental limit state for an FPSO, whereas for the wind turbine the event of a structural failure of the wind turbine leading to dropped parts does not belong within this limit state. This event better fits within the ultimate limit state or fatigue limit state. From these limit states the wind turbine design should be able to withstand all loads so that the event of a dropped wind turbine object will never occur. This, therefore, has to be checked under the new loads that the wind turbine experiences in this new configuration. For the FPSO, dropped object impact creates an accidental load to the FPSO. The impact of dropped wind turbine parts is assessed according to the accidental limit state, to provide insight into the consequences in case an event such as a dropped wind turbine part would occur.

Impact energy of dropped wind turbine parts onto FPSO

According to formula 11.3, the impact energy in the case of dropped objects onto the FPSO has been calculated for different wind turbine parts falling straight down from a static position. Here blade parts are taken into consideration, as well as the entire hub. For this calculation, it is assumed that the weight of the blade is equally distributed over its length. A few different drop heights are taken into consideration since blade parts can drop from different heights depending on the position of the blade within the rotor plane. The results of this calculation are shown in table 11.2.

		Drop height		
Item	Weight [tonne] [23]	60 m	90 m	120 m
1/4 blade	4.44	2.6	3.9	5.2
1/2 blade	8.87	5.2	7.8	10.4
3/4 blade	13.31	7.8	11.7	15.7
full blade	17.74	10.4	15.7	20.9

Table 11.2: Impact energy [MJ] of dropped wind turbine blade parts on FPSO.

In the case of an operational wind turbine not only the gravitational energy is important, but also the kinetic energy due to the rotation of the blades. Depending on the rotational velocity, the energy from this rotation can be added to the gravitational energy, leading to even higher impact energies. Nevertheless, the trajectory of the blades will become important in this case, which can go up to several hundreds of meters in different directions [105].

Within Bluewater, earlier dropped object impact studies have taken into consideration objects and drop heights leading to maximum impact energy of 491 kJ, which occurred due to a 10 tons container dropping from 5 meters height [106][24]. Comparing this to the results of the dropping blades, it shows that even the smallest value of 2.6 MJ is already 5.3 times as large as the 491 kJ of the container. This impact energy is so much larger due to the large drop height of the wind turbine blade part in comparison to the container. The impact angle of the blade also influences the eventual impact on the FPSO. In case of a small contact area between the blade part and FPSO, for example, when it drops on the blade tip first, this energy needs to be absorbed in this small contact area, whereas a different drop angle can spread the impact energy over a larger area on the FPSO.

Besides the fact that the impact energy due to dropped wind turbine parts would be much higher than any existing hazardous impact energies taken into consideration, Thapa [107] considers that all impact energies higher than 500 kJ, would lead to so much damage that the equipment would need to be fully replaced. Knowing both the limit by Thapa and the comparison with existing impact energies, it can be concluded that in the case of dropped wind turbine parts onto the FPSO the FPSO experiences significant damage. Based on the impact angle of the blade, this might even be catastrophic.

11.2.2 Turbulent wind: walking on deck

The presence of the wind turbine influences the wind profile behind the wind turbine. The wind speed decreases downstream of the wind turbine, but the turbulence increases. This is also known as the wake effect. In the hazard identification, it is identified that the wake effects might be a danger to people walking on the FPSO deck.

Figure 11.1 shows the mean and standard deviation of the wind speed over the height of a wind turbine, for wind in front of the turbine, and behind the turbine for different wake distances. A near wake means approximately 1 rotor diameter (D) away from the turbine, and a far wake is more than approximately 5D. The intermediate wake length lies between 1D and 5D. As can be seen from figure 11.1 the wind speed is affected over a larger height of the wind turbine the further away behind the turbine. Most influence is observed around the RNA height, and only a little influence is close to the tower base. A larger standard deviation indicates the presence of more turbulence.

The near wake is important to what happens on the FPSO deck behind the turbine. Here the turbulence occurs at the blade tips of the turbine. At the base of the tower, the wind speed profile is unaffected. However, this wind profile is valid for a fixed wind turbine. For a floating wind turbine, the turbine will experience more motions, which might cause larger variability of the wind speed behind the turbine over the height of the structure. There is a distance of 43.5 meters between the lowest blade tip position and the deck. Therefore the expectation is that the effect of the wind turbine on the wind experienced on the deck level remains small. As an additional safety measure, the use of lifelines can be implemented when walking on the deck behind the wind turbine.

[23] Weights obtained from Jonkman et al. [47]

[24] Reference coming from Bluewater's Intranet database (not publicly accessible).

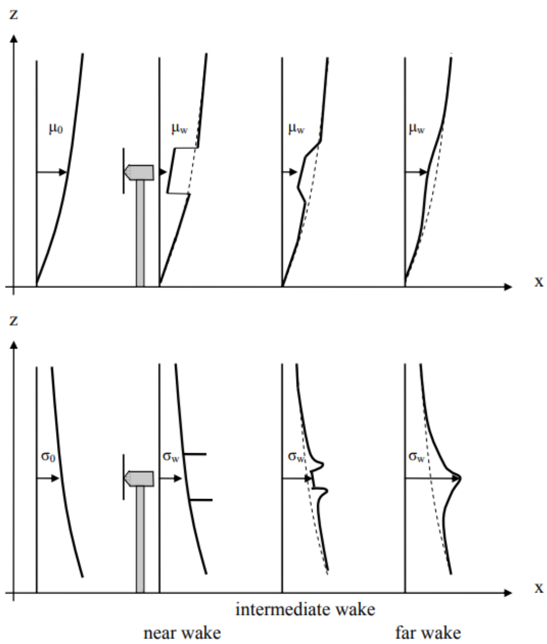


Figure 11.1: Mean (μ) and standard deviation (σ) of wind speed near a wind turbine [108].

11.2.3 Telecommunication disturbance

A somewhat more in-direct hazard that has been identified is the interference of the wind turbine with the telecommunication systems on the FPSO. These systems are used for both navigation and communication. This hazard does not directly impose a dangerous situation but can be very critical for overall safety in case of other hazardous events occur on the FPSO. Besides, in case of occurrence frequently, it is something that could disturb the operations of the FPSO.

Research has been conducted on the effects that a wind farm has on electromagnetic signals. The wind turbine produces an electromagnetic field (EMF). However, according to McCallum et al. [109] background levels of the EMF are already reached at 2 meters from the base of the wind turbine, concluding that exposure to a wind turbine's EMF is not more than any common household equipment. On top of that, shielding and earthing techniques can be applied to reduce the effect of an EMF on the workability of the equipment.

Besides the EMF, a wind turbine structure can (partially) block signals and also cause a frequency shift of the signal due to the Doppler effect occurring due to the rotation of the blades [110]. This impact is already much less for modern-day wind turbines compared to older generations, due to the use of synthetic materials for the blades instead of metal [111]. However these effects have been observed in the case of entire wind farms, it is not yet clear how much interference just a single wind turbine close to telecommunication systems can give. Nevertheless, mitigations are sometimes as easy as placing different devices just a little different with respect to each other.

11.2.4 Fire

The hazard of a wind turbine on fire can lead to many other hazards, such as dropped objects. Fire can occur from different events, for example, a lightning strike, an electrical failure, or a mechanical failure. The hazard of the flare flame setting the wind turbine on fire is already mitigated by the chosen wind turbine placement with respect to the flare tower as described in chapter 8. The challenge with fire is extinguishing, which is difficult at the large hub height.

Similar to the wind turbine failure events in the dropped objects hazard, Uadiale et al. [112] conclude that wind turbine fire statistics are poorly registered. Scotland Against Spin (SAS) reported a total of 177 wind turbine accidents in 2021, of which 21 were related to fire (± 12%), acknowledging the fact that their data only presents the 'tip of the iceberg' [113].

Important are the mitigations that can be done to prevent a fire. Often a distinguishment is made between passive and active fire protection for wind turbines. Passive fire protection includes using lightning protection systems, non-combustible oils, fire barriers within the nacelle, and applying condition monitoring systems [112]. Active protection is making use of several different methods of fire detection systems [114]. In the field of fire extinguishing for wind turbines, there is still room for a lot of development. In the end, concepts such as firefighting drones [115] might become reality.

11.2.5 Helicopter crash

As explained in section 9.6, helicopter operations from and towards an FPSO are a necessity for the transport and delivery of personnel and required supplies. For the Haewene Brim specifically, helicopter operations normally take place twice a week. The safety of the helicopter's passengers is very important, and therefore strict procedures are in place to prevent accidents involving the helicopter. Within the offshore industry between 2014 and 2018 the 5-year fatal accident rate is 3.8 fatal accidents per million flight hours [116]. Already some experience is gained in helicopters flying near wind turbines for the transport of the wind turbine's maintenance crew. In that case, the helicopter comes closer to the wind turbine than the helicopter operations taking place for FPSO crew transport. To reduce the danger, as described in section 9.6, a possible mitigation is to shut down the wind turbine in case helicopter operations take place.

11.2.6 Maintenance operations: climbing at height

One of the identified hazards occurs when personnel climbing the wind turbine performing maintenance at height. The hazard of falling is present in this case, possibly leading to fatality. A wind turbine needs maintenance approximately 4 to 6 times per year. This requires the crew to operate inside or on top of the wind turbine with the risk of falling. Several mitigations can be performed to maintain a safe as possible situation, such as the use of experienced (certified) climbers, and lifelines and only performing maintenance during allowable good weather conditions, to reduce the chance of error. Visual inspections are also a part of maintenance. A choice can be made to use drones, instead of humans to evaluate the status of the wind turbine visually.

11.2.7 Wind turbine full control system failure

A concern identified during the hazard identification is a full control system failure of the wind turbine resulting in an out-of-control spinning rotor. For this to occur, many different systems in the wind turbine would have to fail at the same time, which is a very unlikely event that has rarely occurred in the wind turbine industry. A wind turbine control system consists of different in-built security measures, such as many different types of sensors measuring the performance, duplicate systems so that in case one fails another can take over, blade-tip brakes, mechanical brake, and a backup generator [117]. In the case of a wind turbine on an FPSO, there is another benefit that is normally not the case for wind turbines, which is that there are always people nearby who also visually can estimate the wind turbine's behavior. In case of doubt, early actions can be undertaken to prevent further failure.

11.2.8 Lightning

Lightning is considered a safety hazard due to the danger and damage it can cause to both wind turbine and FPSO. The amount of lightning occurring can differ significantly per location in the world. For Europe, it is estimated that the number of wind turbines that experience damage from lightning lies between 4% and 8% [118]. Due to the use of wind turbine lightning protection systems, the impact that lightning can have on the wind turbine can be reduced. Several methods of lightning protection can be combined, such as detection, external lightning protection, and internal lightning protection, which conducts the lightning impact from the blade tip to the bottom of the tower. In the end, the design should at least fulfill the requirements described in the code by the International Electrotechnical Commission, IEC 61400-24: Lightning protection [119]. It might even be necessary to increase the amount of lightning protection due to the position of the wind turbine on the FPSO, which is continuously close to people on a remote platform, which is an unusual setting for wind turbines. At least, the lightning should be conducted further than just the bottom of the tower to for example the hull of the FPSO.

11.3 Environmental hazards

In HSE, the topic of environment considers risks in which harm to the environment is caused by one of the project's components. In the hazard identification of chapter 6, no new hazards that could harm the environment have been identified besides already existing hazards on an FPSO, such as a hydrocarbon leak into the sea. Only additional causes for this event are present in the form of a wind turbine dropped object, slightly increasing the risk's probability. However, the impact of a hydrocarbon leak remains the same on the environment independent of the wind turbine's presence.

Another wind turbine-related environmental risk which has not been part of the hazard identification is bird killings. However, this can also occur when the wind turbine is placed separately from an FPSO, which is also accepted in those cases. No significant new environmental risks are further identified in the configuration of a wind turbine on top of FPSO, compared to a wind turbine and FPSO separately. Therefore they are not included in the risk evaluation of section 11.4.

11.4 Risk evaluation

The described hazards are evaluated as risks by their impact and probability, as described by equation 11.4. A qualitative risk assessment method is used for this, where the levels of risk, probability, and impact are described in an HSE risk matrix shown in figure 11.2. A green risk level indicates a low risk, yellow a medium risk, orange a high risk, and red an extreme risk.

$$Risk = Probability \cdot Impact \tag{11.4}$$

IMPACT		Severity	1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
		People	Slight Injury	Minor Injury	Major Injury	Single Fatality	Multiple Fatalities
		Asset	Slight Damage	Minor Damage	Local Damage	Major Damage	Extensive Damage
		Environment	Slight Impact	Minor Impact	Localized Impact	Major Impact	Massive Impact
		Reputation	Slight Impact	Limited Impact	Considerable Impact	Major National Impact	Major International Impact
LIKELIHOOD	E Almost Certain	Happens several times per year at location	E1	E2	E3	E4	E5
	D Likely	Happens several times per year in company	D1	D2	D3	D4	D5
	C Possible	Incident has occurred in our company	C1	C2	C3	C4	C5
	B Unlikely	Heard of incident in industry	B1	B2	B3	B4	B5
	A Remotely likely to happen	Never heard of in industry	A1	A2	A3	A4	A5

Figure 11.2: HSE risk matrix [120].

The resulting risk evaluation is shown in table 11.3. This evaluation represents an interpretation of the described risks, and what effect possible risk mitigations can have. In the end, low risk does not necessarily indicate that no effort is required. For each risk, continuous risk management has to be performed, to consistently manage and reduce the risk according to the ALARP principle. The table shows the potential of the health risks being acceptable under sufficient mitigations. Next to this, it shows the need for attention when it comes to the safety of the project.

Risk category	Risk	Brief description	Risk level	Mitigation	Risk level
Health	Noise	Noise levels affecting the health of personnel.	D3	Existing/additional hearing protection, sound-proof rooms.	C2
	Stroboscopic effects	Shadow flicker causes seizure or annoyance.	C3	Evaluation of personnel on photosensitive epilepsy.	C1
	Mental health effects	The mental health effects in this new setting are very uncertain.	Uncertain	Future research.	Uncertain
Safety	Dropped objects	Blade throw, Tower collapse, Dropped rotor	B5	Structural health monitoring, both visual & use of sensors.	A5
	Turbulent wind: walking on deck	Danger for people walking on deck behind the turbine	C3	Use of lifelines.	B2
	Telecommunication interference	Telecommunication systems not available.	C3	Earthing & shielding. Relative positioning.	B3
	Fire	Wind turbine on fire due to failure/lightning.	B5	Active and passive fire protection measures.	A5
	Helicopter crash	Helicopter crashing into wind turbine due to man-made mistake.	B5	Optional: Shutdown wind turbine.	B5
	Maintenance operations: climbing at height	Risk of maintenance personnel falling.	C4	Experienced climbers, drones, good weather, lifelines.	B4
	Wind turbine control system failure.	Uncontrollable wind turbine causing danger/damage to surroundings.	B5	No other than existing control system built-in securities.	A5
	Lightning	Lightning causes damage to wind turbine, leading to escalation on FPSO	D5	Application of wind turbine lightning protective systems.	D3/D4

Table 11.3: HSE risk evaluation.

12 Business case

A business case originates from different incentives. Placing a 5 MW wind turbine on top of an FPSO is based on two different incentives. First of all, reducing emissions of the FPSO. Second, a financial benefit. Due to the power that the wind turbine produces, less fuel is used to power the conventional engines on the FPSO. This saves fuel costs and reduces emissions. These two incentives are further explained in the following sections as part of the business case. At the end of this chapter, it is described how several technical choices can impact the business case.

12.1 Emission reduction

The use of a wind turbine to power (part) of an FPSO reduces emissions. This emission reduction can contribute to obtaining a 'green' FPSO. The amount of emission reduction depends mostly on 2 factors. First of all, the amount of power that the wind turbine will produce. Second, the original method of power production which leads to a certain amount of emissions. With this information, an estimation is made of the amount of emission reduction.

The amount of power that a wind turbine produces can be estimated on a yearly basis. This is done by calculating the Annual Energy Production (AEP) of the wind turbine in a single year. The AEP can be calculated according to equation 12.1.

$$AEP\ [\frac{MWh}{y}] = P_{rated}\ [MW] \cdot T_y\ [\frac{h}{y}] \cdot cf \cdot EAF \tag{12.1}$$

Here, P_{rated} is the rated power capacity of the wind turbine, T_y is the number of hours in a year, cf is the wind turbine's capacity factor, and EAF is the wind turbine Equivalent Availability Factor. The associated values of these parameters are:

- The rated power capacity of the wind turbine is 5 MW.
- The capacity factor is 0.4616 (46.16%) [121].
- The equivalent availability factor (EAF) is assumed to be 95%.

The given values above result in an AEP of 19207.18 MWh per year. The amount of emissions that will be reduced is the amount of emissions that are released by generating 19207.18 MWh per year by using the conventional methods of power production. The emission reduction is largest when FPSOs are powered by diesel engines, which is the case for the Haewene Brim. The fuel that is used to power these diesel engines is Marine Gas Oil (MGO), which is similar to diesel. To determine the amount of emissions, the following parameters are determined:

- The diesel engine has an efficiency of 40% [122].
- The energy content of MGO is 43 MJ/kg [123].
- The density of MGO is 860 kg/m^3 [124].
- Per liter MGO there is 2.64 kg CO2 emitted [125].

For a diesel engine running on MGO the fuel consumption of the engine to generate a single MWh of electricity can be determined with equation 12.2. The total fuel consumption that is saved per year is determined by multiplying this fuel consumption per MWh with the wind turbine's AEP which is shown in equation 12.3. With equation 12.4 it is determined how many liters of MGO would be consumed per year. From this, equation 12.5 is used to calculate the total amount of CO2 emissions that is saved per year. This is equal to 12340.8 tonnes. This would mean that over a lifetime of 20 years, which is typical for a wind turbine [49], almost 250,000 tonnes of CO2 emission are reduced.

$$Fuel\ consumption\ [\frac{kg}{MWh}] = \frac{1}{Engine\ efficiency\ [\%]/100} \cdot \frac{3600\ [\frac{MJ}{MWh}]}{Energy\ content\ [\frac{MJ}{kg}]} \tag{12.2}$$

$$Fuel\ consumption\ [\frac{kg}{y}] = Fuel\ consumption\ [\frac{kg}{MWh}]\ \cdot AEP\ [\frac{MWh}{y}] \tag{12.3}$$

$$Fuel\ consumption\ [\frac{l}{y}] = Fuel\ consumption\ [\frac{kg}{y}]\ \div Density\ MGO\ [\frac{kg}{m^3}] \cdot 1000\ [\frac{l}{m^3}] \tag{12.4}$$

$$Total\ CO2\ emissions\ [\frac{tonne}{y}] = CO2\ emission\ [\frac{kg}{l\ MGO}]\ \cdot\ Fuel\ consumption\ [\frac{l}{y}] \div 1000\ [\frac{kg}{tonne}] \tag{12.5}$$

12.2 Financial

The financial incentive comes from the fuel cost savings that are a result of power production by the wind turbine. However, the exact profit that can be made depends on many different parameters. An estimate of the financials of this project is shown in this section. First of all, a base case is explained, after which the sensitivity of several different parameters is discussed.

12.2.1 Base case

The base case provides an overview of the estimated costs and revenue for this project. The costs of this project can be split into capital expenditures (CAPEX), made at the start of the project, and operational expenditures (OPEX) made throughout the entire lifetime of the project.

Revenue

The revenue retrieved in this project is not money that is earned, but expenditures that are saved. These saved expenditures originate from two different cost items. First of all the costs saved to buy the fuel. Second, the costs that are made because of CO2 emissions due to a form of carbon tax or credits.

With equation 12.3 from section 12.1 the total amount of fuel consumption per year has been determined, which is equal to 4020.11 tonnes per year. Also, the total amount of emission is calculated as 12340.8 tonnes per year. The costs for fuel and CO2 emissions are estimated using the following prices:

- The fuel price of MGO is \$1000,- per tonne which is approximately equal to €1020,- per tonne of MGO[25] [126].
- The fuel price is increased by 15% to account for additional costs of needing the fuel offshore at the FPSO site, resulting in a price of €1173,- per tonne of MGO.
- The CO2 price is €69,60 per tonne of CO2 emission[26] [127].

With this, the yearly savings can be estimated by multiplication of the amount of fuel and CO2 emissions, by the fuel and emission price per tonne respectively. In total, this results in a yearly savings of €5.58 million.

[25] At the time of writing \$1,- was equal to €1.02

[26] At the time of writing £1,- was equal to €1.12

Costs

The costs of the project are split into CAPEX and OPEX. The CAPEX are costs that are made at the start of a project (in year 0). The CAPEX depends on many different components. An overview of several large cost items included in the CAPEX is given in figure 12.1.

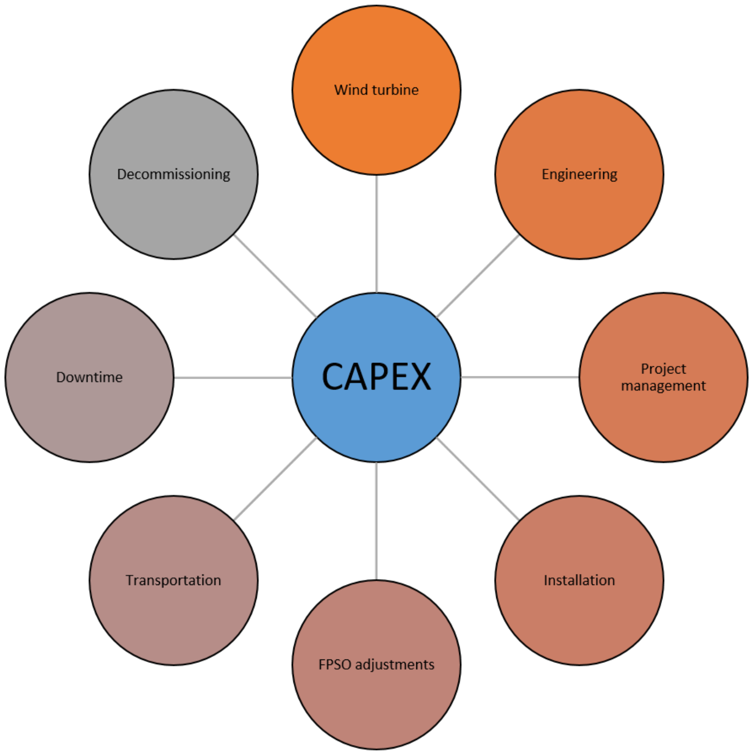


Figure 12.1: Items included in CAPEX.

The wind turbine costs can be estimated based on historical data. A newly built wind turbine costs approximately $1.3 million per MW installed capacity. So for a 5 MW wind turbine, this results in €6.63 million [128]. Other components in the CAPEX are more difficult to estimate, due to many different uncertainties that are still present for this project. These are:

- For engineering a new challenge occurs in which a detailed structural interface has to be designed. Also, several adjustments might have to be designed for the FPSO. The costs of this engineering process are highly dependent on the time that this will take. Normally for wind turbines, the engineering can be generalized for placing many different wind turbines in a farm. In this case, each FPSO has its specific layout and therefore the engineering is a unique challenge for each FPSO over and over again.

- For project management this project is unlike any other wind turbine project that has been built so far. This brings the challenge of managing all the new occurring risks, in which time again plays an important role to determine the eventual costs for this item.

- Installation is also a completely new challenge. Several questions are yet to be answered for this topic. Will the wind turbine be installed offshore, or in the dry dock? What lifting equipment will be used? How long will it take to install? This needs to be determined before any reasonable cost estimate can be made.

- The adjustments that need to be made to the FPSO follow from the engineering. The exact adjustments are yet to be determined. A larger adjustment will give higher costs. For the structural interface itself, it is therefore recommended to design it with the least adjustments to the FPSO, to save costs for this item. For the different design configurations as explained in chapter 8, it is required to make more changes to the FPSO in case of wind turbine placement on the FPSO's center line, which is likely to result in higher costs.

- The costs of transportation depend highly on the chosen installation. Installation offshore requires offshore transportation, which is likely to bring more costs compared to onshore transportation of wind turbine components.

- The downtime the FPSO experiences also generates cost or 'lost revenue'. Depending on the method of installation this downtime can be long or short. Recommended is that in case of dry-dock installation, the installation is performed during already scheduled maintenance in dry-dock for other FPSO components. This is to reduce the additional downtime significantly.

- Decommissioning costs occur at the end of the project when the wind turbine needs to be removed. A choice can be made to attempt to increase its lifetime by performing more maintenance, or the wind turbine can be replaced by a new one. But at some point, decommissioning becomes a necessity, bringing up costs for equipment that can remove the wind turbine and transport of the removed parts.

Because of the many remaining uncertainties on the CAPEX, it is difficult to estimate the exact costs for the CAPEX of this project. The expectation is that the costs of this project are less than the costs for a floating wind turbine since costs for floating sub-structure, mooring, and power cable are saved. Nevertheless, costs for FPSO adjustments and downtime are not included in the costs of a floating wind turbine. Because of this uncertainty, the next part evaluates at what value of CAPEX the project reaches break-even.

Besides the CAPEX there is also the OPEX. The OPEX are costs made each year throughout the lifetime of the project. In this case, the OPEX is fully determined by the wind turbine's operation and maintenance (O&M) costs. For an offshore wind turbine, these costs have been estimated as £75,000 per MW installed capacity per year [129]. This results in an OPEX of €420,000 per year.

Net present value and break-even

In this section, the CAPEX is determined for which the project would reach break-even. Break-even is the moment when a project makes neither profit nor loss. Break-even is reached when the net present value (NPV) of the project is equal to zero. The NPV is the discounted cash flow from which the CAPEX is subtracted as shown in equation 12.6.

$$NPV = \sum \frac{Cash\ flow_t}{(1+r)^t} - CAPEX \tag{12.6}$$

Here r is the discount rate, assumed to be equal to 5%, and t is the year going from 1 to 20. In case the NPV is equal to zero, it is obtained that the CAPEX is equal to the discounted cash flow of the 20 consecutive years after investment. The cash flow per year is determined with equation 12.7. This results in a cash flow of €5.16 million per year.

$$Cash\ flow = Revenue - OPEX \tag{12.7}$$

The discounted cash flow of years 1 till 20 is determined according to its term in equation 12.6. The resulting discounted cash flow per year is shown in figure 12.2.
The CAPEX for an NPV of zero is equal to the sum of the discounted cash flows of all 20 years. This is equal to approximately €64.3 million. Table 12.1 gives an overview of the expected return based on a CAPEX deviation of the value at break-even.

CAPEX (million €)	NPV (million €)	Return
< 64.3	> 0	Profit
$= 64.3$	$= 0$	Break-even
> 64.3	< 0	Loss

Table 12.1: Overview of CAPEX, NPV, and expected return.

Return on investment

The return can be expressed as a return on investment (ROI). A positive ROI indicates that the benefit gained from the investment is larger than the initial cost of the investment. The ROI is calculated with equation 12.8.

$$ROI = \frac{Return\ (Benefit)}{Investment\ (Cost)} = \frac{NPV}{CAPEX + \frac{OPEX}{(1+r)^t}} \tag{12.8}$$

For different values of CAPEX, the ROI is plotted, which is shown in figure 12.3. From the figure can be seen that a positive return on investment can be made if the CAPEX is less than its value at the break-even point, €64.3 million. A CAPEX of €29.5 million or smaller results in an ROI of 100% or larger. Based on the wind turbine costs and the wanted return, it can be determined what the other components of the CAPEX are allowed to cost in total.

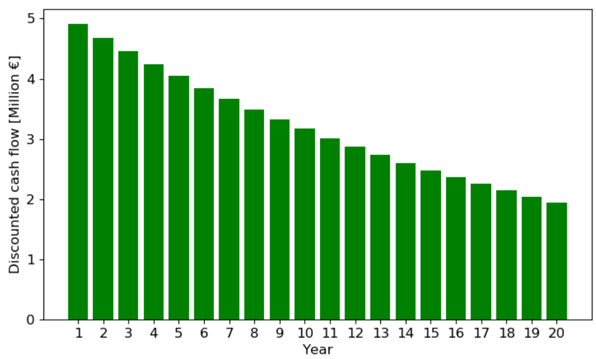


Figure 12.2: Discounted cash flow during a lifetime of 20 years.

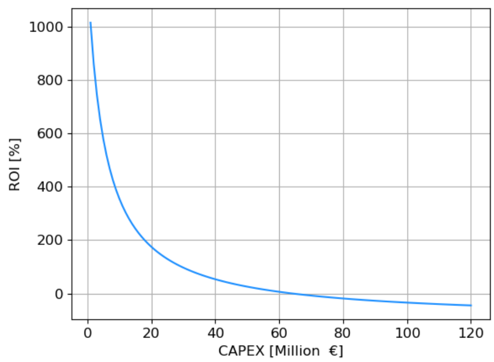


Figure 12.3: Return on investment for different values of CAPEX.

12.2.2 Sensitivity

A sensitivity calculation is performed to identify to which parameters the net present value of the project is most sensitive. The parameters that are evaluated are the CAPEX, OPEX, AEP, fuel price, CO2 price, and discount rate. Each base case value has been decreased and increased with a range of -80% to 80% of its initial base case value. For the CAPEX the initial value that is taken is its break-even value. The result is shown in figure 12.4.

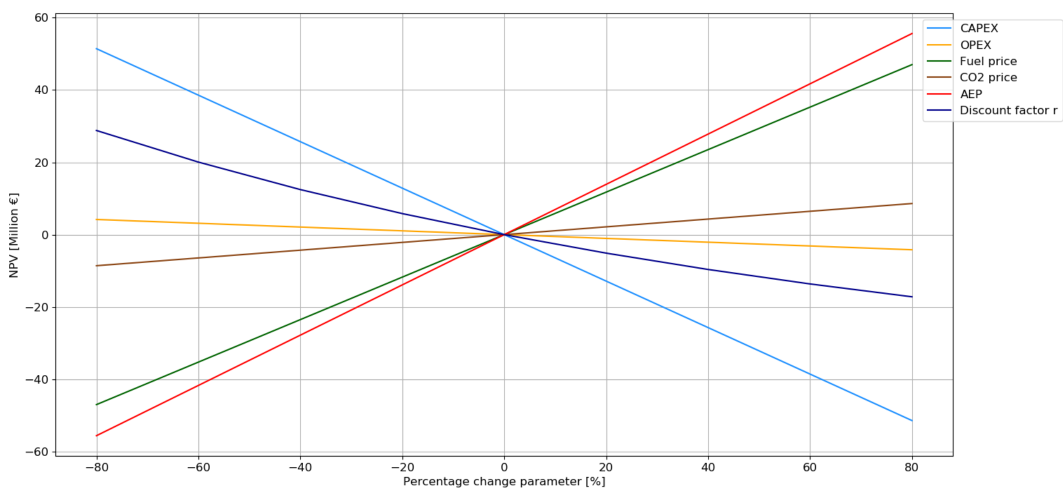


Figure 12.4: Sensitivity of several parameters on NPV.

From figure 12.4 it can be observed to which parameter the NPV is most sensitive. The steepest slope in the curve is the parameter to which the NPV is most sensitive. The least steep parameter is the one to which the NPV is least sensitive. It is therefore observed that the NPV is most sensitive to a change in AEP, followed by CAPEX, fuel price, discount rate, and CO2 price, and least sensitive to OPEX.

12.3 Impact of operational choices on business case

Throughout the report, several choices have been discussed that affect the operations of either FPSO or wind turbine. The choices can affect the business case of the project. How each choice affects the business case is explained in the items below.

- One of the items is the detailed design of the structural interface between the wind turbine and FPSO as discussed in section 8.1.5. This requires most of the engineering work and therefore influences the CAPEX of the business case. Also as part of the CAPEX, the eventual design determines the costs for FPSO adjustments. As was observed the CAPEX was one of the parameters to which the business case experienced high sensitivity.

- Another decision that can be made is whether the yaw angle of the wind turbine RNA will be limited. In the suggested configurations it is not a necessity based on the space, as is explained in section 8.1.6. However, it was observed that vessel stability gives the challenge of working under an angle (heel of the vessel). A limit for the wind turbine's yaw will negatively influence the availability (EAF) of the wind turbine, and therefore lower the amount of power produced (AEP). The more the yaw is limited, the larger its negative effect becomes on the business case financials. This will also cause fewer emissions to be saved since more power has to be produced by conventional fuels.

- From the vessel's stability and strength assessment (sections 9.2 and 9.3) it was found that the in case of the vessel in Fully Loaded condition, the vessel would be too heavy. A possible solution is to reduce the amount of liquid cargo in that case, reducing the vessel's maximum liquid cargo capacity. As explained in section 9.2 it is expected that this reduction is only 1.04% of the vessel's deadweight approximately, for the vessel in its Fully Loaded condition. Nevertheless, in the long term, in case the vessel would keep the same production rate, this would lead to the need for somewhat more frequent offloading, which slightly increases the OPEX of the FPSO operations.

- As a result of the motion analysis (section 9.5 it was observed that the nacelle acceleration was too high in several loading conditions. A mitigation for this is the suggestion of shutting down the turbine. The exact operability window for this would have to be further researched. A wind turbine shutdown might also be necessary during several particular FPSO operations as explained in section 9.6. Nevertheless, shutting down the wind turbine more frequently compared to how it normally shuts down based on its power curve, reduces the EAF of the wind turbine. Similar to the case of yaw limitation, this lowers the AEP and therefore negatively influences the business case the more shutdowns take place.

- From the motion analysis it was also suggested to increase the bending stiffness of the tower or to reduce the tower's height, to reduce the nacelle's acceleration. An increase in the bending stiffness of the tower requires a larger wall thickness and therefore more material, increasing the costs (CAPEX). Opposite, lowering the tower's height again reduces the amount of material needed for the tower, saving costs in the project's CAPEX.

- Shutting down the wind turbine more frequently might also affect the wind turbines performance as discussed in section 9.6.2. This possibly requires more maintenance, increasing the OPEX of the business case. More maintenance means also more wind turbine downtime, so a lower AEP. Possibly also the lifetime of the wind turbine is affected. In case the lifetime would reduce due to this, there is less 'revenue' (cost savings) to cover the initial expenses.

Discussion

In this chapter a discussion is provided in which there is reflected upon the performed work. It consists of a summary of the findings in the report, a reflection on the performed literature research, and it describes several limitations of the research.

Summary of findings

The results of this research have described several showstoppers and possible mitigations that eventually determine the feasibility of the project. The findings are described in relation to the sub-questions of the research.

1. How can feasibility be described and assessed?

The terms 'feasibility' and 'feasibility study' are found to be broad terms that are widely used for different purposes. In chapter 7 the definition of feasibility within this research is defined as: "something can be considered feasible when it is technically achievable, follows the health, safety, and environmental guidelines, and is financially attractive." These three components form the fundamentals for the assessment of feasibility in this research. However, the importance of other non-technical topics is also recognized and is therefore briefly included in the research. The assessment can be performed by identifying the possible strengths and weaknesses of the project.

2. What will be the wind turbine characteristics of the chosen turbine?

In chapter 5 the decision for a 3-bladed 5 MW Horizontal-Axis Wind Turbine (HAWT) is explained. As a reference wind turbine, the NREL 5 MW is introduced. This wind turbine is a commonly used model to represent 5 MW wind turbines. This wind turbine has a rotor diameter of 126 meters, a top mass of 350 tons, and reaches its rated power at a wind speed of 11.4 m/s at hub height. An overview of the full specifications is given in section 5.5. The tower height is increased to 105 meters with respect to the default model, to have sufficient clearance when positioned on the FPSO.

3. What determines the placement of a wind turbine on an FPSO and is it possible to place a wind turbine on existing FPSOs?

As part of the literature research, a hazard identification is performed in which several hazards have been identified in chapter 6. From the findings in the hazard identification, a first design concept is created which is shown in chapter 8. Here the preference is given for a particular FPSO layout, namely with the helideck at the forward and the flare tower at the aft of the vessel. With this layout, the Haewene Brim is identified as a reference FPSO, on which the wind turbine is positioned at approximately the middle of the vessel, on top of a bulkhead, with different options on its transverse position on the vessel. Here space is available in both transverse directions 13 meters from the vessel's center line. For the motions it is expected that placement on the center line is ideal, to reduce the effect of the wind turbine's weight on the center line on the vessel's roll moment. In each case, sufficient clearance is provided between the wind turbine and the cranes on the FPSO.

4. What are the technical limitations that can impact the project's feasibility?

The design concept is evaluated first on several technical aspects in chapter 9. The vessel's stability and strength are evaluated against several existing limits for the Haewene Brim in particular. Here it is identified that the vessel's intact stability and strength are sufficient, but for the vessel in its fully loaded condition, the vessel would be too heavy, so a weight reduction of for example some liquid cargo would be a necessity. It is expected that this reduction is only 1.04% of the vessel's deadweight approximately, for the vessel in its Fully Loaded condition. Besides this, the possible issue of vibrations is explained and a motion analysis in OrcaFlex is performed. This motion analysis used input from a diffraction analysis in HydroStar.

The OrcaFlex model consists of the FPSO model attached to a soft-mooring system. For comparison, the FPSO was modeled including and excluding the 5 MW wind turbine. Two methods of vessel modeling in OrcaFlex have been compared. One method uses displacement RAOs, and the other method uses 1^{st} order wave load RAOs, and frequency-dependent added mass and damping. It was experienced that the second method was significantly reducing the computational time of the model simulations in the time domain, allowing for an implicit solver over an explicit solver.

From the motion analysis results, both the diffraction results and the OrcaFlex time domain results is observed that the presence of the wind turbine influences significantly the roll of the vessel. From the time domain analysis, low-frequency motions in surge and sway are observed, which could lead to a possible issue when it comes to the excursion limits related to the mooring system of the vessel. However, these responses are (partially) likely to be a result of modeling, representing a transient response. Besides, the motion analysis identifies the wind turbine to be the limiting factor over the vessel, due to excessive nacelle accelerations under several environmental loading conditions, which is mostly a result of higher wind speeds. It should however be noted, that the nacelle acceleration limits are taken from a different floating wind turbine model, and that each wind turbine has different limits provided by its manufacturer.

In the operating conditions, the excessive nacelle accelerations could be reduced by shutting down the wind turbine earlier compared to its power curve. Since the occurrence of high wind speeds is low compared to lower wind speeds, the results indicate that the wind turbine can produce a significantly large amount of power for the FPSO. However, in the extreme case, the wind turbine is already shut down, which makes it impossible to use this as mitigation. This is an issue for the vessel in its Fully Loaded condition, for which no configuration meets the nacelle acceleration criteria in case of extreme environmental loading. Nevertheless, there are still several options to reduce the nacelle acceleration, such as lowering the height of the tower, or since it was shown that tower bending has a significant contribution, the stiffness of the tower can be increased. Also, this result is linked to the Haewene Brim's location, which is the Pierce Field offshore UK in the central sector of the North Sea. This location is known to be a harsh environment. A different location with less rough conditions can possibly still facilitate this concept.

The need for a wind turbine shutdown is also suggested when it comes to several operational events on the FPSO, such as crane operations, flaring, or helicopter operations. However, the effect that frequent starts/stops have on the wind turbine's performance and lifetime is something that is yet to be further evaluated.

5. What are common non-technical aspects that can impact the feasibility of this project?

Chapter 10 provides an overview of several relevant non-technical aspects. Here the importance of sufficient risk- and stakeholder management is described. On top of that, the acceptability of the project by its different stakeholders is identified as a possible showstopper. Especially, the personnel working on the FPSO can play a key role in this. Also, several alternative solutions are described, such as floating wind or solar near the FPSO. Here it is recommended to perform a comparison between different solutions based on risks and financials.

6. What are the Health, Safety, and Environmental (HSE) hazards and possible mitigations that can impact the feasibility of the project?

Chapter 11 describes in more detail several HSE-related hazards that have been identified in the hazard identification of chapter 6. The hazards are evaluated with a qualitative risk assessment method using an HSE risk matrix, based on their probability and impact. The results show that any event leading to significant damage to the wind turbine resulting in dropped objects can lead to significant damage or even catastrophes on the FPSO. However the likelihood of such events is very small, the impact is so high that it results in several considerable safety risks. Especially, when a blade's impact angle is such that the blade drops tip first for which the small contact area has to absorb the high impact energy.

Health-related risks show enough potential in their mitigations, however, there is still a lot of uncertainty due to the lack of experience in the industry on what the effect is on people that are close to a wind turbine for a longer period. Additional significant risks to the environment have not been identified in the hazard identification of chapter 6.

7. What is the business case of this project and which aspects can impact its financial attractiveness?

Chapter 12 provides insight into the business case of the project. An estimation is made of the emission reduction due to the unused fuels as a result of the wind turbine's presence, which shows the potential of reducing 250,000 tonnes of CO2 emissions during the wind turbine's lifetime.

The revenue of the project is estimated, and a description of the costs for the project is given. It is approximated that for a CAPEX below €64.3 million a positive return on investment can be made. However, a sensitivity analysis shows that this result is sensitive to several parameter changes, such as a change in the wind turbine's power production or MGO fuel price. On top of that, several effects on the business case due to choices in operations are explained to affect these sensitive parameters, possibly reducing the attractiveness of the project's business case. Most relevant here is the use of frequent start/stops of the wind turbine, reducing the power production of the wind turbine.

Reflection on literature research

In literature several studies have looked into reducing an FPSO's carbon footprint during its operations to eventually obtain a 'green' FPSO, by suggesting different methods of renewable energy use [15, 16, 17]. However, the idea of placing a wind turbine on top of an FPSO has not yet been considered, which led to many new challenges. To identify these challenges, the literature research provides several fundamentals for the feasibility study, through the choice of a particular wind turbine and the results of a hazard identification. A combination of these findings has led to a first design concept and the selection of the performed research.

The hazard identification is used with the intent to produce new literature concerning a wind turbine on top of an FPSO. However, this is a very subjective method. This can be observed by the different ways that individuals define the HAZID worksheet [53, 55, 56, 57]. Also, Crawley [53] mentioned, the success and quality of the HAZID highly depend on the experience of the HAZID team. With the selection of a large and diverse HAZID team, as indicated in appendix A, it is intended to get rid of the sensitivity to individual subjectivity for this method. However, it should be noted that the results remain an interpretation of the situation by all of the present HAZID team members.

Research limitations

FPSO in operations

A boundary condition of the research is that the research focuses on the FPSO's 'normal' day-to-day operations. These are the operations taking place when the FPSO is located at its site. This includes production, storage, offloading, and on-site maintenance. The decision for using this boundary condition has been made to achieve more in-depth content within the scope of the research.

Reference FPSO and specific offshore location

To evaluate the feasibility of placing a wind turbine on top of an FPSO two reference FPSOs have been introduced in chapter 4. From these two, the Haewene Brim is selected, based on its preferred layout. With this choice, it is intended to eliminate several identified hazards as described in chapter 8. Further technical evaluations are then based on the use of this reference FPSO. Here the FPSO characteristics and location are taken as input for multiple analyses, namely on vessel stability, vessel strength, and the system's motions, of which the motion analysis also takes input from the FPSO's specific location, the Pierce Field offshore UK. The research is limited to the use of this FPSO and its location as a reference. It is important to note, that another choice of FPSO or FPSO location, might result in yet unidentified showstoppers, or might reduce the number of showstoppers. An example could be the FPSO and wind turbine system's motions in case the FPSO would be placed in a different location with calmer water and less wind. A less rough environment is likely to reduce the nacelle's acceleration, maybe even till the point that the limits are no longer exceeded.

Wind turbine choice and design concept

Similar to the use of a reference FPSO, a decision is made for a particular wind turbine in chapter 5, and its position and properties on the FPSO as explained in chapter 8. The research is limited to an assessment of the situation based on this chosen wind turbine and position. As explained in section 7.2, the design process is an iteration of concepts and assessments, from which only the first steps have been taken in this research. The results presented are related to the chosen wind turbine and its position. A different choice in these items might result in similar or new challenges regarding feasibility. Here adjustments to the tower provide perspective for reducing the nacelle's acceleration. Options to achieve this are reducing the tower height, which will likely impose limits on several operational events such as crane operations, or increasing the stiffness of the tower, which will require a larger wall thickness that results in a heavier tower, which again can affect the stability, strength, and motions of the FPSO.

Vessel stability in damage condition

For the assessment of the vessel's stability, it is explained in section 9.2 that the validity of the criteria for the vessel's stability in damaged conditions can be questioned. This is a result of the fact that for a range of wind speeds, larger heeling moments are imposed on the vessel in case the wind turbine is in its operating condition, compared to its parked condition. Because of this, the stability evaluation is limited to the vessel in its intact condition, since for the damaged condition, a new set of criteria are likely to be a necessity due to this uncommon combination of a wind turbine on top of FPSO.

Yaw controller wind turbine

As part of the motion analysis of the wind turbine and FPSO system, an existing 5 MW wind turbine model is used, which is provided by Orcina as explained in section 9.5. A limitation of this wind turbine model is that it does not consist of a yaw control system. To prevent large misalignment between the wind turbine's orientation and the wind direction, a limit had to be imposed on the weathervaning capabilities of the FPSO. This is done by modeling a soft-mooring system connected to the FPSO, instead of a catenary mooring system. To take into account the variability of the wind turbine's orientation relative to the FPSO's orientation, the wind turbine's initial rotational position is changed throughout a set of different simulations. This way the misalignment between the wind turbine and wind direction was controlled and kept to a minimum.

Use of HSE risk matrix

In chapter 11 the HSE-related hazards are further described and evaluated using an HSE risk matrix. This approach is an overall well-known method for estimating risks based on their impact and likelihood. However, this qualitative form of risk assessment is limited in the user's interpretation of the risk and the definition and shape of the risk matrix itself. Therefore, the risk evaluation intends to provide insight into the possible risks, but not to exactly rank them from most severe to least severe risks.

Conclusion and recommendations

This chapter provides the conclusion of the research. Besides that, several recommendations for future research related to the performed work are given.

Conclusion

This report considers the option of using a wind turbine to power an FPSO's internal electricity grid, to reduce emissions during an FPSO's operational processes. Based on findings in literature research, which consists of a hazard identification in which possible critical hazards have been identified, an assessment is made of several technical and non-technical aspects of this project. For non-technical topics, additional focus is put on health, safety, and environmental aspects, and the business case of this project. The goal was to find an answer to the question:

To what extent is placing a 5 MW wind turbine on top of an FPSO feasible?

The research has identified several strengths and weaknesses in placing a 5 MW wind turbine on top of an FPSO. As a reference, Bluewater's FPSO the Haewene Brim is used in the assessments. Per the overarching topic, the conclusions are presented in this section.

Technical feasibility

- The FPSO with a 5 MW wind turbine on top shows sufficient stability according to its intact stability criteria. However, the Fully Loaded load case would consist of too much weight, resulting in an exceedance of the FPSO's summer draught. A reduction of approximately 1.04% of the vessel's deadweight can resolve this.
- The longitudinal vessel strength of the FPSO is insufficient for the vessel's Fully Loaded condition. However, this can again be resolved by a weight reduction of approximately 1.04% of the vessel's deadweight. For the vessel in Ballast condition, the vessel strength is already sufficient.
- The motions of the combined wind turbine and FPSO system generally lie within the FPSO's allowable limits for the selected operational cases and extreme cases. However, the wind turbine shows an issue by exceeding the limits for its nacelle acceleration, which was found to exceed its operational limit, which was mostly dominated by wind speed, and survival limit in different environmental conditions. In the operational cases, a proposed mitigation of wind turbine shutdown can be performed, while for the survival condition in extreme load cases, this is not an option. This results in an issue for the vessel's Fully Loaded condition, in which no configuration meets the survival criteria of nacelle acceleration under extreme environmental loading. The design concept can be further improved to reduce the nacelle's acceleration, with options such as reducing tower height and increasing the tower's bending stiffness by increasing the wall thickness. Also, this result is linked to the Haewene Brim's location, which is the Pierce Field offshore UK in the central sector of the North Sea. This location is known to be a harsh environment. A different location with less rough conditions can possibly still facilitate this concept.

Non-technical feasibility

- For non-technical feasibility risk- and stakeholder management are highlighted as important. This relates then to the acceptability of the project, in which personnel on the FPSO is identified to play a key role. On top of that, alternative solutions can cause the project to be executed or not, in case a better alternative is found.

Health, Safety, Environment

- The significant safety risks that have been identified as considerable are related to the scenario of a wind turbine's dropped objects onto the FPSO, which can occur from different causes such as fire, structural failure, or lightning. While the probability of occurrence of these events is low, the impact can be very high.

- No critical health or environmental risks that can function as a showstopper for the project's feasibility have been identified.

Business case

- The business case shows the potential of saving 250,000 tonnes of CO2 emissions during a typical wind turbine's lifetime of 20 years.

- The project shows the potential of having a positive return on investment in case the project's capital expenditures are less than €64.3 million. However, this result is found to be most sensitive to changes in, among other parameters, wind turbine power production and fuel costs. Since wind turbine shutdowns are proposed to be needed in several events, this reduces the business case attractiveness.

With the above factors identified, the conclusion to the question: 'To what extent is placing a 5 MW wind turbine on an FPSO feasible?' is as follows. In the current evaluated conditions, the exceedance of the nacelle acceleration extreme limits poses a showstopper. However, this result is location and design bound. Therefore, based on the evaluated topics, the concept can be considered feasible, in the case of a design configuration in which the wind turbine's tower height is reduced or bending stiffness is increased, or a different location is found for which this showstopper is no longer present. Further recommendations for future research are described below.

Recommendations for future research

- In the stability assessment of section 9.2 it was found that the stability criteria for the vessel in damaged condition are no longer valid due to the presence of the wind turbine. Therefore, it is recommended to establish new criteria for the vessel's damaged stability, which ensure safe operations at all time.

- Further research is recommended on the topic of vibrations. Here can be evaluated if the wind turbine damages local equipment on the FPSO, influencing the FPSO's production processes and resulting in higher maintenance costs.

- As part of the discussion the limitation of the availability of a model with a wind turbine yaw controller is explained. It is recommended to develop a controller for the wind turbine's yaw. With the availability of this controller, the motions of the combined wind turbine and FPSO can be evaluated in its turret-moored catenary mooring system, and the effect of the wind turbine's presence on the FPSO's vessel heading can be evaluated when allowing both yaw of the wind turbine and weathervaning of the FPSO. In this case, it is also recommended to further investigate the observed low-frequency motions and to take into account the current to see the combined effects and evaluate the catenary system on fatigue and extreme loads.

- In the motion analysis of section 9.5 a large fluctuation in the output forces on the wind turbine was observed. A model test is recommended to validate the simulated forces against measurement data.
- The research has identified the need for frequent start/stops of the wind turbine. The influence of this on the wind turbine's performance and lifetime is recommended for further evaluation.
- Since a showstopper was identified in the wind turbine's nacelle acceleration under extreme environmental loading, which is location bound, a recommendation is to made to evaluate the concept at different locations, ideally with less severe environmental extreme conditions. This is to reduce the effect of the environment on the nacelle's acceleration.
- The installation process of the wind turbine on the FPSO is recommended for future research. During installation, several situations occur that can bring up new safety issues. Furthermore, a question might arise: which equipment can be used and where can installation take place? Another aspect is that when a wind turbine is placed on an FPSO, it cannot easily be brought down. This might result in issues when passing bridges when moving out of harbors.
- A recommendation is to research the effect on an individual's mental health due to living and working near a wind turbine for a longer period.
- A comparison study is recommended in which this concept is compared to other alternative solutions. The main question here would be if the financials of this concept, outweigh the (safety) risks, and how this relates to the risks and financials of other renewable alternatives. As mentioned in chapter 10, a better alternative can prevent the concept of a wind turbine on top of FPSO to become reality.

References

[1] International Association of Oil & Gas Producers, "How the oil and gas industry contributes to a lower carbon future | IOGP," 3 2021. [Online]. Available: https://www.iogp.org/blog/news/how-the-oil-and-gas-industry-contributes-to-a-lower-carbon-future/

[2] International Energy Agency, "The Oil and Gas Industry in Energy Transitions – Analysis - IEA," 1 2020. [Online]. Available: https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions

[3] Bluewater, "What is an FPSO? – Bluewater." [Online]. Available: https://www.bluewater.com/fleet-operations/what-is-an-fpso/

[4] A. Muspratt, "Guide to FPSO (Floating Production Storage and Offloading) | Oil & Gas IQ," 7 2018. [Online]. Available: https://www.oilandgasiq.com/fpso-flng/articles/guide-to-floating-production-storage-and-offloading-fpso

[5] Y. Shimamura, "FPSO/FSO: State of the art," pp. 59–70, 9 2002. [Online]. Available: https://doi.org/10.1007/s007730200013

[6] Bluewater, "ESG Report," Tech. Rep., 2020.

[7] J. L. Caradonna, *Sustainability : a history*. New York :: Oxford University Press,, 2014. [Online]. Available: https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/detail.action?docID=1745809.

[8] United Nations, "Sustainability | United Nations." [Online]. Available: https://www.un.org/en/academic-impact/sustainability

[9] J. Misachi, "What Is The Difference Between Green And Sustainable? - WorldAtlas," 1 2021. [Online]. Available: https://www.worldatlas.com/articles/what-is-the-difference-between-green-and-sustainable.html

[10] S. 'Van Hoof, "European Commission launches proposals to reach 55% emissions reduction by 2030," 2021. [Online]. Available: https://www.unsdsn.org/european-commission-launches-proposals-to-reach-55-emissions-reduction-by-2030

[11] W. L. Gallo, A. G. Gallego, V. L. Acevedo, R. Dias, H. Y. Ortiz, and B. A. Valente, "Exergy analysis of the compression systems and its prime movers for a FPSO unit," *Journal of Natural Gas Science and Engineering*, vol. 44, pp. 287–298, 8 2017.

[12] Lloyd's Register, "Measuring the carbon footprint of offshore production." 2020. [Online]. Available: https://www.lr.org/en/insights/articles/measuring-carbon-footprint-of-offshore-production/

[13] Bluewater, "FPSO EMEA Congress Presentation," Tech. Rep., 2022.

[14] StellaeEnergy, ""Recipe" for a "Green" FPSO? – Stellae Energy," 2 2021. [Online]. Available: http://stellaeenergy.com/recipe-for-a-green-fpso

[15] J. MacDonald, "Providing Scope for Reducing the Carbon Footprint of an Offshore Oil Rig," University of Strathclyde, Tech. Rep., 9 2014. [Online]. Available: http://www.esru.strath.ac.uk/Documents/MSc_2014/MacDonald.pdf

[16] S. Tawiah, S. A. Marfo, and D. B. Jnr, "Solar power for sustainable offshore petroleum exploration and production in Africa," *Society of Petroleum Engineers - SPE/AAPG Africa Energy and Technology Conference 2016*, 12 2016.

[17] W. He, K. Uhlen, M. Hadiya, Z. Chen, G. Shi, and E. del Rio, "Case Study of Integrating an Offshore Wind Farm with Offshore Oil and Gas Platforms and with an Onshore Electrical Grid," *Journal of Renewable Energy*, vol. 2013, pp. 1–10, 1 2013.

[18] Aker Solutions, "Feasibility of the Electrification of FPSO Vessels Offshore Newfoundland and Labrador, Canada," Tech. Rep., 12 2020. [Online]. Available: https://energynl.ca/wp-content/uploads/2021/01/FINAL-Feasibility-of-the-Electrification-of-FPSO-Vessels-Offshore-Newfoundland-and-Labrador-IFI-2020.pdf

[19] S. M. Samarakoon and O. T. Gudmestad, "Retaining the Sustainability of Oil and Gas Operations: Qualifying the Best Available Techniques," *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol. 1, pp. 11–17, 12 2010. [Online]. Available: https://asmedigitalcollection.asme.org/OMAE/proceedings-abstract/OMAE2010/11/349143

[20] The International Energy Agency, "Energy security: Ensuring the uninterrupted availability of energy sources at an affordable price," 12 2019. [Online]. Available: https://www.iea.org/areas-of-work/energy-security

[21] N. Gallagher, "What Is Happening in European Energy Markets?" 10 2022. [Online]. Available: https://www.sharecafe.com.au/2022/10/27/what-is-happening-in-european-energy-markets/

[22] Fluenta, "FPSOs: mobile processing," 3 2019. [Online]. Available: https://www.fluenta.com/fpsos-mobile-processing/

[23] J. R.-L. Moses, "FPSO System: Technology and Benefits," 5 2012. [Online]. Available: https://www.vanguardngr.com/2012/05/fpso-system-technology-and-benefits/

[24] D. Seah, *Sea Transport of FPSO Topside Modules: Managing the Legal Risks*, 6 2020.

[25] S. Murugaiah, "A review study of floating, production, storage, and offloading (FPSO) oil and gas platform," Ph.D. dissertation, University Tunku Abdul Rahman, 9 2015. [Online]. Available: http://eprints.utar.edu.my/1759/1/A_Review_Study_of_Floating%2C_Production%2C_Storage_and_Offloading_(FPSO)_Oil_and_Gas_Platform.pdf

[26] E. Abraham and H. Miller, "Meet compression train base package design requirements for FPSOs—Part 1," 2016. [Online]. Available: http://gasprocessingnews.com/features/201710/meet-compression-train-base-package-design-requirements-for-fpsos%E2%80%94part-1.aspx

[27] Bluewater, "FPSO fleet." [Online]. Available: https://www.bluewater.com/floating-production/fpso-fleet/

[28] R. Brown, "FPSO electrical systems-lessons learned [ship power systems]," *Record of Conference Papers. Industry Applications Society. Forty-Ninth Annual Conference. 2002 Petroleum and Chemical Industry Technical Conference*, pp. 111–118, 9 2002.

[29] M. Latarche, "Dual-fuel and gas engines," *Pounder's Marine Diesel Engines and Gas Turbines*, pp. 59–86, 1 2021.

[30] Bluewater, "FPSO Technical Fact sheets," 2009. [Online]. Available: https://www.bluewater.com/media-contacts/downloads/technical-fact-sheets/

[31] Bluewater, "HB09-E-400-PH-9013-001-1 Operation Philosophy," Tech. Rep., 9 2021.

[32] The Renewable Energy Hub, "The history of Wind Turbines." [Online]. Available: https://www.renewableenergyhub.co.uk/main/wind-turbines/history-of-wind-turbines/

[33] Wind-turbine-supplies.co.uk, “History Of Wind Turbines .” [Online]. Available: http://www.wind-turbine-supplies.co.uk/history-wind-turbines/

[34] R. Landberg, “Bloomberg New Energy Finance: Clean Energy Is Approaching a Tipping Point,” 9 2017. [Online]. Available: https://www.bloomberg.com/news/articles/2017-09-19/tipping-point-seen-for-clean-energy-as-monster-turbines-arrive

[35] S. M. Islam, C. V. Nayar, A. Abu-Siada, and M. M. Hasan, “Power Electronics for Renewable Energy Sources,” *Power Electronics Handbook*, pp. 783–827, 1 2018.

[36] R. Whittlesey, “Vertical Axis Wind Turbines: Farm and Turbine Design,” *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines*, pp. 185–202, 1 2017.

[37] E. Möllerström, “Whatever became of the vertical axis wind turbine?” 5 2019. [Online]. Available: https://www.modernpowersystems.com/features/featurewhatever-became-of-the-vertical-axis-wind-turbine-7183833/

[38] D. Clayton, “Types of Wind Turbines: HAWT, VAWT and More Explained,” 6 2021. [Online]. Available: https://energyfollower.com/types-of-wind-turbines/

[39] K. A. Adeyeye, N. Ijumba, and J. Colton, “The Effect of the Number of Blades on the Efficiency of A Wind Turbine,” *IOP Conference Series: Earth and Environmental Science*, vol. 801, no. 1, 7 2021.

[40] S. Kerrigan, “The Scientific Reason Why Wind Turbines Have 3 Blades,” 3 2017. [Online]. Available: https://interestingengineering.com/the-scientific-reason-why-wind-turbines-have-3-blades

[41] CNBM International Wind Power, “Wind Turbine Tower Types: 3 Main Types Comparison | Pros And Cons Explained,” 5 2018. [Online]. Available: http://www.steelwindtower.com/wind-turbine-tower-comparison-pros-and-cons-explained/

[42] E. Lantz, O. Roberts, J. Nunemaker, E. DeMeo, K. Dykes, and G. Scott, “Increasing Wind Turbine Tower Heights: Opportunities and Challenges,” National Renewable Energy Laboratory, Tech. Rep., 5 2019. [Online]. Available: https://www.nrel.gov/docs/fy19osti/73629.pdf

[43] CNBM International Wind Power, “Wind Turbine Tower Types Reviews,” 3 2017. [Online]. Available: http://www.steelwindtower.com/wind-turbine-tower-types-reviews/

[44] Francesco Miceli, “Wind turbine tower,” 5 2012. [Online]. Available: https://www.windfarmbop.com/tag/concrete-tower/

[45] K. Hammerum, E. Herbsleb, L. F. S. Larsen, and F. Caponetti, “Tilting wind turbine,” 2013. [Online]. Available: https://patents.google.com/patent/US9909569B2/en

[46] Hexicon, “TwinWind™ Floating Technology.” [Online]. Available: https://www.hexicongroup.com/twinwind/

[47] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, “Definition of a 5-MW Reference Wind Turbine for Offshore System Development,” National Renewable Energy Laboratory, Tech. Rep., 2 2009. [Online]. Available: https://www.nrel.gov/docs/fy09osti/38060.pdf

[48] The Wind Power, “Manufacturers and turbines.” [Online]. Available: https://www.thewindpower.net/turbines_manufacturers_2_en.php

[49] TWI, “How long do wind turbines last? Can their lifetime be extended?” [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/how-long-do-wind-turbines-last

[50] Office of Energy Efficiency & Renewable Energy, "Advanced Wind Turbine Drivetrain Trends and Opportunities | Department of Energy," 7 2019. [Online]. Available: https://www.energy.gov/eere/articles/advanced-wind-turbine-drivetrain-trends-and-opportunities

[51] Y. Gu and Y. Ju, "LNG-FPSO: Offshore LNG solution," *Frontiers of Energy and Power Engineering in China*, vol. 2, no. 3, pp. 249–255, 9 2008.

[52] M. Xu, "Guideline for managing marine risks associated with FPSOs," Tech. Rep., 4 2006. [Online]. Available: https://www.academia.edu/9690476/Guideline_for_managing_marine_risks_associated_with_FPSOs

[53] F. Crawley, *A Guide to Hazard Identification Methods: 5 - HAZID*. Elsevier, 1 2020.

[54] A. F. Molland, *The Maritime Engineering Reference Book, Chapter 11 - Marine Safety*, A. F. Molland, Ed. Butterworth-Heinemann, 2008.

[55] R. Wadhwani, V. Kumar, and P. Singh, "Hazards on offshore platform: a review," 12 2012.

[56] T. Joung, H. Kim, Y. Kim, S. Cho, K. Kang, Y. Liu, and M. Lundteigen, "Hazard identification for a dynamic positioning and mooring system in Arctic condition," in *Safety and Reliability – Safe Societies in a Changing World*, 1st ed. London: CRC Press, 2018, pp. 1735–1742.

[57] American Bureau of Shipping (ABS), "Guidance Notes on Risk Assessment Applications for the Marine and Offshore Industries," Tech. Rep., 5 2020.

[58] N. Siddiqui, A. Nandan, M. Sharma, and A. Srivastava, "Risk Management Techniques HAZOP & HAZID Study," vol. 1, pp. 5–8, 2014.

[59] Cambridge Dictionary, "Meaning of feasibility in English." [Online]. Available: https://dictionary.cambridge.org/dictionary/english/feasibility

[60] UK's National Institute for Health and Care Research, "Glossary: Feasibility studies." [Online]. Available: https://www.nihr.ac.uk/about-us/glossary.htm?letter=F&postcategory=-1

[61] Corporate Finance Institute, "Feasibility Study," 4 2022. [Online]. Available: https://corporatefinanceinstitute.com/resources/knowledge/other/feasibility-study/

[62] R. Adams and C. Atman, "Cognitive processes in iterative design behavior," in *FIE'99 Frontiers in Education. 29th Annual Frontiers in Education Conference. Designing the Future of Science and Engineering Education. Conference Proceedings (IEEE Cat. No.99CH37011*. Stripes Publishing L.L.C, 11 1999, pp. 13–11.

[63] B. Roseke, "The Life Cycle of an Engineering Project," 12 2012. [Online]. Available: https://www.projectengineer.net/the-life-cycle-of-an-engineering-project/

[64] Bluewater, "Structural drawing, orientation on vessel, definition and coordinate system - HB-A-100-DR-0016-001," Tech. Rep., 2019.

[65] DNV, "DNVGL-OS-E301 - Position Mooring," 7 2018.

[66] Civil Aviation Authority, "Standards for offshore helicopter landing areas - CAP437," Civil Aviation Authority, Gatwick Airport South, West Sussex, Tech. Rep., 7 2021. [Online]. Available: https://publicapps.caa.co.uk/modalapplication.aspx?appid=11&mode=detail&id=523

[67] E.-M. Lourens, "Offshore Wind Farms Design - Support Structure Design," 2021.

[68] Bluewater, "Vessel heading analysis - HB06-A-100-RP-0040-001-B.DOC," Tech. Rep., 2013.

[69] "File:Wind.turbine.components.and.coordinates.svg - Wikimedia Commons." [Online]. Available: https://commons.wikimedia.org/wiki/File:Wind.turbine.components.and.coordinates.svg

[70] Bluewater, “HB09-A-100-RP-0068-001-A: Loading Manual,” Tech. Rep., 6 2021.

[71] International Maritime Organisation, “IMO A.749,” Tech. Rep., 11 1993.

[72] DNV, “DNVGL-OS-C301 - Stability and watertight integrity,” Tech. Rep., 7 2020.

[73] Health and Safety Executive and BOMEL Ltd, “Stability,” Tech. Rep., 2005. [Online]. Available: https://www.hse.gov.uk/research/rrpdf/rr387.pdf

[74] Bluewater, “Stability Limit Curves - HB09-A-100-CA-0069-001-A,” Tech. Rep., 6 2021.

[75] L. Wan, Z. Gao, T. Moan, and C. Lugni, “Comparative experimental study of the survivability of a combined wind and wave energy converter in two testing facilities,” *Ocean Engineering*, vol. 111, pp. 82–94, 1 2016.

[76] P. van der Male, “Aerodynamic loading - OE44005 Introduction to Offshore Engineering,” Tech. Rep.

[77] “NREL 5-MW reference turbine - CP, CQ, CT Coefficients.” [Online]. Available: https://forums.nrel.gov/t/nrel-5-mw-reference-turbine-cp-cq-ct-coefficients/456

[78] American Bureau of Shipping, “Guidance notes on ship vibration,” Tech. Rep., 5 2021.

[79] Shell Global Solutions (UK) Ltd, “Pierce - Metocean Reference Document - HB06-G-100-RP-0133-001,” Tech. Rep., 11 2013.

[80] Bureau Veritas, “HydroStar for experts user manual,” Tech. Rep., 4 2021.

[81] J. Jonkman, “Using Aggregate Mass in ADAMS to Check NREL CS_Monopile.bmi,” 6 2020. [Online]. Available: https://forums.nrel.gov/t/using-aggregate-mass-in-adams-to-check-nrel-cs-monopile-bmi/696

[82] Bluewater, “Haewene Brim: RAO report - 2013-0070,” Tech. Rep., 2013.

[83] S. Chakraborty, “Ship stability - Understanding intact stability of ships,” 12 2016. [Online]. Available: https://blog.naver.com/PostView.nhn?isHttpsRedirect=true&blogId=seokhaeng&logNo=220893349866

[84] A. Ross, “Orcina Project 1405 - Wind Turbine Validation Report,” Orcina, Daltongate, Tech. Rep., 4 2018. [Online]. Available: https://www.orcina.com/wp-content/uploads/resources/validation/R14050101-Wind-Turbine-Validation-Report.pdf

[85] Bluewater, “Report - Mooring - Model Test - Mooring system and seakeeping results - LUF-L-800-RP-0512-001-1,” Tech. Rep., 2 2022.

[86] DNV, “DNVGL-RP-C205 - Environmental conditions and environmental loads,” Tech. Rep., 9 2019.

[87] Norwegian Petroleum Directorate, “Regulations relating to loadbearing structures in the petroleum activities,” Tech. Rep., 1996.

[88] API, “Design and Analysis of Stationkeeping Systems for Floating Structures - API RP 2SK,” American Petroleum Institute, Tech. Rep., 2005.

[89] Bluewater, “Mooring Analysis - Extreme Conditions - HB08-L-830-CA-0602-001-1,” Tech. Rep., 2016.

[90] Bluewater, “BES Specification for FPSO Topside Equipment - BWS-M-100-SP-1016-001-B,” Tech. Rep., 2 2019.

[91] M. Y. Mahfouz, M. Salari, S. Hernández, F. Vigara, C. Molins, P. Trubat, H. Bredmose, and A. Pegalajar-Jurado, "Public design and FAST models of the two 15MW floater-turbine concepts," Corewind, Tech. Rep., 4 2020. [Online]. Available: http://corewind.eu/wp-content/uploads/files/publications/COREWIND-public-design-and-FAST-models-of-the-two-15mw-floater-turbine-concepts.pdf

[92] A. Dron, "SAFETY: North Sea vs. Gulf of Mexico," 8 2000. [Online]. Available: https://www.offshore-mag.com/home/article/16763594/safety-north-sea-vs-gulf-of-mexico

[93] U. E. Ite, "Non-Technical Risks Management: A Framework for Sustainable Energy Security and Stability," in *All Days*. SPE, 8 2016.

[94] H. L. Bakker and J. P. de Kleijn, *Management of Engineering Projects: People are Key*. NAP - The Process Industry Competence Network, 2014.

[95] A. Adekoya and E. Ekpenyong, "Managing Non-Technical Risk in Exploration and Production (E&P) Projects: Opportunity to leverage the IA Process," Tech. Rep., 5 2016. [Online]. Available: https://conferences.iaia.org/2016/Final-Papers/Adekoya,%20Adebanji%20-%20Managing%20Non-Technical%20Risk%20in%20E%20and%20P%20Projects.pdf

[96] K. Scholes, G. Johnson, and R. Whittington, *Exploring Corporate Strategy*. Hoboken: Financial Times Prentice Hall, 2002.

[97] M. Maizi, M. H. Mohamed, R. Dizene, and M. C. Mihoubi, "Noise reduction of a horizontal wind turbine using different blade shapes," *Renewable Energy*, vol. 117, pp. 242–256, 3 2018.

[98] "Health effects related to wind turbine sound: an update | RIVM." [Online]. Available: https://www.rivm.nl/publicaties/health-effects-related-to-wind-turbine-sound-update

[99] Bluewater, "Project Noise Philosophy - HB01-X-100-PH-1001-001-A," Tech. Rep., 2 2003.

[100] L. D. Knopper, C. A. Ollson, L. C. McCallum, M. L. Whitfield Aslund, R. G. Berger, K. Souweine, and M. McDaniel, "Wind Turbines and Human Health," *Frontiers in Public Health*, vol. 2, 6 2014. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpubh.2014.00063/full

[101] Rijksinstituut voor Volksgezondheid en Milieu, "Factsheet - gezondheidseffecten van windturbinegeluid," Tech. Rep., 7 2021.

[102] R. Bakhshi and P. Sandborn, "Overview of Wind Turbine Field Failure Databases: A Discussion of the Requirements for an Analysis," in *Volume 1: Fuels, Combustion, and Material Handling; Combustion Turbines Combined Cycles; Boilers and Heat Recovery Steam Generators; Virtual Plant and Cyber-Physical Systems; Plant Development and Construction; Renewable Energy Systems*. American Society of Mechanical Engineers, 6 2018.

[103] RIVM, "Rekenvoorschrift Omgevingsveiligheid - Module IV: Windturbines," Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Tech. Rep., 10 2020. [Online]. Available: https://omgevingsveiligheid.rivm.nl/documenten/rekenvoorschrift-omgevingsveiligheid-module-iv-versie-okt-2020

[104] DNV GL, "DNVGL-RP-C204: Structural design against accidental loads," DNV GL, Tech. Rep., 9 2019.

[105] S. Larwood and D. Simms, "Retracted: Analysis of blade fragment risk at a wind energy facility," *Wind Energy*, vol. 21, no. 8, pp. 681–681, 8 2018.

[106] Bluewater, "AM-X-100-RP-0310-001-1 - Dropped Object Study," Hoofddorp, Tech. Rep., 4 2019.

[107] P. B. Thapa, "Floating Production Storage and Offloading Vessel (FPSOV) Production Deck Dropped Object Risk Analysis Approach," Tech. Rep., 8 2016.

[108] A. J. Brand, J. Peinke, and J. Mann, "Turbulence and wind turbines," *Journal of Physics: Conference Series*, vol. 318, no. 7, p. 072005, 12 2011.

[109] L. C. McCallum, M. L. Whitfield Aslund, L. D. Knopper, G. M. Ferguson, and C. A. Ollson, "Measuring electromagnetic fields (EMF) around wind turbines in Canada: is there a human health concern?" *Environmental Health*, vol. 13, no. 1, p. 9, 12 2014. [Online]. Available: https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-13-9

[110] I. Angulo, D. de la Vega, I. Cascón, J. Cañizo, Y. Wu, D. Guerra, and P. Angueira, "Impact analysis of wind farms on telecommunication services," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 84–99, 4 2014.

[111] E. Binopoulos and P. Haviaropoulos, "Environmental impacts of wind farms: myth and reality," Centre for Renewable Energy Sources (CRES), Tech. Rep., 1 2006.

[112] S. Uadiale, E. Urbán, R. Carvel, D. Lange, and G. Rein, "Overview of Problems and Solutions in Fire Protection Engineering of Wind Turbines," *Fire Safety Science*, vol. 11, pp. 983–995, 2014.

[113] Scotland Against Spin (SAS), "Turbine Accident Statistics," 6 2022. [Online]. Available: https://scotlandagainstspin.org/turbine-accident-statistics/

[114] C. Hetyei and R. Nagy, "Review of Wind Turbine Failures, Highlighting Fire Accidents," *Műszaki Katonai Közlöny*, vol. 30, no. 2, pp. 43–55, 2020.

[115] G. Y. Won and K. W. Kyung, "Fire extinguishing firefighting drone," 2015. [Online]. Available: https://patents.google.com/patent/US10413763B2/en?q=Fire+extinguishing+firefighting+drone&oq=Fire+extinguishing+firefighting+drone

[116] HeliOffshore, "Helicopter Safety Performance," Tech. Rep., 12 2019. [Online]. Available: https://skybrary.aero/bookshelf/helicopter-safety-performance-2013-2018

[117] Danish Wind Turbine Manufacturers Association (DWTMA), "Guided tour on Windenergy," 2001. [Online]. Available: http://mstudioblackboard.tudelft.nl/duwind/Wind%20energy%20online%20reader/

[118] F. Rachidi, M. Rubinstein, J. Montanya, J.-L. Bermudez, R. Rodriguez Sola, G. Sola, and N. Korovkin, "A Review of Current Issues in Lightning Protection of New-Generation Wind-Turbine Blades," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2489–2496, 6 2008.

[119] International Electrotechnical Commission, "IEC 61400-1: Wind energy generation systems - Part 1: Design requirements," Tech. Rep., 2 2019.

[120] PETRONAS, "Managing and Mitigating Environmental Impact in Malaysian Drilling Activities: PETRONAS Approach ," 2015. [Online]. Available: http://www.iadc.org/wp-content/uploads/2015/03/AP15Rozita-Musib.pdf

[121] National Renewable Energy Laboratory (NREL), "Annual Technology Baseline: Offshore Wind," 7 2022. [Online]. Available: https://atb.nrel.gov/electricity/2022/offshore_wind

[122] Bright Hub Engineering, "The Efficiency of Power Plants of Different Types," 5 2010. [Online]. Available: https://www.brighthubengineering.com/power-plants/72369-compare-the-efficiency-of-different-power-plants/

[123] R. Aronietis, C. Sys, E. van Hassel, and T. Vanelslander, "Forecasting port-level demand for LNG as a ship fuel: the case of the port of Antwerp," *Journal of Shipping and Trade*, vol. 1, no. 1, 12 2016.

[124] Marine Insight, "A Guide To Marine Gas Oil and LSFO Used On Ships," 1 2021. [Online]. Available: https://www.marineinsight.com/guidelines/a-guide-to-marine-gas-oil-and-lsfo-used-on-ships/

[125] R. Mclean, "How Much CO2 Emissions Per Litre of Diesel - Slightly Unconventional." [Online]. Available: https://slightlyunconventional.com/co2-per-litre-diesel/

[126] Ship & Bunker, "World Bunker Prices - Ship & Bunker." [Online]. Available: https://shipandbunker.com/prices#MGO

[127] "Compensation for the indirect costs of the UK ETS and the CPS mechanism: guidance for applicants - GOV.UK." [Online]. Available: https://www.gov.uk/government/publications/uk-emissions-trading-scheme-and-carbon-price-support-apply-for-compensation/compensation-for-the-indirect-costs-of-the-uk-ets-and-the-cps-mechanism-guidance-for-applicants

[128] D. Blewett, "Wind Turbine Cost: How Much? Are They Worth It In 2022?" 12 2021. [Online]. Available: https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/

[129] BVG associates, "Guide to an offshore wind farm," The Crown Estate and the Offshore Renewable Energy Catapult, Tech. Rep., 1 2019. [Online]. Available: https://www.thecrownestate.co.uk/media/2861/guide-to-offshore-wind-farm-2019.pdf

[130] Bluewater, "Report: Hydrodynamic Transfer Functions (RAO) - HB06-A-100-RP-0036-001," Tech. Rep., 2013.

[131] HPD Construction, "Definition and Application of Metacentric Height," 7 2021. [Online]. Available: https://www.hpdconsult.com/metacentric-height/#:~:text=The%20natural%20period%20of%20rolling%20of%20a%20hull,height%20is%20regarded%20as%20optimum%20for%20passenger%20ships.

[132] Orcina, "OrcaFlex Examples: Renewables." [Online]. Available: https://www.orcina.com/resources/examples/

Appendices

A HAZID attendance list

No	Name	Company	Function/Discipline
1	Youri Öhlschläger	Bluewater/TU Delft	Trainee/student
2	Teddy Simanjuntak	Bluewater	Structural Engineer, supervisor
3	Gerard Sirks	Bluewater	Section Head HSE
4	Amir Kavoosi	Bluewater	HSE Engineer
5	Clemens van der Nat	Bluewater	Manager Strategic Developments
6	Bastiaan van den Berg	Bluewater	Principal Engineer, Naval & Marine
7	Barend Zwets	Bluewater	Section Head Floating Production Engineering
8	Ellis Huijsmans	Bluewater	Tender Manager
9	Marta Masachs	Bluewater	Regulatory Compliance Engineer
10	Sander Fuchs	Bluewater	Consultant Engineer, Technology Management
11	Pim van der Male	TU Delft	TU Delft supervisor
12	Michiel Zaaijer	TU Delft	Professor Wind Energy
Additional interviews			
13	Kees van Beveren	Bluewater	Section Head Marine & Subsea
14	Richard Leeuwenburgh	Bluewater	Section Head Mooring & Subsea
15	Nico van Es	Bluewater	Section Head Electrical & Instrumentation
16	Olayinka Abiola Oluyede	Bluewater	Electrical & Instrumentation

B Terms of reference

Contents

Abbreviations

BES	Bluewater Energy Services BV
CMS	Corporate Management System
EIA	Environmental Impact Assessment
ESD	Emergency Shutdown
FPSO	Floating Production Storage (and) Offloading (Unit)
FEHA	Fire Explosion Hazard Assessment
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HSE	Health, Safety & Environment
LOPA	Layer of Protection Analysis
MAH	Major Accident Hazard
P&ID	Piping & Instrumentation Diagram
PFD	Process Flow Diagram
QRA	Quantitative Risk Assessment
RC	Regulatory Compliance
SPM	Single Point Mooring System
TMS	Turret Mooring System
TOR	Terms of Reference
WHP	Wellhead Platform

1 Introduction

1.1 General

Nowadays sustainability and the reduction of greenhouse gas emissions are getting more and more important. Studies towards 'green' FPSOs look into mainly four aspects: improving energy usage efficiencies, reducing waste and greenhouse gas emissions, implementing carbon capture measures, and increasing the use of clean energy renewables in the energy mix. Placing a wind turbine on an FPSO topside can have a large contribution in FPSOs to becoming green.

It is assumed that placing a 5 MW wind turbine on an FPSO topside is a good business case. Here the power generation by the wind turbine saves significant fuel costs. The lifetime for which this is determined is 20 years. Here a distinction can be made in using a new or refurbished turbine.

For the 5 MW wind turbine there is looked at the NREL 5 MW reference turbine is provided by the National Renewable Energy Laboratory [3]. An overview of its dimensions and several characteristics is shown in appendix B.

The wind turbine is integrated into the electricity grid as an addition to the existing grid where conventional diesel engines and gas turbines are used. Whenever the wind turbine is producing power, this power is first in line to be used. Any required additions and shortages are replenished by the already-in-place gas turbines and/or diesel engines.

Placing a wind turbine on an FPSO topside raises multiple questions. The question of what hazards might occur is one of them, for which this HAZID is performed. To have more specific insight into the structure of an FPSO, general arrangements and hazardous area plans are available for several FPSOs. Nevertheless, the decision of whether the turbine is placed on an existing FPSO, or whether a new design is required, has not been made yet and is one of the questions taken into consideration in this thesis.

Figure 1: Bluewater's Haewene Brim [4]

1.2 Purpose of this Document

The purpose of this Terms of Reference document is to define the scope of the HAZID and to summarize the study methodology and the available documentation. Also, background information concerning wind turbines and FPSOs is provided. Planning information such as date, location, team composition, and reporting by all parties involved will also be specified. The HAZID is intended to document the team's considerations on risk analysis and to identify major HSE issues in the case study of a wind turbine on an FPSO topside. The HAZID is in the end part of a master thesis consisting of a larger feasibility study concerning a wind turbine on an FPSO topside and will be the basis for the decision on the continuation of the thesis.

1.3 References

[1] Bluewater Energy Services, Hazard Identification (HAZID),BES Doc. BW3-X-100-PR-0062-001
[2] Bluewater Energy Services, HAZID Study Guidewords, BES Doc. BW4-X-100-CL-0077-001J.
[3] Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW Reference WindTurbine for Offshore System Development," National Renewable Energy Laboratory, Tech. Rep.,2 2009. [Online]. Available: https://www.nrel.gov/docs/fy09osti/38060.pdf27
[4] Bluewater, "Haewene Brim – Bluewater." [Online]. Available: https://www.bluewater.com/fleet-operations/our-fpso-fleet/haewene-brim/
[5] N. Tazi, E. Châtelet, and Y. Bouzidi, "Using a Hybrid Cost-FMEA Analysis forWind Turbine Reliability Analysis,"Energies 2017, Vol. 10, Page 276, vol. 10, no. 3,p. 276, 2 2017. [Online]. Available: https://www.mdpi.com/1996-1073/10/3/276/htm
[6] Office of Energy Efficiency & Renewable Energy, "Advanced Wind Turbine DrivetrainTrends and Opportunities | Department of Energy," 7 2019. [Online]. Available: https://www.energy.gov/eere/articles/advanced-wind-turbine-drivetrain-trends-and-opportunities
[7] M. D. Reder, E. Gonzalez, and J. J. Melero, "Wind Turbine Failures - Tackling currentProblems in Failure Data Analysis,"Journal of Physics: Conference Series, 9 2016. [Online].Available: https://www.researchgate.net/publication/308807866_Wind_Turbine_Failures_-_Tackling_current_Problems_in_Failure_Data_Analysis/citations
[8] Caithness Windfarm Information Forum, "Summary of Wind Turbine Accident data to 30 June2021." [Online]. Available: http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm
[9] E. Abraham and H. Miller, "Meet compression train base package design requirements for FPSOs—Part 1," 2016. [Online]. Available: http://gasprocessingnews.com/features/201710/meet-compression-train-base-package-design-requirements-for-fpsos%E2%80%94part-1.apsx
[10] "FM 55-17 Chapter 2 Harbor Facilities and Vessels." [Online]. Available: https://www.globalsecurity.org/military/library/policy/army/fm/55-17/ch2.htm
[11] T. Sildnes, "FPSOs - Regulatory regimes - Division of responsibilities and implications," 2001. [Online]. Available: https://www.gard.no/web/updates/content/53267/fpsos-regulatory-regimes-division-of-responsibilities-and-implications
[12] C. Zhu and Y. Li, "Reliability Analysis of Wind Turbines,"Stability Control and Reliable Performance of Wind Turbines, 3 2018. [Online]. Available: https://www.intechopen.com/chapters/59756
[13] P. Pedro, "Cause of Wind Tower Collapse Still A Mystery," 1 2018. [Online]. Available: https://blackburnnews.com/chatham/chatham-news/2018/01/30/ck-wind-tower-collapse-still-mystery/
[14] European Platform Against Windfarms, "Wind turbine on fire at the Groß Eilstorf wind farm," [Online]. Available: http://epaw.org/photos/WKA_ausgebrannt_5.jpg.
[15] E. Doran, "113-foot blade falls off windmill that previously toppled in Madison County," 2 2016. [Online]. Available: https://stopthesethings.com/2016/02/25/wind-industry-claims-flying-blades-crashing-turbines-a-landmark-tourist-attr/
[16] Gegenwind Borchen, "Windrad-Havarie: neue 200m-Windkraftanlage in Borchen völlig zerfetzt,", 3 2018. [Online]. Available: http://gegenwind-borchen.de/windrad-havarie-neue-200m-windkraftanlage-in-borchen-voellig-zerfetzt
[17] G. Robinson, "Wind turbine catches fire after being struck by lightning," 5 2018. [Online]. Available: https://metro.co.uk/2018/05/30/wind-turbine-catches-fire-struck-lightning-7591593/

The basis for the execution of the HAZID study is the attached listing documents. The HAZID participants were provided the following drawings.

S. No	Drawing No	Title
1.	56962-AE-N-XD-0058-01 001	General Arrangement Drawing – Haewene Brim
2.	BH-A-100-DG-0001 001	General Arrangement Drawing – FPSO Bleo Holm
3.	AM-A-100-DG-0100 001	General Arrangement Drawing – FPSO Aoka Mizu
4.	DB 006.20	Hazardous Area Plan – FPSO Haewene Brim
5.	BH-X-600-DG-0009 001	Hazardous Area Plan – FPSO Bleo Holm
6.	AM-A-100-DG-2002 001	Hazardous Area Plan – FPSO Aoka Mizu

2 Background information

2.1 General

Background information on both wind turbines and FPSOs is provided. Furthermore, an overview of the situations that are taken into consideration during the HAZID is given in this section.

2.2 Wind turbines

For the wind turbine on an FPSO, a 5 MW horizontal axis wind turbine is taken into consideration. The dimensions of the NREL 5 MW reference turbine can be seen in appendix B. The terminology of a wind turbine and its components is according to figure 2.

Figure 2 shows a wind turbine of which the drive train has a gearbox. Besides this, there are also wind turbines that do not have this gearbox, called direct drive. Not having this gearbox often reduces required maintenance, and prevents downtime [6]. Nevertheless, the generator becomes much larger for the direct-drive train. The NREL 5 MW does consist of a gearbox. Nevertheless, for the HAZID both types can be taken into consideration. Figure 3 shows an image of both a drive train with a gearbox and a direct-drive train. Similar to an FPSO, the wind turbine has yawing abilities, in which it can align in accordance with the wind direction.

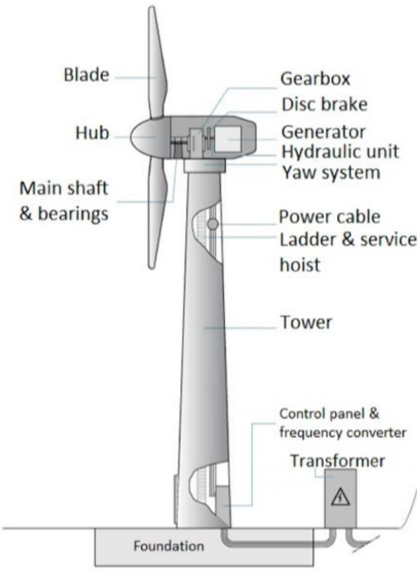


Figure 2: Wind turbine naming conventions [5]

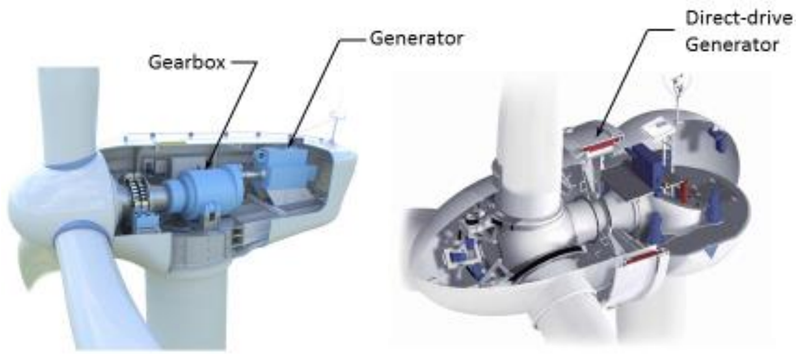


Figure 3: Wind turbine drive trains, left a drive train with gearbox, right a direct-drive [6]

A complex system such as a wind turbine has multiple different types of failure modes. An extensive overview of these wind turbine failure modes and their causes is given in table C.1 in appendix C. To provide more insight, images of several different types of failure modes are also provided in appendix C.

There is also a difference between the failure rates of a wind turbine with a gearbox, and a wind turbine having a direct-drive generator. The failure rates of both of these types of turbines are determined in research on failure data analysis.

The analysis looks at 3 years of data. Here the failures and downtimes per turbine per year of a yearly average number of 2270 wind turbines larger than 1 MW, and 215 direct-drive turbines are considered [7]. The failure rates are normalized to the total number of failures. The component's downtimes are shown as a percentage of the turbine's total downtime. The results are shown in figures 4 and 5.

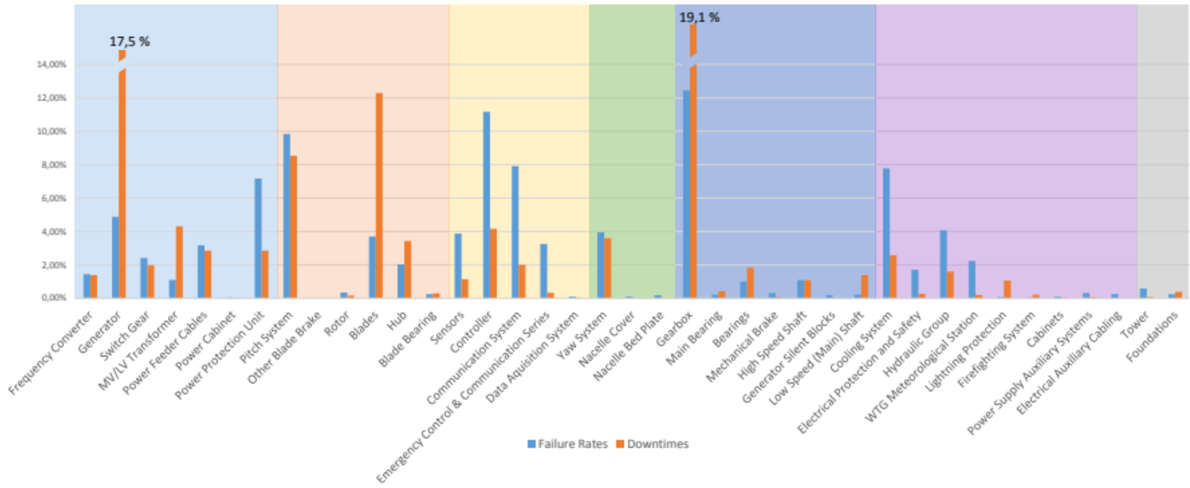


Figure 4: Normalised failure rates and downtimes: Wind turbines having a gearbox > 1 MW [7]

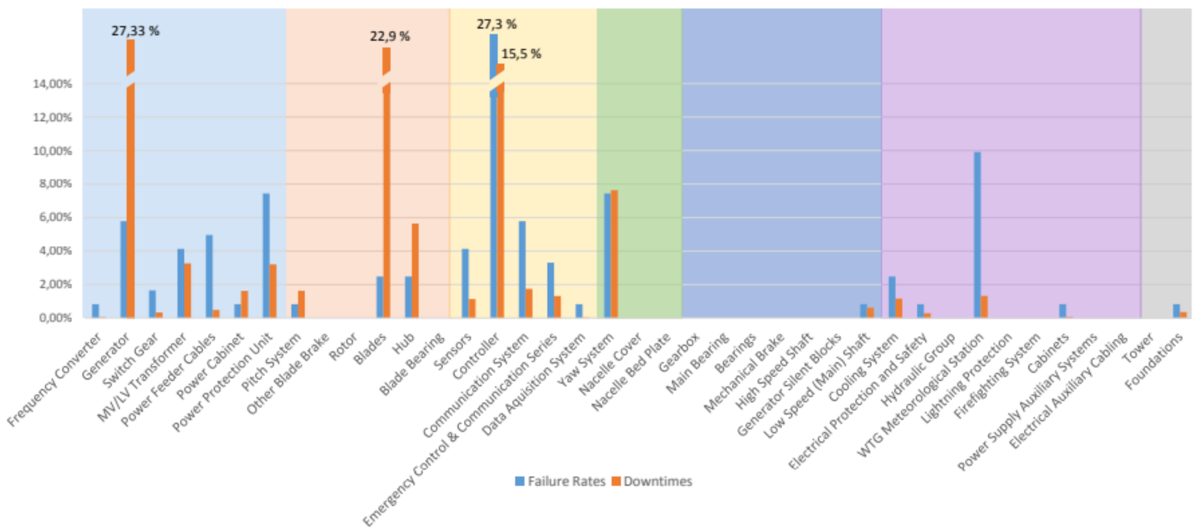


Figure 5: Normalised failure rates and downtimes: Wind turbines with a direct drive [7]

Since 1996, the Caithness Windfarm Information Forum keeps track of wind turbine-related accidents. Figure 6 shows which incidents occurred between 1996 and 30th of June 2021. In total there were 3033 incidents reported [8].

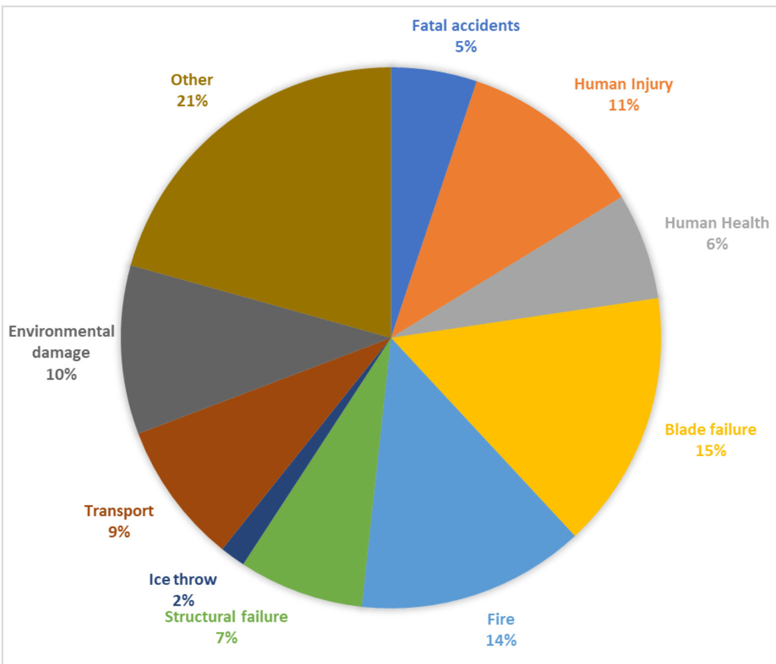


Figure 6: Reported wind turbine related accidents [8]

2.3 Floating, Production, Storage, and Offloading systems

FPSO systems are floating movable vessel-shaped platforms which can process hydrocarbons that are extracted from wells which are located in areas with deep water conditions which are not reachable for current fixed oil and gas platforms. FPSOs can either be newly designed or be created using an already existing hull which often originates from an oil tanker.

FPSOs provides a sequence of tasks available during their operations, starting with the extraction of hydrocarbons from their well, processing the hydrocarbons, and storing them inside the hull of the vessel. Often, gas is re-injected into the well to maintain the pressure in the well. Finally, it can offload the processed hydrocarbons towards pipelines or a transportation oil or gas tanker. Besides this, the personnel working on the FPSO are facilitated with a large accommodation on the vessel providing all their basic needs.

For an FPSO to be able to efficiently execute its operations, it has to be kept in place. This is done using a mooring system. There are many different types of mooring system configurations and technologies. The most advanced option is the use of an (internal) turret mooring system, which allows the FPSO to rotate based on the local conditions in which it has to operate (wind, waves, and current). This is called weathervaning. The deck of an FPSO consists of multiple components, namely process equipment, a flare tower, cranes, a helideck, and more. A typical FPSO layout is shown in figure 7.

Figure 7: typical FPSO layout [9]

Often FPSOs are designed from a very hazardous area on one side (far away from the living quarters), towards a less and less hazardous area on the other side (close to the living quarters). For the HAZID participants the general arrangement drawings and hazardous area plans are available. This is provided for 3 of Bluewater's FPSOs, namely the Haewene Brim, the Bleo Holm, and the Aoka Mizu.

2.4 Situation overview

Before the overview of the situation, the naming conventions for a vessel such as an FPSO are provided in figure 8.

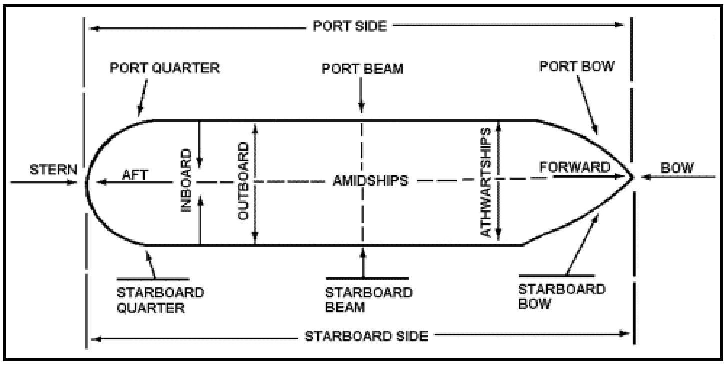


Figure 8: Vessel naming conventions [10]

In the case of a wind turbine on an FPSO topside, there are currently 2 main components identified on the deck that can contribute significantly to the placement of the wind turbine. These are the flare tower and the helideck. There are two main configurations of FPSO layout. One with the helideck at the aft, and the flare tower at the forward. And one with the flare tower at the aft, and the helideck at the forward. The helideck is in both cases accompanied by the accommodation facilities. Besides this, there is also the turret, which is always at the forward, and many process equipment accompanied by cranes, mostly spread out over the middle of the deck.

The actual placement of the wind turbine on the FPSO topside is at the moment still considered a variable within the thesis report. For the HAZID, 6 different cases are provided, which can be used as a reference during the HAZID. For all 6 cases is assumed that necessary deck space can be made available. For the HAZID, the 6 cases that are taken into consideration are:

1. Placing the turbine at the aft, when the flare tower is at the aft and the helideck at the forward.

2. Placing the turbine in the middle, when the flare tower is at the aft and the helideck at the forward.

3. Placing the turbine at the forward, when the flare tower is at the aft and the helideck at the forward.

4. Placing the turbine at the aft, when the helideck is at the aft and the flare tower at the forward.

5. Placing the turbine in the middle, when the helideck is at the aft and the flare tower at the forward.

6. Placing the turbine at the forward, when the helideck is at the aft and the flare tower at the forward.

These 6 cases are visualized (on scale) in figures 9 until 14. Here the FPSO Haewene Brim and Bleo Holm are used as reference. The locations and tower height should be considered as an indication of the placement and size, but are not fixed. Also the possibility to shift the wind turbine in the directions port side and starboard side is still a possibility.

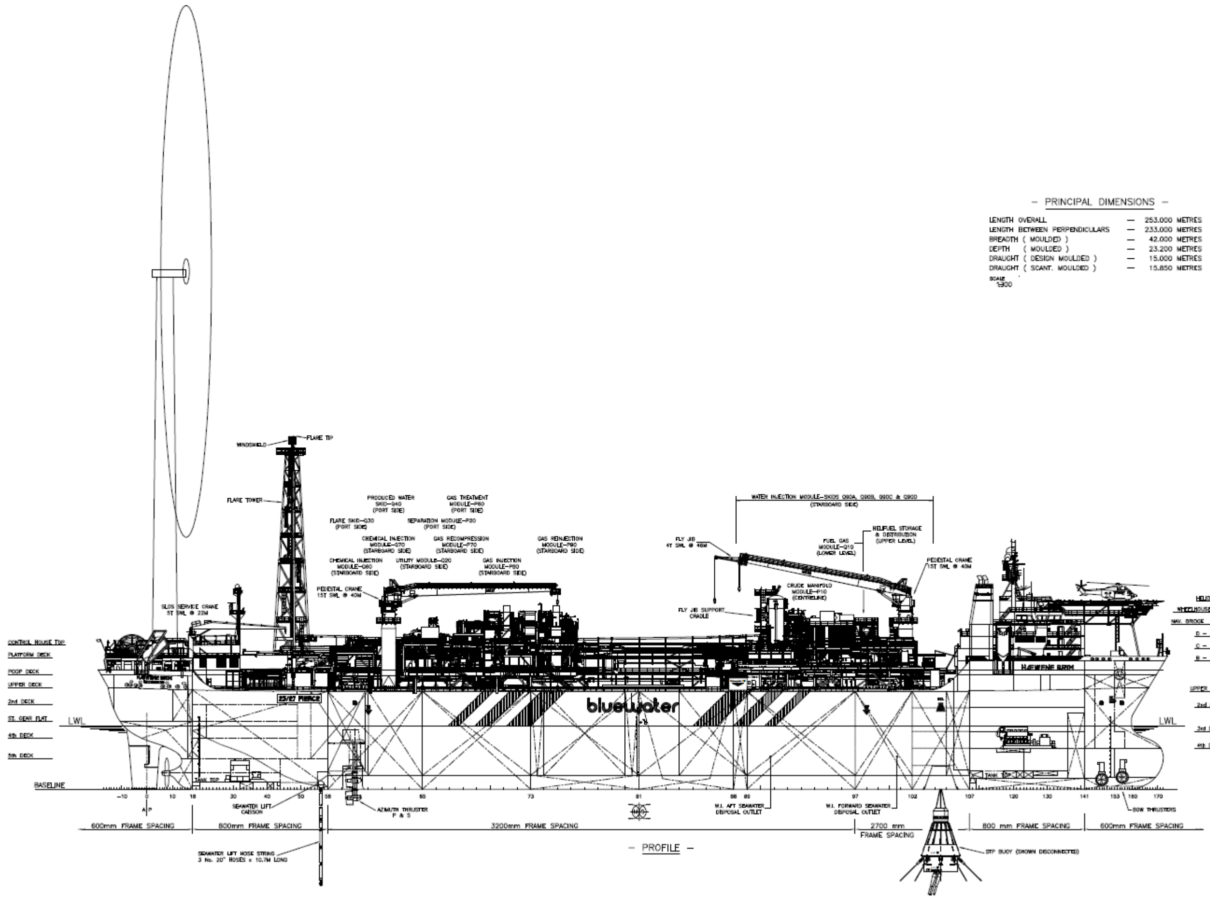


Figure 9: Wind turbine placed on aft of Haewene Brim. Vessel length: 252 m, turbine height: 90 m, rotor diameter: 126 m.

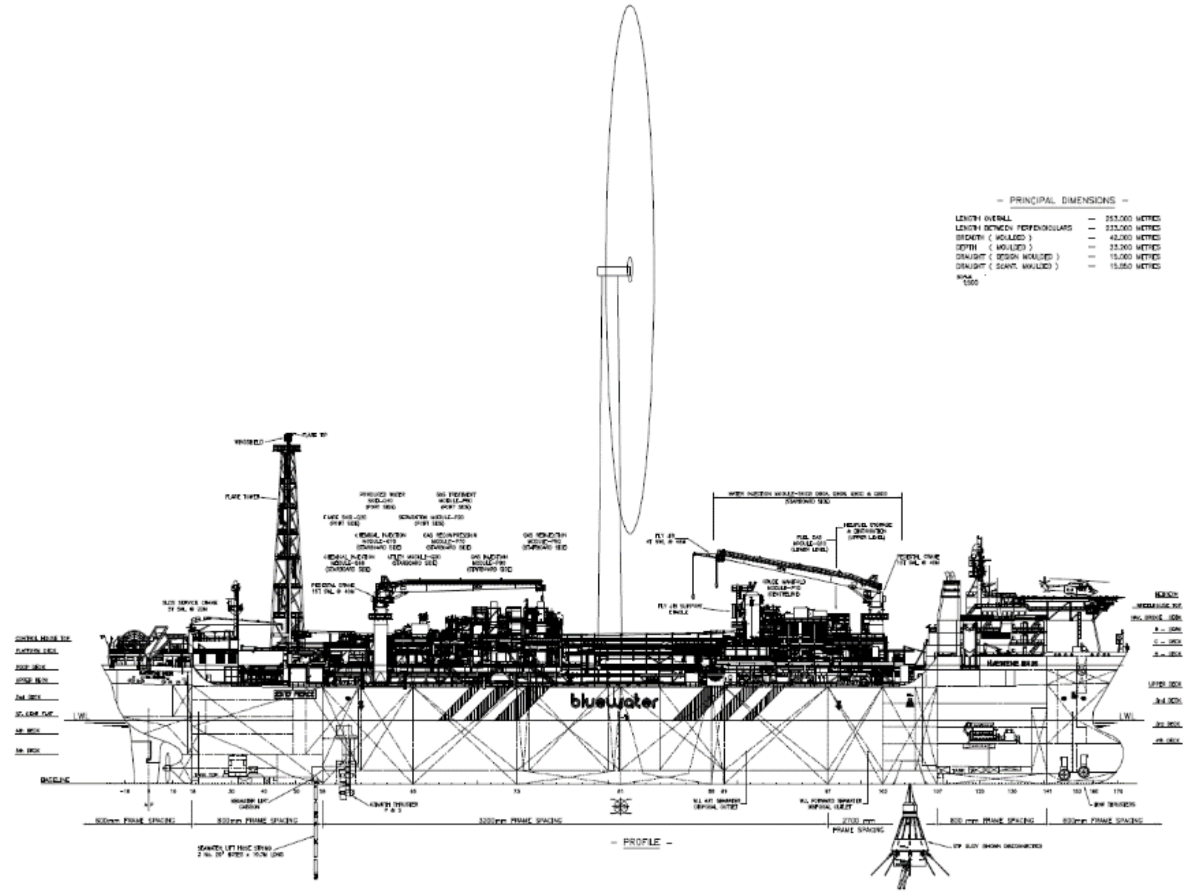


Figure 10: Wind turbine placed in the middle of Haewene Brim. Vessel length: 252 m, turbine height: 90 m, rotor diameter: 126 m.

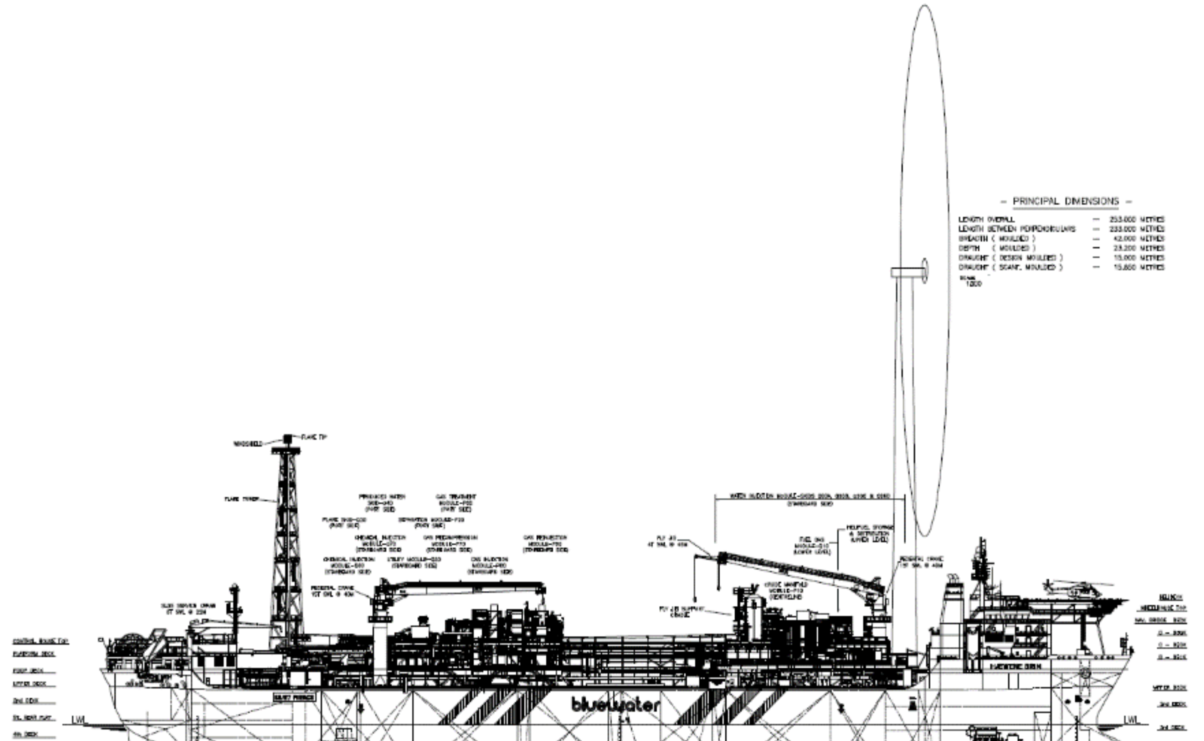


Figure 11: Wind turbine placed on forward of Haewene Brim. Vessel length: 252 m, turbine height: 90 m, rotor diameter: 126 m.

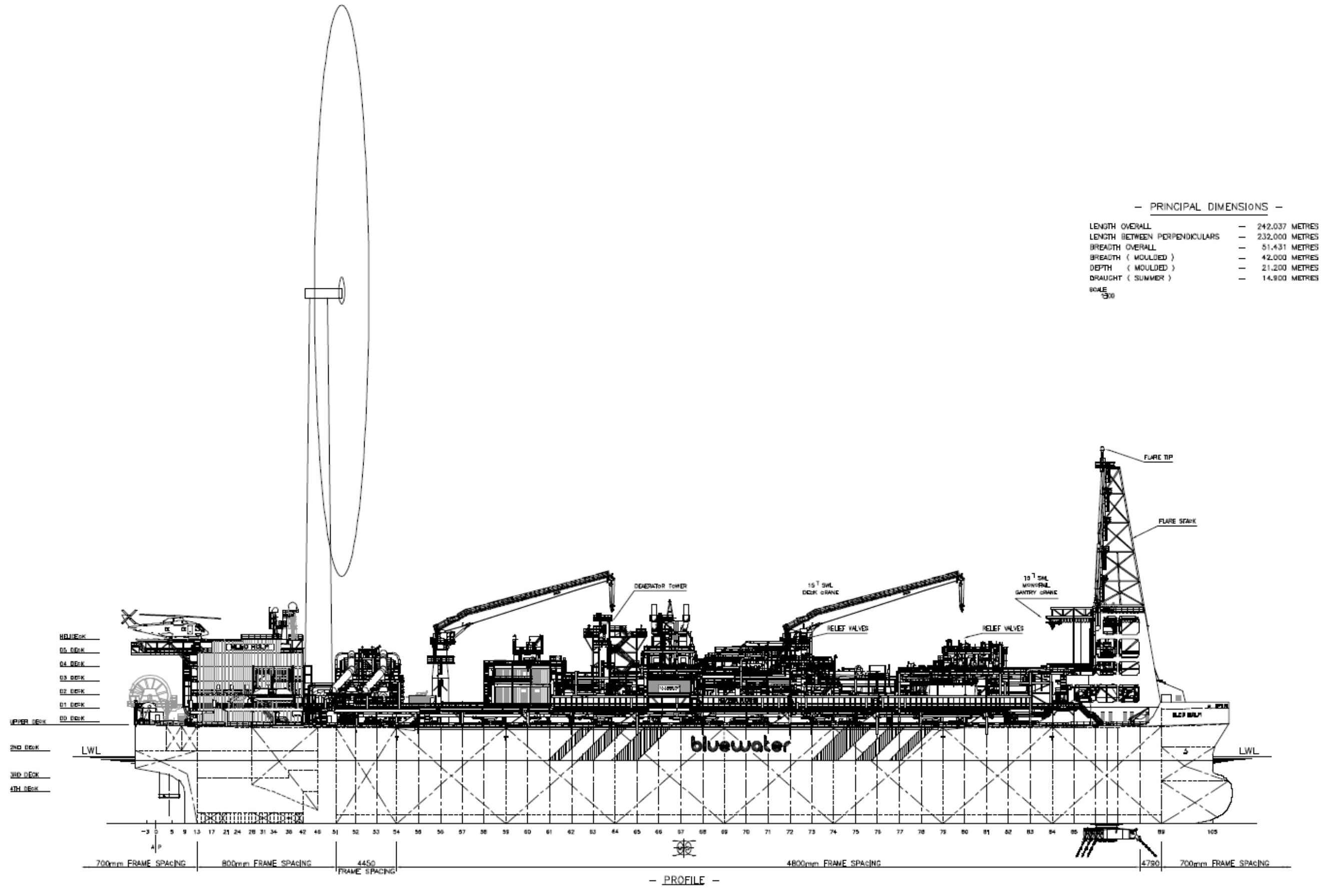


Figure 12: Wind turbine placed on aft of Bleo Holm. Vessel length 242.3 m, turbine height: 90 m, rotor diameter: 126 m.

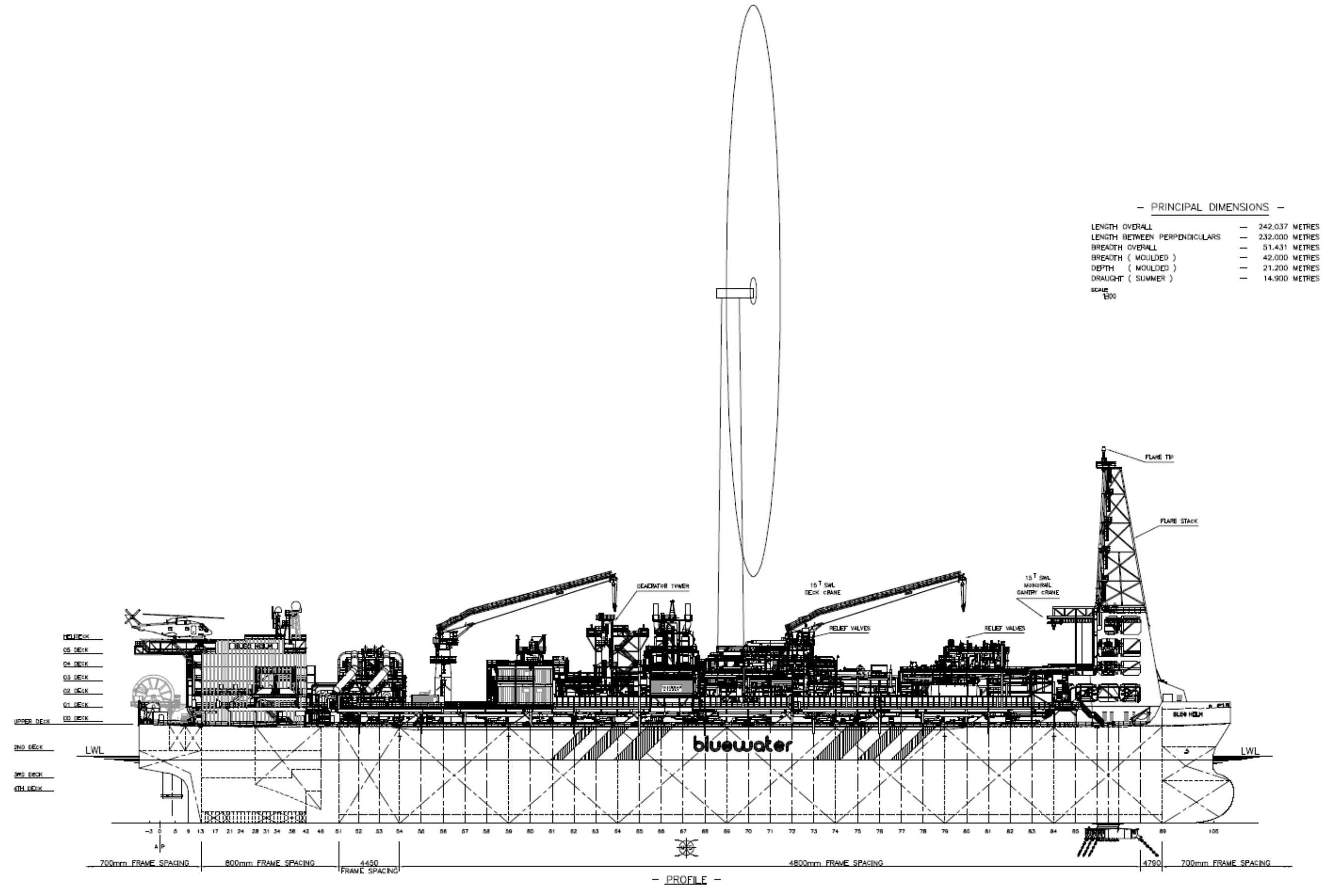


Figure 13: Wind turbine placed in the middle of Bleo Holm. Vessel length 242.3 m, turbine height: 90 m, rotor diameter: 126 m.

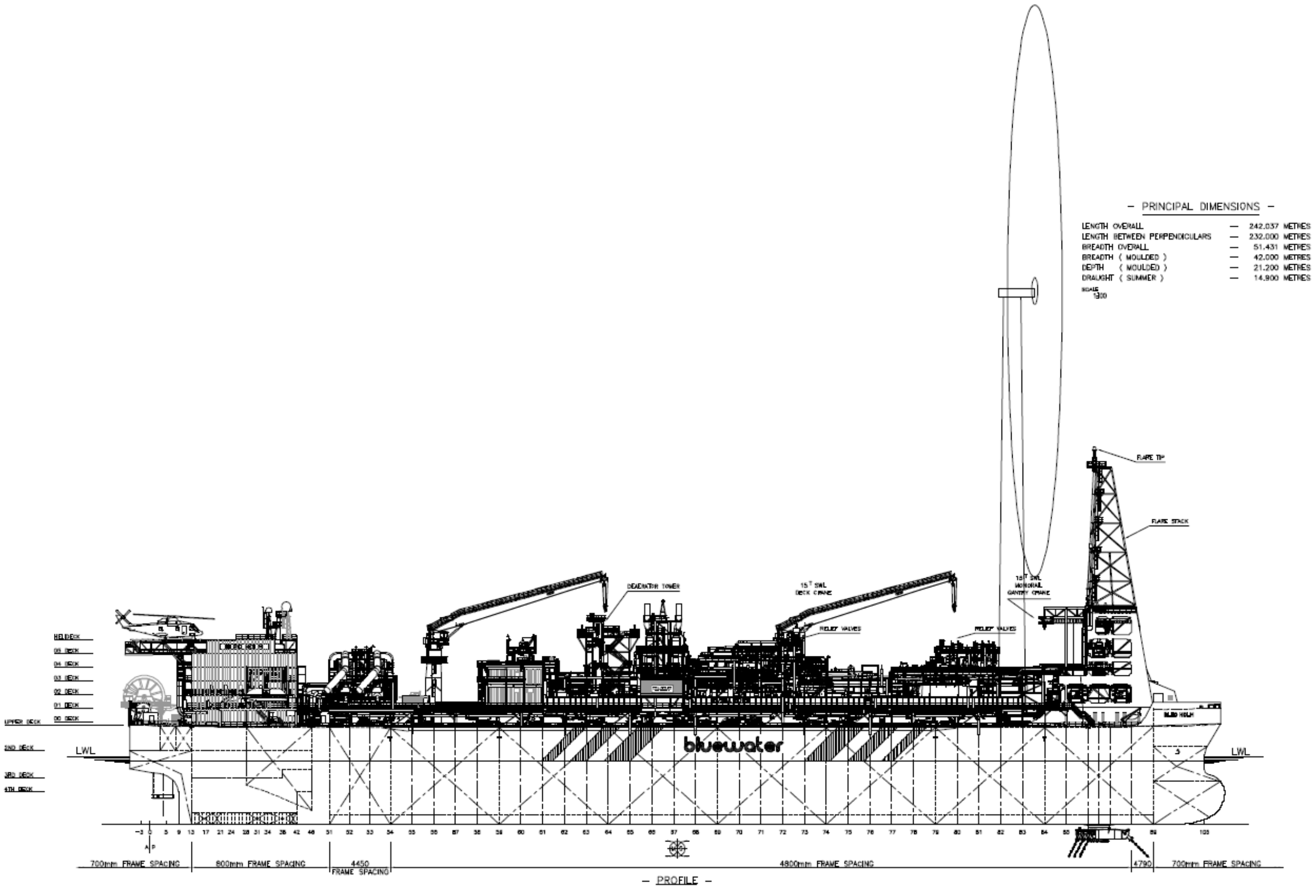


Figure 14: Wind turbine placed on forward of Bleo Holm. Vessel length 242.3 m, turbine height: 90 m, rotor diameter: 126 m.

2.5 Regulatory Compliance

In offshore operations, there are different regulatory regimes to take into account. These regulations contain strict legal guidelines and rules that have to be followed. This is to prevent disasters from occurring. For a floating vessel such as an FPSO, both class, flag state, and coastal regimes are relevant. Most of the FPSOs are flagged and classed, even though this is not always mandatory from a legislative perspective [11]. Class and flag regimes should always be complied with, independent of the FPSO's location. Coastal regimes are dependent on the FPSO's location and are according to the regulations of the country of which the FPSO lies within its coastal area.

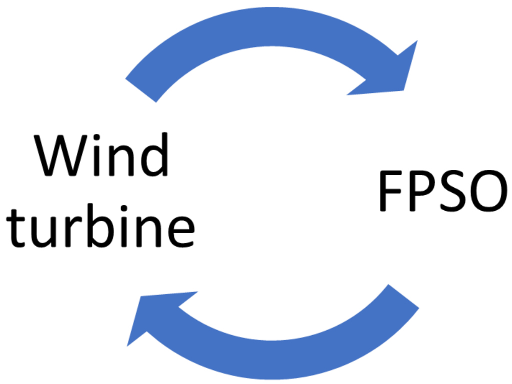
Besides these regimes, there are also design codes and standards. Next to this the helicopter operators also have their guidelines on offshore landing areas, the CAP437.

The goal of the HAZID is not to think of every rule and guideline that might or might not contribute to the realization of the project, but to approach the situation from a regulatory compliance perspective. Since a wind turbine on an FPSO topside is not considered, the legislation also might need to be formed after (technical) feasibility is proven.

3 Methodology

3.1 General

A HAZID (Hazard Identification) study is a technique for early identification of potential major accident hazards and major environmental incidents, which affect the operation of FPSOs with potentially a wind turbine on its topside (e.g. harmful to human life, environment and assets). The method focuses on identifying the additional hazards that would not be there if there was no wind turbine on the FPSO topside. It is considered very important that the hazard identification focuses on both hazards that occur due to the wind turbine which might affect the FPSO, and hazards that occur due to the FPSO which might affect the wind turbine.



3.2 Objectives of HAZID Study

The main objectives for the HAZID study are as follows:

- Recognise and identify the Health, Safety, and Environmental issues rather than to discuss the consequences and propose solutions;
- Evaluate alternatives, techniques, and technologies to maximize the positive and minimize the negative effects;
- Establish the requirements for further study and assessment in subsequent project activities;

3.3 Guidewords

The intention of applying guidewords [2] (see Appendix A) is to facilitate the discussion of the team with the identification of hazards. However, a study of this nature must never be limited to just the listed guidewords and opportunities will be provided for discussion of any other concerns raised by members of the team. For the assessment, a set of HAZID guidewords will be used. These guidewords are divided into four main sections:

- External and Environmental Hazards;
- Facility Hazards;
- Health Hazards;
- Project Implementation Issues.

3.4 Study Methodology

The HAZID study method is a combination of identification, analysis, and brainstorming based on the hazards identified with the support of a standardized set of HAZID Study Guidewords (refer to Appendix A). The major benefit of the HAZID technique is the identification and assessment of potential hazards, which provide essential input to project development decisions.

The Bluewater HAZID Study procedure [1] is used as guidance for this HAZID study, which will be performed systematically by a multi-disciplinary team with proper knowledge of FPSOs and wind turbines.

The HAZID will concentrate on the normal operating mode (design case) of both the FPSO and wind turbine. Here several different limit states are taken into consideration, namely the fatigue limit states (FLS), ultimate limit states (ULS), accidental limit states (ALS), and serviceability limit states (SLS). Furthermore, maintenance has to be performed during normal operations. Other operating modes i.e. start-up, shutdown, and pigging can be addressed during a HAZOP study in future research. If any points are found to be critical in other operating modes, or project phases for example installation, it may be discussed shortly.

3.5 Recording

The HAZID workshop shall be recorded using a HAZID worksheet that will be continuously projected onto a display screen during the workshop, to ensure that the worksheet is complete and understood by the team. The HAZID worksheet shall be completed as final as possible during the HAZID session itself. In general, it is expected that during the finalization of the report, only small textual additions or writing/ typos have to be supplemented.

An example of a typical Bluewater HAZID worksheet is also shown in Appendix A.

All identified potential hazards considered by the study team will be noted irrespective of whether an action is required. This is to record why certain hazards were dismissed or what safeguards rendered a particular risk as being insignificant. The team will make recommendations where necessary.

Risk ranking will not be performed for all hazard entries. If deems necessary and agreed upon during the workshop, risk ranking can be done for specific hazards.

All actions shall be assigned to a specific individual and not an organization or company. The actionee (who may not be present in the meeting) must have a clear understanding of the team's concern as well as the objectives and limits of the recommendation. The action/ recommendation must be clear, concise, and understandable on its own.

3.6 HAZID Study Report

The HAZID report will be prepared by the HAZID chairman, scribe, and student. The report will be created in such a way that it can integrate into the final thesis report.

3.7 HAZID Follow-up

From the results of the HAZID analysis, a choice is made for the scope for the continuation of the thesis. A risk assessment might take place. The choice is made in consultation with the graduation committee during a progress meeting where the student will bring up (several) suggestions. The results of the HAZID and the follow-up research will be documented in the thesis report.

4 Schedule and Planning

The HAZID study workshop is scheduled as follows:

Date: 25-02-2022

Time: 13:00 – 17:00

Venue: Bluewater Office, Taurusavenue 46, Hoofddorp, The Netherlands

The HAZID reviews will also be undertaken online via Microsoft Teams and the worksheet will be shared on screen.

At the beginning of the session, the Chair will kick off the meeting, followed by a short presentation on HAZID, and a more detailed presentation of the case study by the student. This is to ensure the team has a common understanding before starting the assessment.

Agenda points

13:00 – 13:15	Welcoming, Introduction presentation
13:15 – 15:00	HAZID brainstorm session
15:00 – 15:10	Break
15:10 – 16:50	HAZID brainstorm session continued
16:50 – 17:00	Round-up, final comments and questions, closing word

5 Participants

From BES and TU Delft the following participants with different backgrounds are required to attend the HAZID brainstorm session either at the venue or trough Microsoft Teams:

- Wind turbines
- Structural
- Naval
- Mooring
- Process
- HSE
- RC
- Maintenance
- Electrical

The attendees will fill in an attendance list at the start of day.

Appendix A – HAZID guide words and worksheet

Section A: External and Environmental hazards		
Category	**Guide Word**	**Expanders**
Natural and Environmental Hazards	Climate Extremes	Temperature, waves, currents, wind, dust, ice and snow (also accumulated), blizzards
	Lightning	Moving and dropped objects, rotating objects, mechanical equipment.
	Erosion	Operations outside design, fatigue
	Seismic Effects	Ground slide, structural failure
	Subsidence	Ground structure, foundations, reservoir depletion
Created (Man-made) Hazards	Security Hazards	Internal and external security threats
	Terrorist Activity	Riots, civil disturbance, strikes, military action, political unrest
	Aircraft impact	Visiting helicopters, passing helicopters, passing fixed wing aircraft.
	Loss of station	Mooring failure (mooring lines, anchor, spider, turret snagging of mooring lines). Loss of stability, loss of hull integrity, loss of control.
	Vessel Impact	Rig tenders, supply vessels, offloading (shuttle) tanker, standby vessel, lay barges, not-attendant vessel, support vessel, diving support vessels, floating installations, crane barges, bulk oil transports, tugs, material failure.
Effect of the Facility on the Surroundings	Geographical -Infrastructure	Location, pipeline routing
	Adjacent Area Use	Fishing grounds, other installations
	Proximity to Transport Corridors	Shipping lanes, airline routes, etc.
	Environmental Issues	Previous exploration/production campaign on locations, vulnerable fauna and flora, visual impact Social Issues Local population, local attitude, social/cultural areas of significance
Infrastructure	Normal Communications	Road links, air links, water links, radio link
	Communications for Contingency planning	
	Supply Support	Consumables/spares holding
Environmental Damage	Continuous Plant Discharges to Air	Flares, vents, fugitive emissions, energy efficiency
	Continuous Plant Discharges to Water	Target/legislative requirements, drainage facilities, oil/water separation
	Emergency/upset Discharges	Flares, vents, drainage
	Contaminated location	Previous use or events
	Facility Impact	Pipeline routing, environmental impact assessment
	Waste Disposal Options	
	Timing of Construction	Seasons, periods of environmental significance

Section B: Health Hazards		
Category	**Guide Word**	**Expanders**
Health Hazards	Disease Hazards	Endemic diseases, infection, malarial mosquitoes, hygiene - personal and/or catering, contaminated water or foodstuff, social, e.g. AIDS, VD, etc. stagnant water, poor living conditions
	Asphyxiation hazards	Asphyxiating atmospheres, failure to use appropriate PPE, vessel entry, working in confined spaces, smoke, exhaust
	Carcinogenic	Chemicals in use
	Toxic	Hazardous atmosphere, asphyxiating atmosphere, chemicals in use
	Physical	Noise, radiation (ionising, e.g. radioactive scale or non-ionising, e.g. flares, UV, sunlight), ergonomics
	Mental	Shift patterns
	Working Hazards	Diving, working in water, working at heights, hazardous equipment, hazardous surfaces, electricity
	Transport	Excessive journeys, extreme weather, quality of roads(mitigation measures include: effective journey management

Section C: Project Implementation Issues		
Category	**Guide Word**	**Expanders**
Contracting Strategy	Prevailing influence	Stability and contractual conditions, contractor selection constraints
	Legislation	Governmental contracting requirements
	External Standards	Additional engineering and construction standards
	External Environmental Constraints	Governmental environmental requirements
Hazards Recognition and Management	Hazard Studies	HAZOP, FEHA, Explosion Study, QRA , EIA, etc
	HSE Case	
	Hazards and Effects Register	
	Project Controls	Quality assurance (change control, interdepartmental involvement and interfaces)
Contingency Planning	Geographical Infrastructure	Plant location, plant layout
	Recovery Measures	Medical support, firefighting support, spill leak/clean-up support, security/military support, evacuation
Competency	Level of Indigenous Training	Quality of local workforce and contractors
	Training Requirements	
	Level of Technology	
Control Methods Philosophy	Manning/operations Philosophy	Effect on design, effect on locality (Manned, unmanned, visited)
	Operations Concept	Single train, multiple trains, simplification
	Maintenance Philosophy	Plant/train/equipment item, heavy lifting, access, override, bypass, commonality of equipment, transport

Section C: Project Implementation Issues		
Category	**Guide Word**	**Expanders**
	Control Philosophy	Appropriate technology, (DCS/local panels)
	Manning Levels	Accommodation, travel, supports requirements. Consistency with operations and maintenance, etc. philosophies
	Emergency Response g	Isolation, ESD philosophy, blow down, flaring requirements
	Concurrent Operations	Production, maintenance requirements
	Start-up Shutdown	Modular or plant wide

Section D: Facility Hazards		
Hazard Category	**Guide Word Expanders**	**(Examples of guide word application – not exclusive)**
Layout	Fire and Explosion hazards	
	Process hazards	
	Utility systems	
	Maintenance hazards	
	Construction/existing facilities	
Fire and Explosion Hazards	Stored Flammables	Improper storage, operator error (release), defect, impact, fire (mitigation measures include: substitute non-flammable, minimise and separate inventory), gas based fire, flight systems, hot material release (solid, liquid, gas)
	Sources of Ignition	Electricity, flares, sparks, hot surfaces (mitigation measures include: identify, remove, separate), hot work
	Equipment Layout	Confinement, escalation following release of explosive or flammable fluid (operator error, defect, impact process control failure, corrosion), module (cellulosic) layout/proximity, engine room, orientation of equipment, predominant wind direction (mitigation measures include: reduce degree of confinement, spacing based on consequence assessment, escalation barriers
	Toxic fumes and smoke generation/accumulation	Hydrocarbon release, methanol release, corrosive chemicals, lighting
	Fire Protection and Response	Active/passive insulation, fire/gas detection, blow down/relief system philosophy, firefighting facilities
	Operator Protection	Means of escape, PPE, communications, emergency response, plant evacuation

Section D: Facility Hazards		
Hazard Category	**Guide Word Expanders**	**(Examples of guide word application – not exclusive)**
Process Hazards	Hazardous Materials	Well fluid (storage) , processing equipment, natural gas, heli fuel, steam, bottled gas (e.g. acetylene, oxygen, halon, CO2, nitrogen propane), asbestos, processed gas, crude oil, condensate, corrosive chemicals, nitrogen, glycol, methanol, diesel, heavy fuel oil, high temperature materials, refrigerants, cryogenic materials.
	Inventory	Excess hazardous material (mitigation measures include: minimise hazardous inventory, alternate processes and utility systems)
	Release of inventory	Excessive process stress, impact (penetration by foreign object), process control failure, structural failure, erosion or corrosion (mitigation measures include: recognise and minimise process hazards during design, inherently safe plant, and containment and recovery measures), offloading operations, production slow out.
	Over Pressure	Offsite sources, process blockage, thermal expansion, connection of process to utility systems, chemical reaction
	Over/under Temperature	Atmospheric conditions, blow down, fire, hot surfaces, chemical reaction
	Excess/zero Level	Overfill storage tanks, loss of function in separation vessels, blow by to downstream vessels
	Wrong Composition/Phase	Offsite contamination, failure of separation process, build-up of wrong phase (sand, hydrates, etc.), toxic substances
	Diving Hazards	Operations control, interface of emergency system, failure of life support systems, sub surface difficulties, loss of diving vessel, entrapment.
Utility Systems	Firewater Systems	
	Fuel Gas	
	Heating Medium	
	Diesel Fuel	
	Power Supply	
	Steam	
	Drains	
	Inert Gas	
	Waste Storage and Treatment	
	Chemical/fuel Storage	
	Potable Water	
	Sewerage	

Section D: Facility Hazards		
Hazard Category	**Guide Word Expanders**	**(Examples of guide word application – not exclusive)**
Maintenance Hazards	Access Requirements	Processing facilities, engine room, pump rooms, confined sphere working, modifications, non-ionising radiation, slips, trips and falls, men over board, radioactive material and toxic substances.
	Override Necessity	
	Bypasses Required	
	Commonality of Equipment	
	Heavy Lifting Requirements	
	Transport	
Construction/ Existing Facilities	Tie-ins (shutdown requirements)	
	Concurrent Operations	
	Reuse of Material	
	Corrosion	
	Common Equipment	
	Capacity	
	Interface -	
	Shutdown/blow down/	
	ESD	
	Skid Dimensions (weight handling/equipment(congestion)	
	Soil Contamination(existing facilities)	
	Mobilisation/ demobilisation	

Sample HAZID worksheet

Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date

Appendix B – Wind turbine specifics

Turbine	NREL 5 MW reference turbine [3]
Control	Variable speed, collective pitch
Drivetrain	High speed, Multiple-Stage Gearbox
Operational data	
Rated power [MW]	5
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	25
Rated wind speed [m/s]	11.4
Cut-in speed [rpm]	6.9
Nominal speed [rpm]	12.1
Rated tip speed [m/s]	80
Rotor	
Orientation, Configuration	Upwind, 3 blades
Diameter [m]	126
Hub diameter [m]	3
Tower	
Hub height [m]	±90 (project dependent)
Tower mass [ton]	±347.5 (project dependent)
Top mass [ton]	
Rotor (hub + blades)	110
Nacelle + generator	240
Total top mass	350
Coordinate location overall center of mass	(-0.2 m, 0.0 m, 64.0 m)

Table B.1: Information on the NREL 5 MW reference turbine [3]

Appendix C – Wind turbine: overview possible failure modes

Objects	Function	Failure mode	Cause	Detection method
Blades	Capture wind	Fracture, edge crack, stuck, motor failure, pitch bearing failure	Fatigue loads higher than anticipated, extreme loads, environment influences, imbalance	Excessive vibration sensed by rotor bearing accelerometer in hub; high stresses recorded by operating instrumentation
Main shaft	Transmit large torque	Fracture	Fatigue loads underestimated; operation of WTG at off-design conditions; material properties below specs	Low-speed sensor; bearing vibration sensor
Yaw system	Enable the nacelle to rotate on the tower	Increased bearing friction	Cracked roller; galled surface; lack of lubrication	Yaw error signal
High-speed shaft	Stop and hold the shaft during shutdown and operation	Low or higher brake torque	Environment effect	Tachometer
Gearbox	Transmit torque with speed increase	Internal gear tooth failure	Fatigue loads underestimated; exceeding design load; improper material; loss of lubricating oil	Vibration sensor
Hub assembly	Transmit torque from blades	Structure failure; bolt failure	Excessing design loads; excessive preload; stress corrosion	Rotor bearing accelerometer; periodic inspection for loose or missing bolts
Oil seals	Retain oil in main bearing housing; exclude foreign matter	Cut or wear in lip	Installation damage; wear	Low oil switch
Filters	To extract and hold all particulate contaminants from hydraulic fluid	Case leakage	Damage to case or seals	Low oil; level switch
Generator	Generate electric power	Overheat; fault; jammed bearing; bearing seizure; overspeed;	Overload; no excitation; environmental effects; misalignment; fatigue; mechanical failure; loss of drivetrain control	Protective relays; overspeed detection; testing
Lubrication	Lubricate gearbox and rotor bearing	Loss of oil; overheating; oil under temperature	Pump failure; leakage; diverting valve failure; ambient temperature above or below design conditions; excessive friction losses; diverting valve failure	Oil flow switch; oil temperature sensor; air temperature

Table C.1: Overview of a wind turbines different types of failure modes [12]

Several wind turbine failures with big impact

Figure C.1: Wind turbine tower failure [13]

Figure C.2: Wind turbine hub on fire [14]

Figure C.3: Wind turbine blade throw [15]

Figure C.5: Wind turbine on fire after hit by lightning [17]

Figure C.4: Wind turbine blade failure [16]

C HAZID worksheet

See HAZID worksheet on next page.

Meeting:	Wind Turbine on FPSO topside - HAZID
Node	-
Meeting Date:	25th of February 2022
Notes:	The case study looks into the feasibility of placing a wind turbine on an FSPO topside. The wind turbine will provide electricity for the FPSO's electrical grid. The exact configuration of the wind turbine and FPSO is yet to be determined. This HAZID session is used to identify hazards for several different configurations. The terms of reference has provided the participants with background information on the case study and knowledge on the HAZID procedure.

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
	Facility Hazards								
	Layout	Configuration 1- Wind turbine close to flare tower	Flare flame / thermal radiation impact on WTG.	Potential damage of WTG blade and structure, losing the integrity of WTG, possibly resulting in dropping objects on FPSO escalating to FPSO integration leading to FPSO catastrophic failure, i.e. loss of position, fire, and explosion, causing multiple fatality and environmental impact.			The impact of dropping objects on the FPSO topside is to be assessed in detail with respect to severity and probability. Assumption of no continuous flaring. Assess flare radiation impact (during emergency flaring) on WTG. Can WTG be designed for the thermal radiation impact?		
			Flare flameout, flammable gas dispersion exposure to WTG.	Possible ignition of flammable gas cloud by WTG electrical system.	The sealing of WTG to be air/gas tight.		The quality of WTG sealing should be further investigated, since WTG have not been exposed to gas clouds before.		
			WTG blades collision with flare tower.	Loss of structural integrity. Damage or escalation due to dropping (parts of) WTG or flare tower.	Design should always have sufficient clearance between WTG and flare tower in all different configurations to prevent collision.		Based on the final decision of the positioning of the WTG, the WTG tower height might need to be adjusted.		
			Wake effect of flare tower on the WTG.	Wake effect of flare tower on WTG causing variable loading, potentially leading to loss of WTG integrity.	The WTG should be designed to fit for purpose, so it can deal with either free wind or turbulence.		The way that the WTG is handling the variable loading including this turbulence is to be assessed.		
		Configuration 2- Wind turbine close to process equipment	Loss of WTG blade and falling to the topside process area.	Loss of FPSO integration leading to FPSO catastrophic failure, i.e. loss of position, fire, and explosion, causing multiple fatalities and environmental impacts.			Assess if WTG blade falling on topside can penetrate the FPSO deck taking into account the brittleness of the blade structure versus the impact forces on the deck.		
			Loss of WTG blade and falling to the topside free topside deck.	See above.					
			WTG blade collision with crane boom. (SIMOPS[1])	Loss of structural integrity. Damage or escalation due to dropping (parts of) WTG or crane.	Design should always have sufficient clearance between WTG and cranes.				

[1] SIMOPS: Simultaneous Operations, procedure defines when and what simultaneous operation and activities can be done.

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Configuration 3- Wind turbine close to the helideck	Noise caused by the WTG WTG interference with helideck operation WTG blade falls on helideck, bridge, and general accommodation WTG location is close to telecommunication system in LQ.	Health implications for personnel. Possible collision of a helicopter with WTG leading to escalation on FPSO. Possible loss of total helideck leading to LQ impairment, causing multiple fatalities. Loss of FPSO access and exit. Potential of the WTG having impact on the telecommunication system of the FPSO resulting in disturbances of the system.	Sufficient noise-proof isolation of accommodations and use of hearing protection. Frequent start/stop of WTG when helicopter operation takes place.		Evaluating noise levels of WTG compared to existing FPSO equipment. Frequent start/stop needs to be assessed with respect to variable loading of WTG. Also, the impact on WTG lifetime is relevant. Assess if WTG blade falling on helideck can penetrate to LQ. Assess the impact of WTG operation on telecommunication.		
		Configurations general/all	WTG located at the aft of the FPSO. WTG blade or tower loss of integrity will fall down on FPSO topside. Interfering with crane activity. (SIMOPS) Offloading	Turbulence is created due to wind flowing over the FPSO deck which is exposed to the WTG. Potentially leading to FPSO's catastrophic failure as described above. Potential loss of structural integrity. Damage or escalation of the FPSO due to dropping (parts of) WTG or crane. During the shuttle tanker, no leading hazard scenario was identified especially when the wind turbine was placed on the bow side. In case of blade failure, the blade falls direction is at the side.	Design should always have sufficient clearance between WTG and cranes.		Check the WTG capabilities in design conditions, turbulence, environmental conditions, and location.		
		Maintenance Hazards of turbines	See later						
		Structural events (ship strength)	WTG load impact on FPSO.	Potential loss of FPSO integration, position, etc. leading to the catastrophic scenario if not designed for such loads.			The structural strength of the FPSO (hull) should be assessed for this new configuration including the WTG. Ballast tank opportunity for strength		
		Fire and Explosion Hazards (WTG to Ship)	Over speed of WTG Double failure of WTG control systems.	Double failure potentially results in fire of WTG. This might cause dropping pieces of WTG. Loss of structural integrity possibly leads to escalation on FPSO.			Check the possibilities of fire extinguishing means i.e. gaseous fire suppression system for WTG at height (>100m).		
		Fire and Explosion Hazards (Ship to WTG)	See later						
		Process Hazards	See later						
		Utility Systems	Consider large equipment, e.g. transformer to be located inside tower base.	The transformer can be placed inside WTG -> Opportunity.					

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Stability of vessel (VV[2])	Vessel motion Momentum due to wind force on WTG Not an issue: trimming of the FPSO	Resonance of the whole WTG and FPSO might occur. The momentum results in heeling of the vessel. This requires operation of the FPSO engines and WTG in inclination.	Average FPSO tonnage = 70000 tonne Average FPSO Dead weight tonnage = 100000 tonne Average 5 MW WTG weight = 700 tonne		To be clarified and assessed in more detail. Suggestion: Analysis of the motions of WTG on FPSO and consider both limitations of the vessel as WTG. Check how WTG operates under an angle.		
		Stability of WTG (VV)	WTG motion	Resonance of the whole WTG and FPSO. Variable loading of WTG due to roll motion of FPSO.			Perform a natural frequency check of WTG and FPSO.		
		Weather vane							
		Other							
	Maintenance Hazards of turbines	Access Requirements	4-6 time per year maintenance is required (including planned services). Adverse weather conditions	Maintenance operations inside the WTG. During adverse weather conditions the accessibility of the WTG is limited.	Scheduling yearly maintenance in statistically good weather seasons.				
		Override Necessity							
		Bypasses Required	Harbor entry	Harbor entries might not be possible due to the size of WTG on FPSO not fitting under bridges.	Maintenance has to be performed on-site or at specific harbors.				
		Commonality of Equipment							
		Heavy Lifting Requirements	Lifting of gearbox, generator, blade, ones or twice in a lifetime of 20 years	Potentially man-made mistake leading to dropped objects (see above consequence for falling blade, structure). An additional vessel is required for the lifting of the blade or other large components. This will introduce additional risks.	Heavy lift risk assessment before lifting.				
		Transport	Insufficient lay-down area available on FPSO for blades.	Need for crane vessels and equipment vessels. More SIMPOS and vessels movements required.					
		Lighting							
		Working at height	Climbing for visual inspection of the blades checking erosion, cracks, and fatigue.	The risk of someone falling during inspection which might lead to fatality.	Visual inspection using drones. Use of experienced climbers (competency certification).				
		Inspections	Who and How?	Training, no of POB, Rope access possible at same time with normal FPSO operations.					
	Structural events	Structural failure of the vessel	Fatigue by vibrations (VV)	Excessive vibration from generator not deemed a threat.					

[2] VV: Vice Versa

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Structural failure of WTG	WTG tower collapse due to bolt failure increase threat. Blade throw (see above). The main frequency of WTG vs large process rotating equipment.	Catastrophic failure, escalation. Impact on other subsea equipment equivalent or less than other drop object scenarios. Blade drops on FPSO deck (see above). Or blade hits the tower. The tower might fail towards the upwind direction.	Bolt tightening. Tower often fails towards the downwind side of WTG. A small probability of occurrence.		Occurrences/probabilities of tower failure or blade throw hazard. Check that blade throw often moves sideways from the wind direction. Assumption of sideways throws. Natural frequency/resonance check.		
		Mooring failure/riser lines	Rotor blade and total WTG structure fall into the water cutting 1 or more mooring cables or risers. The same scenario damaging subsea equipment.	FPSO loss of position, potential HC riser failure leading to fire and explosion, and environmental impacts due to hydrocarbons released into sea. Failure by either velocity impact and or weights of dropped objects.			To assess if the falling of WTG structure into the sea would lead to mooring line or riser failure. Impact assessment of sinking object (WTG parts).		
		Excessive motions / Vessel balance.	WTG control system not functional. Vessel motions have an effect on WTG yaw. Rotor blades act as sail.	Worse alignment of the blade with the wind (wrong pitch condition), leading to severe vibration, and instability of WTG tower and collapse. Tower will collapse before leading to instability of the entire FPSO. Forces on rotor blades acting as sail deemed as no real threat.	Back-up power for WTG (control pitch system), only double failure of WTG will lead to this situation. Natural frequency WTG tower 0.2 -2 Hz. Not an issue.		Assess likelihood of WTG control system (double) failure.		
		Foundation failure	Foundation, in this case could be deck or hull, failing.	Falling over of entire WTG structure.	Foundation bolt tightening.				
		Loss of buoyancy/increase of buoyancy	No threat, mostly horizontal forces (no significant effects).						
	Fire & Explosion	Turbine fires Transformer fires	WTG fire. Electrical fire, overheating, transformer oil.	Loss of WTG mainframe integrity leading to catastrophic failure and escalation on FPSO.	Fire retardant material i.e. for cable.		Assess probability of occurrence for a WTG fire. Check the possibilities of fire extinguishing means i.e. gaseous fire suppression system for WTG at height (>100m).		
		Sources of Ignition	Transformers, mechanical equipment failure. (Switchgear in the base of the wind turbine tower.)	Possible ignition of gas leak scenario from FPSO topside process area.			Check with flare gas dispersion and FPSO topside process area leak scenario if they could impact and reach the wind turbine.		
		Electrical Fire	No HV slip ring in this configuration.						
		Equipment Layout	Spacing requirements based on heat radiation contours.	See page 1 question 1-3					
			Location of TR (Temporary Refugees) impact on WTG failure.	See page 1 question 1-3			Temporary Refugee and Primary Muster area impairment by WTG failure is to be assessed.		

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Toxic Fumes & smoke generation / accumulation	Toxic fumes, gasses accumulation in tower shaft		The turbine is well sealed. Hard for gas (clouds) to enter. Shaft is a normally unmanned area in the WTG.				
		Fire Protection and Response (ERP)	Fire protection from (topside) vessel scenario. ERP: Rope access required. Maintenance and Inspections need for evacuation lines.		Passive fire protection (PFP) material.		Check the possibilities of fire extinguishing for WTG at height (>100m). Means of escape and evacuation (survivability and timing) from WTG to be assessed against FPSO MAH (major accident hazards).		
		Operator protection	Hazards with respect to egress and escape routes.	More travel distance and time from personnel working on a WTG to muster area.			See above action.		
	Process Hazards	Hazardous Materials (from vessel to WTG)	Toxic and explosive gasses as above.				ATEX Check if electrical and mechanical equipment need to meet ATEX requirement.		
		Inventory	Unchanged as a result of the WTG project.						
		Release of Inventory / toxic gasses	No hazards identified. No toxic gas is handled inside the WTG.						
		Over Pressure from vessel to WTG	Not applicable. Fire scenario is only expected from WTG.	Explosion scenario from process area impacting WTG.	WTG shall be designed for accidental blast load.				
		Over Pressure from WTG to the vessel	Fire only						
		Over/under temperature	No threat identified						
		Excess / Zero Level	No threat identified						
		Wrong Composition / Phase	No threat identified						
		Flaring	See above question 1. Emergency flare.		Switch off WTG.				
		Cranes	Exposed by wind hit every 3 seconds due to wake effects by WTG.	Potential loss of integrity of crane structure.			Check influence of WTG wake effects on crane operability and structural integrity.		
		Vents / Exhaust	N/A Various exhaust location		Normally airtight tower design. Exhaust gasses cannot penetrate tower base.				
		Diving Hazards (WTG on diving personnel)	N/A						
		Shadow	Flickering effects of WTG rotating blades	Possibly disturbs visual detection systems.					
	Utility Systems for WTG	Firewater Systems	N/A				Gaseous fire repressing systems required?		

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Fuel Gas	As a minimum unchanged or even positively influenced as a result of WTG project using the electrical energy on-board (zero emission).				Opportunity. Gas turbine feed with (stored) compressed natural gas versus diesel usage nowadays (CO_2 Footprint).		
		Heating Medium	Unchanged as a result of the WTG project.						
		Diesel Fuel	As a minimum unchanged or even positively influenced as a result of WTG project using the electrical energy on-board (zero emission). Opportunity for electrical propulsion.						
		Power Supply	(VV) Electrical grid FPSO and WTG. Use of transformer.		Demand-supply balancing.		Discuss with E&I separately		
		Electrical sub-sea cables	No HV slip ring in this configuration						
		Steam	As a minimum unchanged or even positively influenced as a result of WTG project using the electrical energy on-board (zero emission).						
		Drains	No threat identified						
		Inert Gas	Unchanged as a result of the WTG project.						
		Waste Storage and Treatment	Unchanged as a result of the WTG project.						
		Chemical / Fuel Storage	No threat identified						
		Potable Water	Unchanged as a result of the WTG project						
		Sewerage	No need for sewerage						
	Other (WTG specific)	Hazards introduced during abnormal states	Breaks of WTG failing. Other WTG failure modes.	Out of control WTG. Similar scenarios as explained above. (Dropping objects leading to FPSO escalation) No additional hazards	Redundancy in failure modes, low likelihood for double failure of WTG control systems.				
	External and Environmental Hazards								
	Natural and Environmental Hazards	Climate Extremes	Extreme Weather. 1000 years storm.	See wind loads, Vibrations, Balancing etc.					
			High wind speed	The possibility of having extreme wind condition in combination with worst blade alignment results in an excessive failure of WTG leading to crazy spinning of the WTG blades.	WTG provides counter torque for spinning. The Control systems should all fail before this occurs (Double failure). Low likelihood.				
			Extreme waves	See above, extreme forces on the tower.					
			Temperature	No consequence identified.					
			Current	No consequence identified.					
			Swell	No consequence identified.					

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
			Salty air conditions	Possibly leading to corrosion of WTG.	Use of a corrosion preventive coating.				
		Lightning	Lightning Impact	Fracture at wind turbine blade since lightning impact instantly heats up the air inside the blade.	Existing lightning protection mechanisms for WTG.				
		Erosion	Fatigue	Cracks in blades potentially leading to blade failure or dropped blade (parts) in case of not properly tracked maintenance.	Visual inspections leading to WTG blade repairs or replacements.				
		Seismic Effects	No threat identified Tsunami as large swell						
		Other	No other threat identified						
	Created (Man-Made) Hazards	Security Hazards	Not looked at in detail						
		Terrorist Activity	Not looked at in detail						
		Aircraft impact (the highest point being >100 m)	Helicopter operations (landing and take-off limitations)	Potential collision of helicopter with WTG. Especially when WTG is effecting the wind conditions while operating.	Always shut down WTG for helicopter operations.		Speak to helicopter operator to receive insight on their viewpoint.		
		Loss of Station	Loss of station has not been looked in detail.						
		Vessel Impact/collision	External vessel i.e. shuttle tanker, supply vessel, etc. impact to FPSO causing acceleration force to wind turbine.	Potential wind turbine tower collapse. Loss of structural integrity leads to escalation.					
		Shuttle tanker loading	Different position through unexpected weather vane motion.		ESD - Disconnect				
		Dropped Objects	Discussed. See above.						
	Effect of Facility on the Surrounding	Geographical – Infrastructure	Ports to enter with overall height > 100 meters has been discussed as a potential risk in future port options.						
		Adjacent Area use	Any limitations, by legislation? Surge by blades has been discussed and deemed a minimum risk.	Limited use of area under blades.			Are we allowed to work under / in the vicinity of rotating blades?		
		Proximity to Transport Corridors	Not discussed in detail. Standard is 500 meter zone around FPSO.						
		Environmental Issues	See later. No other issues identified.						
	Infrastructure	Normal Communications	Unchanged as a result of the WTG project. As per FPSO and Marine regulations.						
		Communications for Contingency planning	External need to stop producing electricity to the grid not part of the options.		Contingency is the back-up generator in case of shut-down, no wind etc.				
		Supply Support	As per FPSO / vessel today						
	Environmental Damage	Continuous Plant Discharges to Air	Discharges are not foreseen.						

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Continuous plant Discharges to Water	Discharges are not foreseen.						
		Emergency / Upset Discharges	Diesel generator as is existing today.						
		Contaminated Location	N/A						
		Facility Impact (on e.g. sea, marine life, birds)	Not looked at in detail						
		Waste Disposal Options	N/A						
		Timing of Construction	Construction Hazards will be treated as separate items.						
		Other	Leak in FPSO deck due to blade impact on FPSO.	Hydrocarbons leak into the sea resulting in environmental damage for local ecosystem.			Brittleness of the epoxy blades shall be verified.		
	Health Hazards								
	Safety and Health Hazards (to personnel)	Work disease hazards	Stroboscopic effects. Sound in accommodation.	Mental problems Health implications - Sleep problems					
		Asphyxiation Hazards	Asphyxiation Hazards are not foreseen. See toxic gasses.						
		Carcinogenic	Carcinogenic Hazards are not foreseen.						
		Toxic	Toxic release from topside and flare fumes into the enclosed shaft.		See above.				
		Electrocution	Not discussed in detail E&I not present in this part of the HAZID.				Discuss with E&I separately		
		The noise of WTG to personnel	Additional noise due to WTG.	Health implications for personnel.	Sufficient noise-proof isolation of accommodations and use of hearing protection.		Check of noise levels of WTG compared to existing FPSO equipment.		
		Physical of WTG to personnel	Climbing 80 meter shaft.		Lift				
		Mental of WTG to personnel	Flickering effects of rotating blades of WTG.	Shock reactions of personnel / anxiety. Possibly results into mental but also physical harm on the long term.					
		Vibrations of WTG to personnel	None foreseen.						
		Working Hazards	Normal operations: High turbulent wind Upset conditions: Work from TR Maintenance: Height, rope access, training, heavy lifts.	Due to wake effects of WTG vortices occur which might be a danger to people walking on deck. Upset conditions can automatically be addressed and bring wind turbine to a safe condition.	All remote operated.		Confirm wake effects to operation personnel on main deck are limited.		
		Transport	No change.						

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Recovery of injured personnel	Limitations on Helicopter.						
		Evacuation	Hazards with respect to egress and escape routes.	More travel distance and time from personnel working on a WTG to muster area.					
		Fear of/for windmill	Dangerous situation by distraction Non acceptance of personnel						
	Project Implementation Issues (not looked at in detail)								
	Contracting Strategy	Obtaining WTG	Manufacturers will not provide just any WTG for this purpose.		WTG has to be designed for this specific configuration.		Cooperation with the manufacturer to obtain WTG.		
		Electrical Power Connection	Not discussed in detail E&I not present in this part of the HAZID.				Discuss with E&I separately		
		Legislation	Not discussed in detail						
		External Standards	Outside regular FPSO, Flag & State or coastal.	Class and coastal have to evaluate the new situation.	Not many existing requirements.				
		External Environmental Constraints	Sea life interference	Not determined in this session					
	Hazards Recognition and Management	Hazard Studies	Not discussed						
		HSE Case	Not discussed						
		Hazard and Effects Register	Not discussed						
		Project Controls	Not discussed						
	Contingency Planning	Geographical - Infrastructure	N/A						
		Recovery Measures	N/A						
	Competency	Level of In house Training	New specialist operator needed on FPSO						
		Training Requirements	Not discussed						
		Level of Technology (High Voltage)	Not discussed in detail E&I not present in this part of the HAZID.				Discuss with E&I separately		
	Control Methods Philosophy	Manning / Operations Philosophy	New specialist operator needed on FPSO						
		Operation Concept	Multiple start – stop situations, by e.g. helicopter landing, hard wind, etc. leading to unsafe situations in the long run as the life expectancy of a WTG is dependent of no. start / stops.						
		Maintenance Philosophy	Discussed						

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
		Control Philosophy	Discussed no issues foreseen.						
		Manning Levels	No issues foreseen.						
		Emergency Response	During WTG erection as above.						
		Concurrent Operations	SIMOPS as detailed out above also available during project execution.						
		Start-up / Shutdown	Not discussed						
	Facility Hazards								
	Construction / Existing Facilities	Tie-ins (shutdown requirements)	Connect to 'Island' grid of FPSO.				Discuss with E&I separately		
		Concurrent operations	SIMOPS as detailed out above						
		Reuse of Material	N/A						
		Corrosion / structural strength	As discussed above. Metal frame in tower exposed to rain, wind and salt.						
		Common Equipment	Location of transformer.						
		Capacity	Not discussed						
		Interface(s)	Not discussed in detail here.						
		Shutdown / Blowdown	Hazards introduced by frequent start – stop.						
		ESD	Discussed						
		Equipment Dimensions (weight handling / equipment (congestion)	1000 tons heavy lifting.						
		Heavy lifting	Replacing blades.						
		Lay–down area	See above on vessel risks						
		Structural Loading	See above on details and opportunities				Talk to Structural / Marine on the opportunities.		
		Soil Contamination	N/A						
		Mobilisation / demobilisation	No significant changes.						

Hazards resulting from separate interviews with Mooring Discipline and Electrical & Instrumentation.

#	Hazard Category	Guideword	Threat/Cause	Consequence	Safeguards	#	Action	Actionee	Date
	Mooring, Marine, Subsea								
		Weather vane	WTG placed further away from turret.	Increasing impact on heading of FPSO.	Possibility of using WTG as weather vane compensation. Reduction in power production as a consequence.		Assessment of weather vane capabilities for new configuration.		
		Dropped objects	Dropped object onto risers or polyester mooring components.	Broken risers resulting in leaking hydrocarbons into sea. Potential loss of station (mooring).	Subsea protection until 10 ton on seabed.				
			Opportunity: further away from turret means further away from mooring and risers in the water column.		Opportunity: steel mooring chains.				
		Mooring system	Uncertainty impact forces due to WTG on mooring system.	Potential loss of station.			Assessment of additional wind loads on WTG. Influence on mooring.		
	Electrical & Instrumentation								
		Environmental hazards	Lightning	Blackout Fire Electric shock	Lightning protection material. Use of correct material for foundation.				
		Power balancing	Excess Supply	Grid overload	Energy storage: batteries. Start stop turbine.		Requires power balance monitoring systems.		
		Cable Installation	Excessive movements wind turbine hub	Cable might damage/break	Strong connection and proper installation of cables.				
			Control System Failure	Power shortage for FPSO. Shutdown.	Back-up power and control systems.				
		Transformer	No hazard Opportunity: Inside tower						
			Opportunity: Batteries inside tower.						
		EMC Interference	Electric magnetic fields	Results in disturbance of antennas and radars.	Shielding and earthing of equipment.		Effect of WTG on FPSO systems has to be investigated. The range of electric magnetic field is critical here.		

Opportunities

Opportunities	
Layout	A transformer with the size of approximately a container can be placed inside the WTG.
	Regarding placement of the WTG: the motions (especially pitch and heave) excited by the FPSO onto the WTG are least in the middle or just aft of the middle of the FPSO. This results in the least forces on the WTG equipment.
	Placing WTG on the side of the FPSO, resulting in similar integration as a crane.
Design	Inclined WTG tower (outside of hull)
	Downwind WTG
Information	Speaking to helicopter operator
Energy Production	Connection to grid simultaneously or producer for local grid as standalone platform (use of FPSO in lay-up)

D Vessel properties for Haewene Brim

The vessel data in this appendix is extracted from Bluewater's loading manual for Haewene Brim prepared by DNV Maritime Consultants [104][27]. Tables D.1 and D.2 show how for both load cases Ballast and Fully Loaded including the wind turbine the total weight, mass moment in the longitudinal direction (ML), the mass moment in the vertical direction (MV) and free surface moment (FSM) are computed. The tables D.3 until D.6 show values for several vessel-specific properties under certain specified conditions. The loading manual shows a broader range of values. Only the values that have been used are displayed here. The appendix also contains an overview of the effect that different levels of trim have on the resulting values for GM and KG and an evaluation of the intact stability criteria at these different levels of trim.

D.1 Overview of load cases

	Item	Cap m3	Rho t/m3	Weight t	LCG m	ML t.m	VCG m	MV t.m	FSM t.m
	Lightweight ship			31767.7	121.81	3869765	18.95	602121	0
	Topside fluids			737.2	86.83	64011.08	31.03	22875.32	0
	Water ballast			48687.1	114.08	5554224	8.77	426985.9	4432.7
Wind turbine	Hub			350	117	40950	130.6	45710	0
	Tower			417.64	117	48863.9	69.92	29201.39	0
	Structural integration			250	117	29250	14.1	3525	0
	Total sum			82209.64		9607064		1130419	4432.7

Table D.1: Overview of load case Ballast including wind turbine.

[27] Reference coming from Bluewater's Meridian database (not publicly accessible).

	Item	Cap m3	Rho t/m3	Weight t	LCG m	ML t.m	VCG m	MV t.m	FSM t.m
	Lightweight ship			31768	121.81	3869765	18.95	602121	0
CAL	No. 1 CCo Tk	3580.1	0.907	3180.6	174.35	554537.61	13.2	41983.92	1970.7
	No. 2 CCo Tk	6784.9	0.907	6028.3	154.8	933180.84	13.2	79573.56	3734.9
	No. 3 CCo Tk	6789	0.907	6031.3	129.2	779243.96	13.2	79613.16	3737.2
	No. 4 CCo Tk	6789	0.907	6031.3	103.6	624842.68	13.2	79613.16	3737.2
	No. 5 CCo Tk	6784.9	0.907	6028.3	78	470207.4	13.2	79573.56	3734.9
	No. 6 CCo Tk	3394.2	0.907	3015.6	58.8	177317.28	13.2	39805.92	1868.4
	No. 1 SCO TK P	5389.4	0.907	4788.6	178.29	853759.494	13.32	63784.152	3037.
	No. 1 SCO TK S	5389.4	0.907	4788.6	178.29	853759.494	13.32	63784.152	3037.5
	No. 2 SCO TK P	6474.1	0.907	5752	154.8	890409.6	13.32	76616.64	3740
	No. 2 SCO TK S	6474.1	0.907	5752	154.8	890409.6	13.32	76616.64	3740
	No. 3 SCO TK P	4046.3	0.907	3595	134	481730	13.32	47885.4	2337.5
	No. 3 SCO TK S	4046.3	0.907	3595	134	481730	13.32	47885.4	2337.5
	No. 4 SCO TK P	6474.1	0.907	5752	103.6	595907.2	13.32	76616.64	3740
	No. 4 SCO TK S	6474.1	0.907	5752	103.6	595907.2	13.32	76616.64	3740
	No. 5 SCO TK P	6474.1	0.907	5752	78	448656	13.32	76616.64	3740
	No. 5 SCO TK S	6474.1	0.907	5752	78	448656	13.32	76616.64	3740
	No. 6 SCO TK P	3191.8	0.907	2835.8	58.85	166886.83	13.43	38084.794	1869.7
	No. 6 SCO TK S	3191.8	0.907	2835.8	58.85	166886.83	13.43	38084.794	1869.7
DO	Do Servtk P	14.7	0.9	13	219	2847	11.66	151.58	0.7
	Do Servtk S	14.7	0.9	13	219	2847	11.66	151.58	0.7
	Do Stortk P	62.6	0.9	55.2	219.72	12128.544	14.34	791.568	4.6
	Do Stortk S	62.6	0.9	55.2	219.72	12128.544	14.34	791.568	4.6
	No. 1 HFO Stor P	240.7	0.9	212.3	219.74	46650.802	8.83	1874.609	3.8
	No. 1 HFO Stor S	240.7	0.9	212.3	219.74	46650.802	8.83	1874.609	3.8
	HFO Servtk P	59.9	0.9	52.8	219.8	11605.44	14.07	742.896	2.2
	HFO Servtk S	59.9	0.9	52.8	219.8	11605.44	14.07	742.896	2.2
	HFO Sett tk P	59.9	0.9	52.8	219.8	11605.44	14.07	742.896	2.2
	HFO Sett tk S	59.9	0.9	52.8	219.8	11605.44	14.07	742.896	2.2
	No. 2 HFO Stor S	1143.1	0.9	1008.2	191.87	193443.334	13.35	13459.47	460
FW	No. 1 Drink WTk P	113.9	1	113.9	225.16	25645.724	25.65	2921.535	0
	No.2 Drink WTk P	127.7	1	123.8	225.01	27856.238	25.67	3177.946	169.5
	No.1 FW Tk. (S)	241.6	1	239.3	225.08	53861.644	25.67	6142.831	964
	No.2 FW Tk. (P)	265.4	1	265.4	8.51	2258.554	20.24	5371.696	0
	No. 2 FW Tk.(S)	265.4	1	265.4	8.51	2258.554	20.24	5371.696	0
GLY	No.2 HFO Stor P	1143.1	1.11	222	191.87	42595.14	5.04	1118.88	545
LO	LO Sett tk P	13.7	0.9	11.9	210.58	2505.902	15.39	183.141	1.7
	LO Sett tk S	13.7	0.9	11.9	210.58	2505.902	15.39	183.141	1.7
	Lo Stor tk P	23.8	0.9	20.6	208.57	4296.542	15.38	316.828	4
	Lo Stor tk S	23.8	0.9	20.6	208.57	4296.542	15.38	316.828	4
	No. 1 LO Sump S	22.3	0.9	20.1	205	4120.5	9.25	185.925	0
	No. 2 LO Sump S	24.9	0.9	22	204.92	4508.24	9.24	203.28	34.8
	No. 3 LO Sump S	22.4	0.9	20.2	204.9	4138.98	9.25	186.85	0
	No. 4 LO Sump S	23.2	0.9	20.9	204.87	4281.783	9.25	193.325	0
MIS	Bilge hold tk F	66.3	1	19.7	204.2	4022.74	2.85	56.145	506.2
	Bilge hold tk A	17.7	1	5.2	24.71	128.492	0.42	2.184	6.5
	CHAIN LOCKER TANK PORT	5.87							
	CHAIN LOCKER TANK STB	5.87							
	C.W.Tk	39	1	39	9.19	358.41	3.51	136.89	0
	FO over/drain	37.3	1	11.1	208.6	2315.46	2.85	31.635	160.2
	No. 1 FO/Lo sludge	11.3	1	1.2	212.6	255.12	3.4	4.08	1.6
	No. 2 FO/Lo sludge	11.3	1	1.2	212.6	255.12	3.4	4.08	1.6
	Lo Drain P	6.2	1	1	208.6	208.6	2.74	2.74	0.7
	Lo Drain S	6.2	1	1	208.6	208.6	2.74	2.74	0.7

	Item	Cap m3	Rho t/m3	Weight t	LCG m	ML t.m	VCG m	MV t.m	FSM t.m
MIS	Sepa.bilge tk	33.1	1	9.8	206.6	2024.68	2.85	27.93	252.7
SL	SLOP TK P	1691.3	1	1657.5	45.93	76128.975	13.77	22823.775	274
	SLOP TK S	1691.3	1	1657.5	45.93	76128.975	13.77	22823.775	274
WB	APTK	888.1							
	No.1 FWD DB WBT P	641.5							
	No.1 FWD DB WBT S	641.5							
	FPTK	2269.5	1.025	1856.3	226.7	420823.21	15.87	29459.481	5608.1
	No.1 Mid WBT C	3040.5							
	No.1 AFT WBT P	1448.2							
	No.1 AFT WBT S	1448.2							
	No.2 WBT P	2816.2							
	No.2 WBT S	2816.2							
	No. 3. WBT P	5033.1							
	No. 3. WBT S	5033.1							
	No. 4 DB WBT P	1894.2							
	No. 4 DB WBT S	1894.2							
	No. 5 WBT P	2753.5							
	No. 5 WBT S	2753.5							
	No. 6 WBT P	2154.4							
	No. 6 WBT S	2154.4							
	No. 7 WBT P	3755.2							
	No. 7 WBT S	3714							
	No. 4 Wing WBT P	922	1.025	945.1	103.6	97912.36	12.73	12031.123	0
	No. 4 Wind WBT S	922							
Wind turbine	Hub			350	117	40950	130.6	46497.5	0
	Tower			417.64	117	48863.88	69.92	29501.39	0
	Structural integration			250	117	29250	14.1	3525	0
	DWT Const (AFT)			80	20.4	1632	16.1	1288	0
	DWT Const (MID)			20	118	2360	23.2	464	0
	DWT Const (MID)			50	218	10900	19.3	965	0
	Container laydown area ps			60	142.6	8556	29	1740	0
	P10 Crude Manifol.			38.9	154.99	6029.111	35.95	1398.455	0
	P20 Separation Mo.			154	68.33	10522.82	33.86	5214.44	0
	P60 Gas Treatment.			28.6	77.11	2205.346	32.03	916.058	0
	P70 Gas Recomress.			11.7	74.67	873.639	28.72	336.024	0
	P80 Gas Injection.			60	87.38	5242.8	29.78	1786.8	0
	P90, Gas Re-Inject.			4.1	98.99	405.859	32.77	134.357	0
	Q20 utility Modul.			64	63.76	4080.64	31.11	1991.04	0
	Q30 Flare Skid (f.			13	48.2	626.6	30.1	391.3	0
	Q40 Produced Wate.			21.2	56.9	1206.28	30.23	640.876	0
	Q60 Chemical Inje.			78.5	49.01	3847.285	29.57	2321.245	0
	Q70 Infill Skid (.			8.9	54.98	489.322	36.79	327.431	0
	T100 General Tops.			31.9	100.55	3207.545	33.99	1084.281	0
	T102030 Piperack.			15.6	140.07	2185.092	44.52	694.512	0
	T50 Piperack (flu.			15	74.82	1122.3	32.74	491.1	0
	X104060 (fluids)			34	116.81	3971.54	25.64	871.76	0
	Q90A Filt. skid.			18.4	149.59	2752.456	34.19	629.096	0
	Q90B Water inj. s.			5.2	158.77	825.604	29.07	151.164	0
	Q90C Chem inj aft.			30.3	171.7	5202.51	34.72	1052.016	0
	Q90D Chem inj. fw.			6.5	179.18	1164.67	33.22	215.93	0
	BrownField (fluid.			80.6	81.58	6575.348	21.53	1735.318	0
	P120 SAND HAND &.			16.8	87.68	1473.024	29.35	493.08	0
	Small tk FWD ER			15	205	3075	16	240	0
	Small tk AFT ER			10	30	300	16	160	0
	TOTAL SUM			130387.84		15722708.5		2003009.5	65010.7

Table D.2: Overview of load case Fully Loaded including wind turbine.

D.2 Vessel stability properties

Case	TK [m]	T [m]	VOLT [m^3]	DISP [t]	KMT [m]	LCB [m]	LCF [m]	MCT [tm/cm]	TPC [t/cm]
Trim -1 m	10.32	10.30	78798.1	80768.1	18.939	124.461	120.866	1240.97	84.83
	10.42	10.40	79626.5	81617.2	18.867	124.423	120.728	1245.32	84.94
	10.52	10.50	80456.0	82467.4	18.798	124.384	120.589	1249.74	85.04
Trim 0 m	10.32	10.30	78653.7	80620.0	19.014	122.913	120.339	1262.79	85.31
	10.42	10.40	79486.7	81473.9	18.941	122.885	120.205	1267.70	85.42
	10.52	10.50	80320.6	82328.6	18.871	122.857	120.068	1272.51	85.53
Trim 1 m	10.32	10.30	78526.4	80489.5	19.094	121.335	119.774	1289.20	85.88
	10.42	10.40	79363.7	81347.7	19.02	121.318	119.644	1289.20	85.88
	10.52	10.50	80202.0	82207.1	18.949	121.300	119.514	1294.15	85.99
Trim 2 m	10.32	10.30	78418.6	80379.1	19.180	119.727	119.150	1307.42	86.26
	10.42	10.40	79260.5	81242.0	19.105	119.720	119.023	1312.85	86.38
	10.52	10.50	80103.7	82106.3	19.032	119.712	118.905	1317.88	86.49
	10.62	10.60	80948.1	82971.8	18.961	119.703	118.786	1322.93	86.60
Trim 3 m	10.42	10.40	79179.8	81159.3	19.192	118.091	118.430	1333.10	86.81
	10.52	10.50	80027.4	82028.1	19.120	118.094	118.313	1338.54	86.93
	10.62	10.60	80876.1	82898.0	19.049	118.095	118.196	1343.83	87.04
Trim 4 m	10.42	10.40	79121.5	81099.5	19.286	116.435	117.811	1352.06	87.21
	10.52	10.50	79972.7	81972.0	19.211	116.449	117.706	1357.50	87.33
	10.62	10.60	80825.0	82845.6	19.138	116.462	117.601	1362.91	87.45

Table D.3: Vessel stability properties Haewene Brim load case Ballast.

Case	TK [m]	T [m]	VOLT [m^3]	DISP [t]	KMT [m]	LCB [m]	LCF [m]	MCT [tm/cm]	TPC [t/cm]
Trim -1 m	15.87	15.85	126135.7	129289.1	17.294	121.745	114.470	1453.67	89.61
	15.92	15.90	126572.9	129737.2	17.293	121.720	114.439	1455.28	89.64
	16.02	16.00	127447.9	130634.1	17.291	121.671	114.375	1458.41	89.71
Trim 0 m	15.82	15.80	125779.1	128923.6	17.323	120.635	114.176	1464.80	89.84
	15.87	15.85	126217.5	129372.9	17.321	120.612	114.144	1466.13	89.87
	15.92	15.90	126656.0	129822.4	17.320	120.590	114.112	1467.46	89.90
	16.02	16.00	127533.4	130721.7	17.318	120.545	114.049	1470.09	89.96
Trim 1 m	15.82	15.80	125871.5	129018.3	17.355	119.489	113.876	1476.20	90.09
	15.87	15.85	126311.0	129468.8	17.353	119.470	113.844	1477.46	90.11
	15.92	15.90	126751.5	129920.3	17.351	119.451	113.822	1479.09	90.15
	16.02	16.00	127631.3	130822.1	17.349	119.412	113.759	1481.58	90.20
Trim 2 m	15.82	15.80	125976.2	129125.6	17.391	118.337	113.602	1488.02	90.34
	15.87	15.85	126416.9	129577.3	17.389	118.320	113.572	1489.12	90.36
	15.92	15.90	126857.7	130029.1	17.387	118.304	113.543	1490.22	90.39
	16.02	16.00	127739.7	130933.2	17.384	118.270	113.484	1492.41	90.44
Trim 3 m	15.82	15.80	126090.6	129242.8	17.430	117.177	113.375	1499.92	90.59
	15.87	15.85	126532.8	129696.1	17.428	117.164	113.335	1500.43	90.60
	15.92	15.90	126974.8	130149.1	17.426	117.150	113.304	1501.35	90.62
	16.02	16.00	127859.0	131055.5	17.423	117.123	113.248	1503.34	90.67
Trim 4 m	15.82	15.80	126210.9	129366.1	17.473	116.007	113.156	1511.14	90.82
	15.87	15.85	126654.2	129820.5	17.471	115.997	113.129	1512.03	90.84
	15.92	15.90	127097.6	130275.0	17.468	115.987	113.102	1512.91	90.86
	16.02	16.00	127984.7	131184.3	17.464	115.967	113.049	1514.66	90.90

Table D.4: Vessel stability properties Haewene Brim load case Fully Loaded.

			Heel angles [deg]						
			0.0	5.0	10.0	20.0	30.0	40.0	45.0
Case	TK [m]	T [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]
Trim -1 m	10.32	10.30	-0.007	1.647	3.315	6.740	10.225	12.836	13.686
	10.42	10.40	-0.007	1.641	3.302	6.714	10.198	12.811	13.662
	10.52	10.50	-0.007	1.635	3.290	6.689	10.172	12.785	13.637
Trim 0 m	10.32	10.30	-0.008	1.654	3.327	6.763	10.253	12.860	13.699
	10.42	10.40	-0.007	1.647	3.314	6.737	10.226	12.834	13.673
	10.52	10.50	-0.007	1.641	3.302	6.711	10.199	12.808	13.648
Trim 1 m	10.32	10.30	-0.008	1.661	3.341	6.787	10.282	12.882	13.711
	10.42	10.40	-0.008	1.654	3.328	6.761	10.255	12.856	13.684
	10.52	10.50	-0.007	1.648	3.315	6.735	10.228	12.829	13.658
Trim 2 m	10.32	10.30	-0.008	1.668	3.355	6.813	10.312	12.903	13.722
	10.42	10.40	-0.008	1.661	3.342	6.786	10.284	12.876	13.695
	10.52	10.50	-0.008	1.655	3.329	6.759	10.257	12.849	13.668
	10.62	10.60	-0.007	1.649	3.317	6.734	10.23	12.821	13.64
Trim 3 m	10.42	10.40	-0.008	1.669	3.356	6.811	10.313	12.894	13.704
	10.52	10.50	-0.008	1.663	3.343	6.785	10.286	12.867	13.676
	10.62	10.60	-0.008	1.656	3.331	6.759	10.258	12.838	13.648
Trim 4 m	10.42	10.40	-0.008	1.677	3.371	6.838	10.342	12.910	13.712
	10.52	10.50	-0.008	1.670	3.358	6.811	10.315	12.882	13.683
	10.62	10.60	-0.008	1.664	3.346	6.785	10.287	12.853	13.655

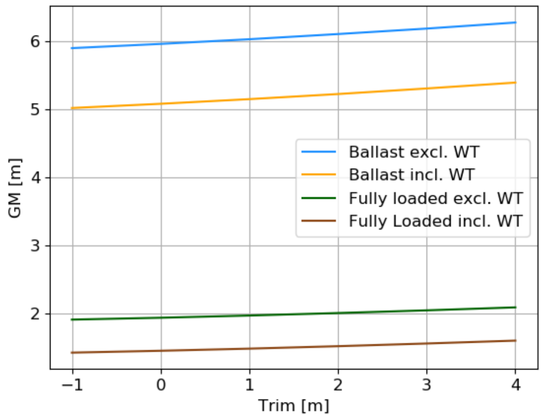
Table D.5: Vessel properties KN Haewene Brim load case Ballast.

			Heel angles [deg]						
			0.0	5.0	10.0	20.0	30.0	40.0	45.0
Case	TK [m]	T [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]	KN [m]
Trim -1 m	15.87	15.85	-0.005	1.505	3.020	6.097	8.845	11.133	12.034
	15.92	15.90	-0.005	1.505	3.020	6.094	8.833	11.116	12.017
	16.02	16.00	-0.005	1.505	3.020	6.091	8.810	11.080	11.982
Trim 0 m	15.82	15.80	-0.005	1.507	3.025	6.107	8.859	11.141	12.040
	15.87	15.85	-0.005	1.507	3.025	6.106	8.846	11.123	12.023
	15.92	15.90	-0.005	1.507	3.025	6.104	8.834	11.105	12.005
	16.02	16.00	-0.005	1.507	3.024	6.101	8.810	11.070	11.970
Trim 1 m	15.82	15.80	-0.005	1.510	3.030	6.117	8.859	11.128	12.026
	15.87	15.85	-0.005	1.510	3.030	6.115	8.847	11.110	12.008
	15.92	15.90	-0.005	1.510	3.030	6.113	8.835	11.092	11.990
	16.02	16.00	-0.005	1.510	3.029	6.110	8.810	11.056	11.955
Trim 2 m	15.82	15.80	-0.005	1.513	3.036	6.125	8.859	11.112	12.008
	15.87	15.85	-0.005	1.513	3.036	6.123	8.846	11.094	11.990
	15.92	15.90	-0.005	1.513	3.036	6.121	8.833	11.076	11.972
	16.02	16.00	-0.005	1.512	3.035	6.117	8.808	11.040	11.936
Trim 3 m	15.82	15.80	-0.005	1.516	3.043	6.134	8.857	11.095	11.987
	15.87	15.85	-0.005	1.516	3.043	6.131	8.844	11.076	11.969
	15.92	15.90	-0.005	1.516	3.042	6.129	8.831	11.058	11.951
	16.02	16.00	-0.005	1.516	3.042	6.123	8.804	11.021	11.914
Trim 4 m	15.82	15.80	-0.005	1.520	3.050	6.141	8.853	11.074	11.963
	15.87	15.85	-0.005	1.520	3.050	6.138	8.840	11.056	11.944
	15.92	15.90	-0.005	1.520	3.050	6.135	8.826	11.037	11.926
	16.02	16.00	-0.005	1.519	3.049	6.128	8.799	11.000	11.889

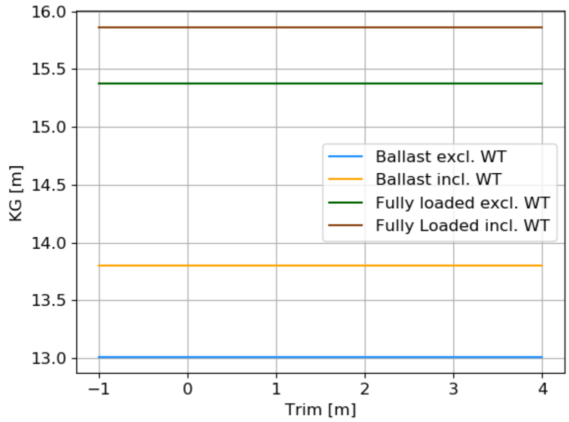
Table D.6: Vessel properties KN Haewene Brim load case Fully Loaded.

D.3 Effect of different levels of trim

Figure D.1 shows the effect of different values for initial trim on the resulting GM and KG. Table D.7 shows that the intact stability criteria are met for the different levels of trim, for both load case Ballast and Fully Loaded including wind turbine. It should be noted that for the Fully Loaded case, the draught is exceeding the summer draught limit of 15.85 meters as explained in section 9.2.



(a) GM



(b) KG

Figure D.1: Effect of different levels of trim.

Ballast including wind turbine										
			Minimum GM				Maximum KG			
Trim	Draught	GM	IMO	DNV	HSE	KG	IMO	DNV	HSE	Meets criteria?
-1	10.47	5.01	0.15	0.054	0.74	13.80	18.70	18.79	18.11	Yes
0	10.49	5.08	0.15	0.072	0.74	13.80	18.76	18.84	18.17	Yes
1	10.50	5.14	0.15	0.10	0.75	13.80	18.83	18.88	18.23	Yes
2	10.51	5.22	0.15	0.13	0.75	13.80	18.90	18.93	18.30	Yes
3	10.52	5.30	0.15	0.16	0.76	13.80	18.98	18.97	18.37	Yes
4	10.53	5.39	0.15	0.20	0.77	13.80	19.07	19.02	18.45	Yes
Fully Loaded including wind turbine										
			Minimum GM				Maximum KG			
Trim	Draught	GM	IMO	DNV	HSE	KG	IMO	DNV	HSE	Meets criteria?
-1	15.97	1.43	0.16	0.33	0.5	15.86	17.13	16.96	16.79	Yes
0	15.96	1.46	0.24	0.35	0.5	15.86	17.08	16.97	16.82	Yes
1	15.95	1.49	0.31	0.37	0.5	15.86	17.05	16.98	16.85	Yes
2	15.94	1.53	0.38	0.40	0.5	15.86	17.01	16.99	16.89	Yes
3	15.93	1.56	0.45	0.43	0.5	15.86	16.98	17.00	16.93	Yes
4	15.91	1.61	0.52	0.46	0.5	15.86	16.95	17.01	16.97	Yes

Table D.7: Evaluation of intact stability limit curves for different levels of initial trim.

E Diffraction analysis output

This appendix shows figures of the output of a diffraction analysis performed in HydroStar for two of Haewene Brim's load cases, Ballast and Fully Loaded. For both cases, the output is shown excluding and including the influence of the wind turbine's additional weight and inertia. Several figures also show the wind turbine's 1P and 3P frequency ranges.

First, the Displacement RAOs (excluding mooring stiffness) are shown. Second, the influence of including the mooring stiffness in the diffraction on these displacement RAOs is shown. Third, the 1^{st} order wave load RAOs are shown. Fourth, the frequency dependent added mass and damping. Fifth, a verification of the displacement RAOs against old RAOs computed for the Haewene Brim is shown. Finally, it is discussed how the wind turbine would influence intermediate load case in between Ballast and Fully Loaded.

E.1 Displacement RAOs

This section shows the displacement RAOs for the different load cases resulting from the diffraction analysis in figures E.1 till E.7. A variation in the color red indicates the Fully Loaded load case. Blue indicates the Ballast load case. The different line-types are indicating different wind turbine placements.

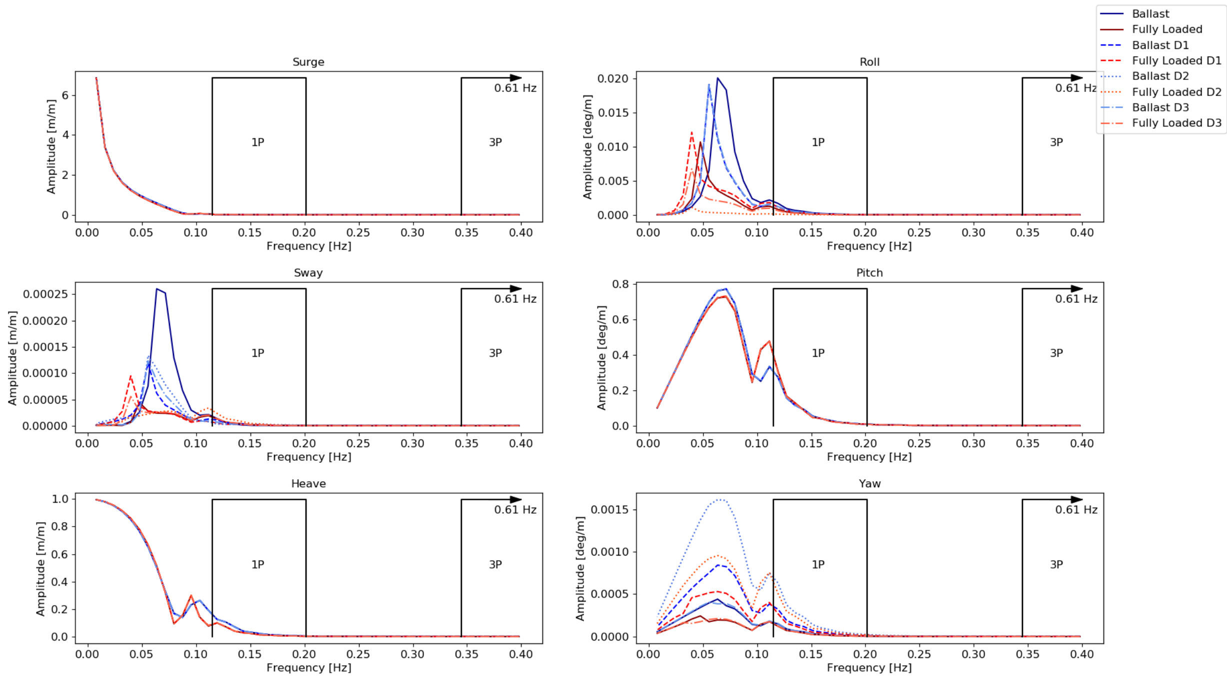


Figure E.1: Displacement RAOs for 6DoF for a vessel heading of 0°.

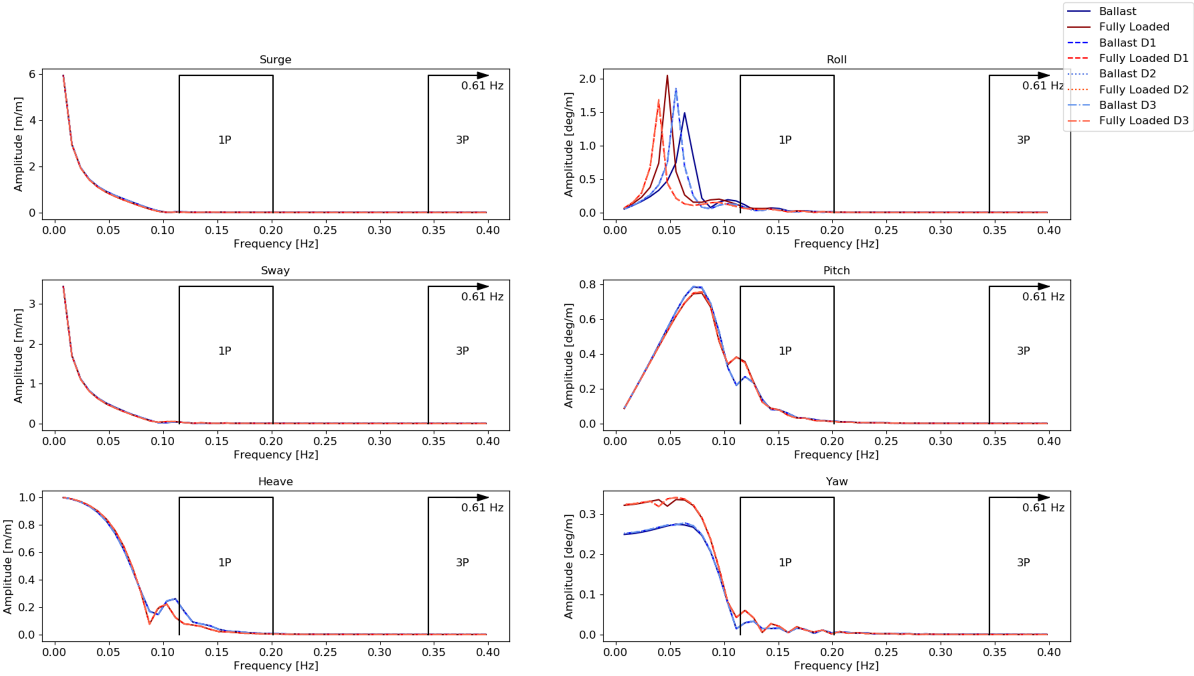


Figure E.2: Displacement RAOs for 6DoF for a vessel heading of 30°.

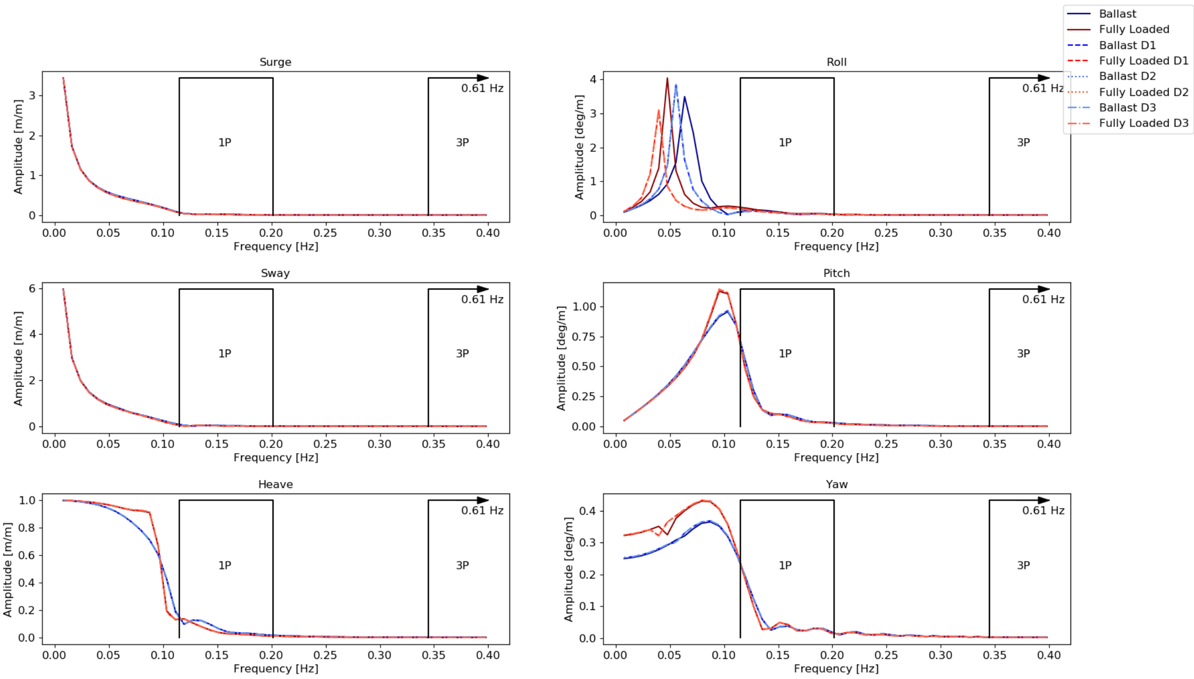


Figure E.3: Displacement RAOs for 6DoF for a vessel heading of 60°.

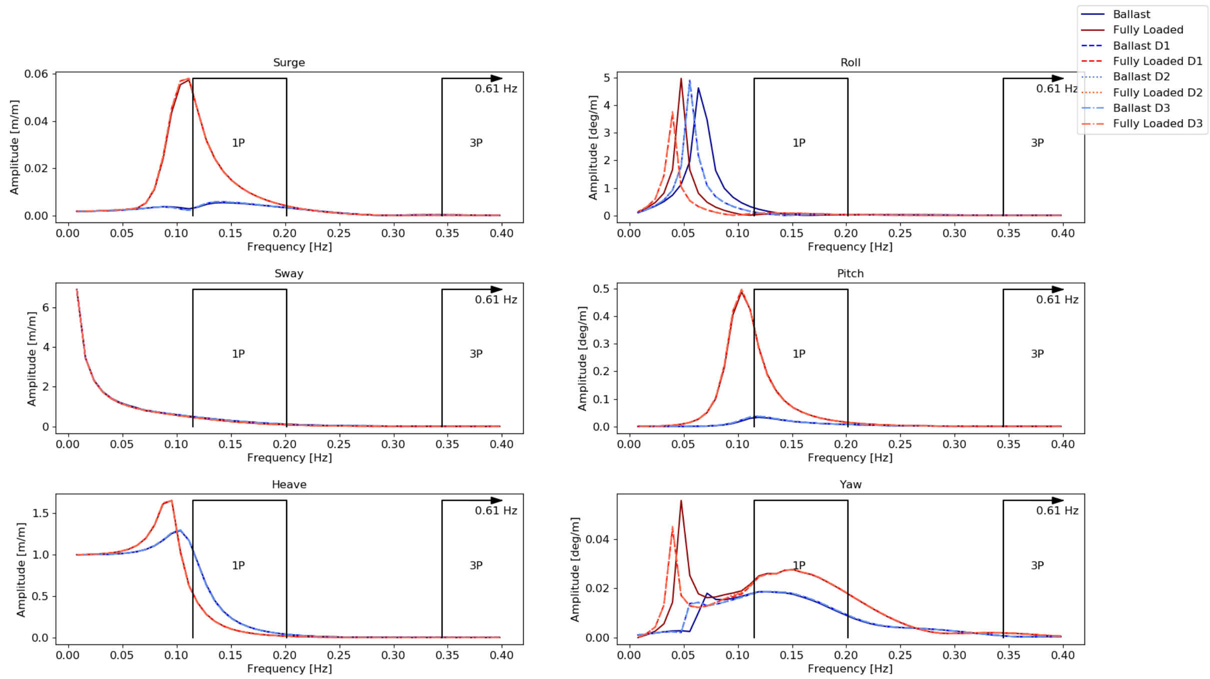


Figure E.4: Displacement RAOs for 6DoF for a vessel heading of 90°.

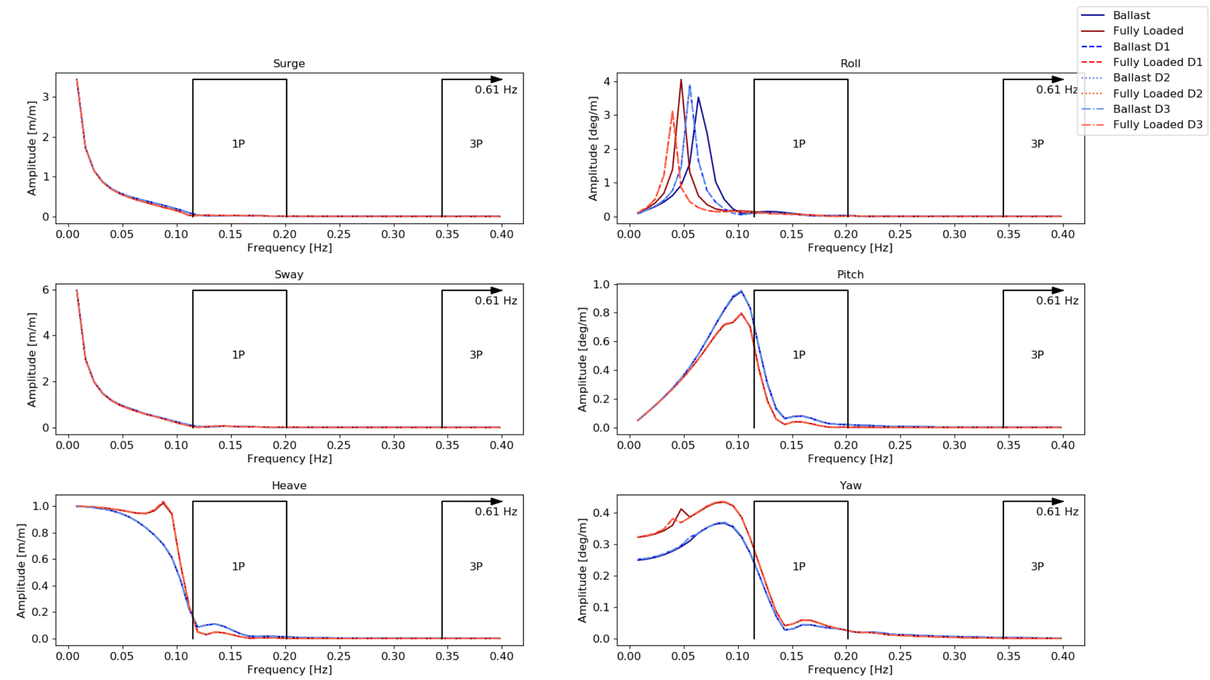


Figure E.5: Displacement RAOs for 6DoF for a vessel heading of 120°.

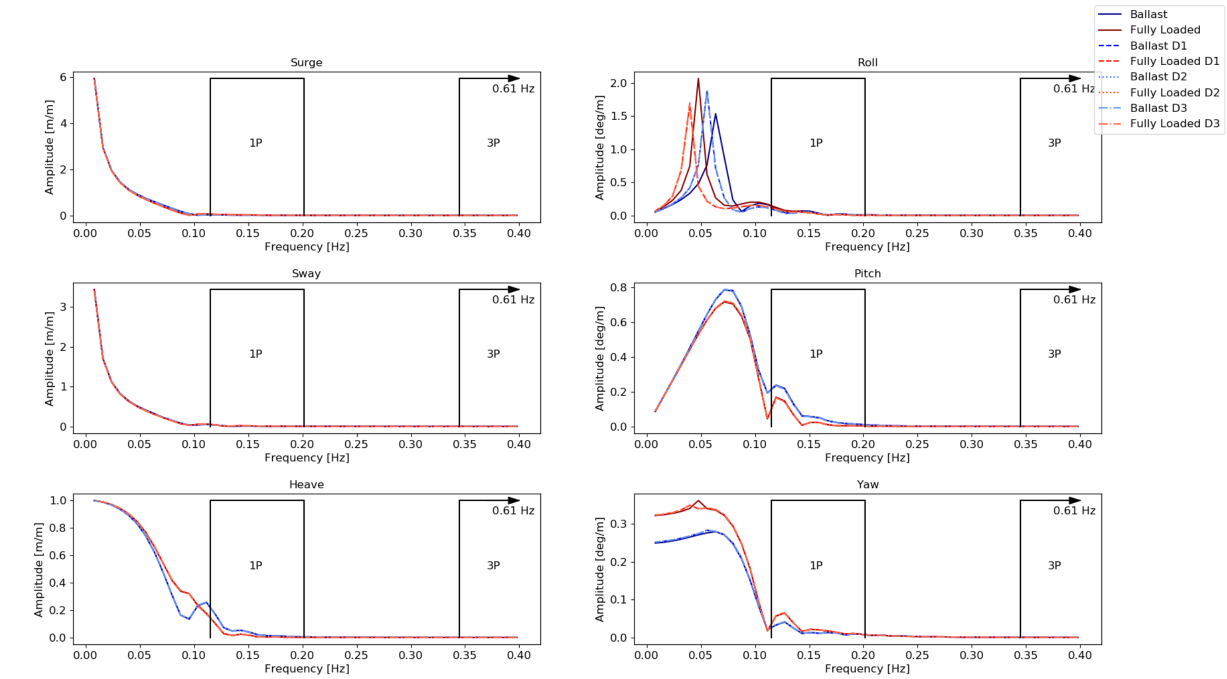


Figure E.6: Displacement RAOs for 6DoF for a vessel heading of 150°.

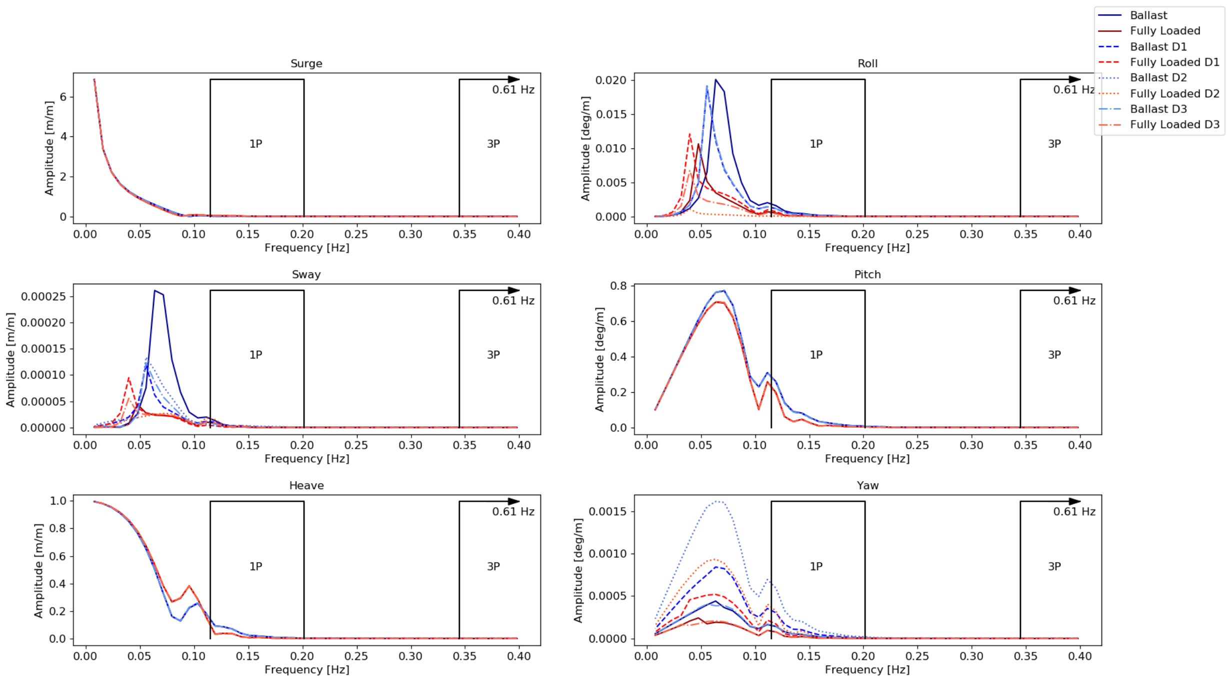


Figure E.7: Displacement RAOs for 6DoF for a vessel heading of 180°.

E.2 Comparison of displacement RAOs including and excluding mooring stiffness

Figures E.8 till E.14 show the influence of the mooring stiffness on the displacement RAOs of the load case Ballast excluding wind turbine for different vessel headings. Mainly the surge, sway, and yaw displacement RAOs are affected, especially in the low-frequency region, which is typical for a soft-mooring system. Differences are also observed in the low-frequency region of the roll RAO. This is expected to be a result of the sway-roll-yaw coupling that is observed in the mooring stiffness matrix in section 9.5.2, equation 9.30. For the heave and pitch RAOs, only negligible differences are observed.

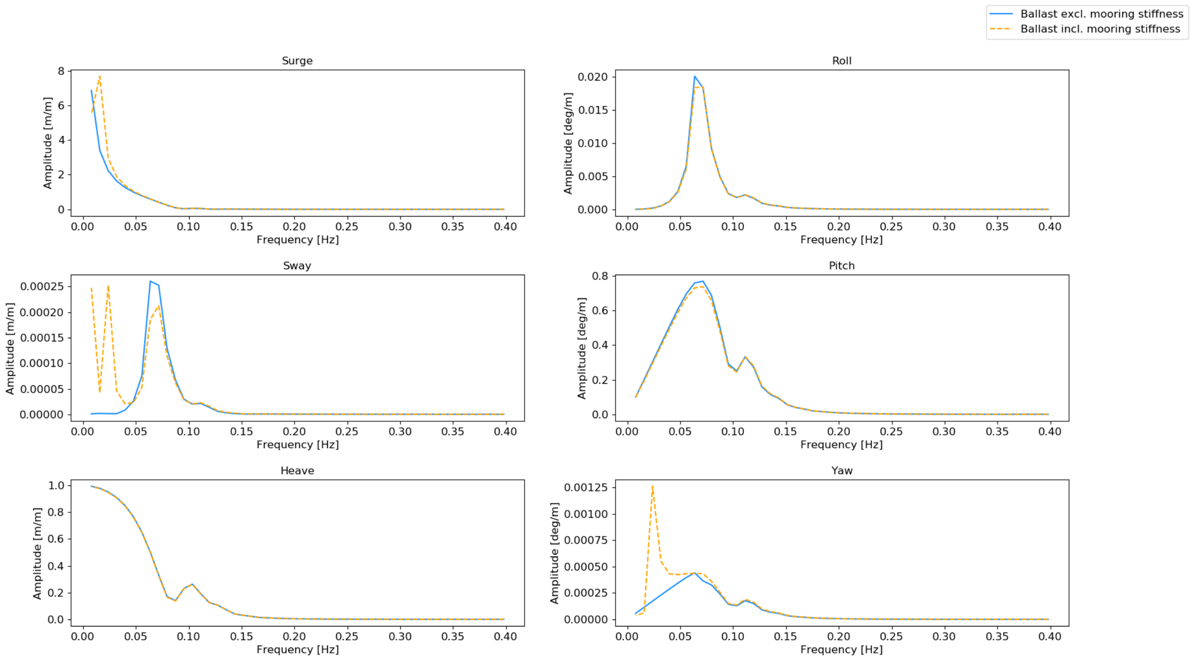


Figure E.8: Influence of mooring stiffness on displacement RAOs for a vessel heading of 0°.

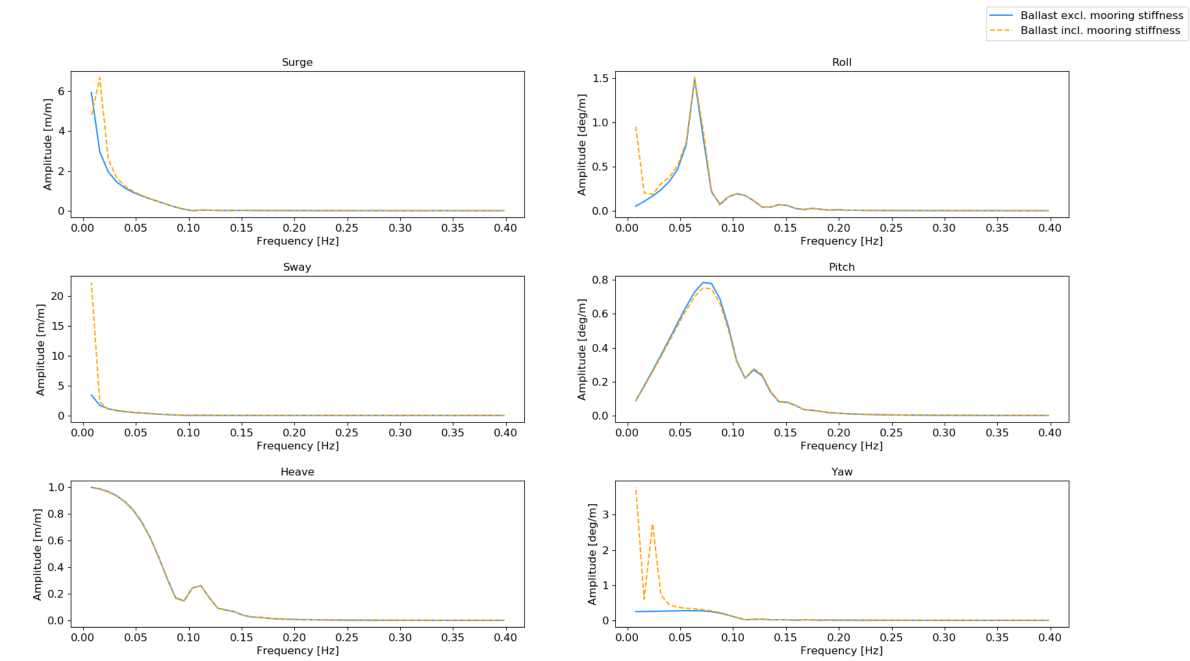


Figure E.9: Influence of mooring stiffness on displacement RAOs for a vessel heading of 30°.

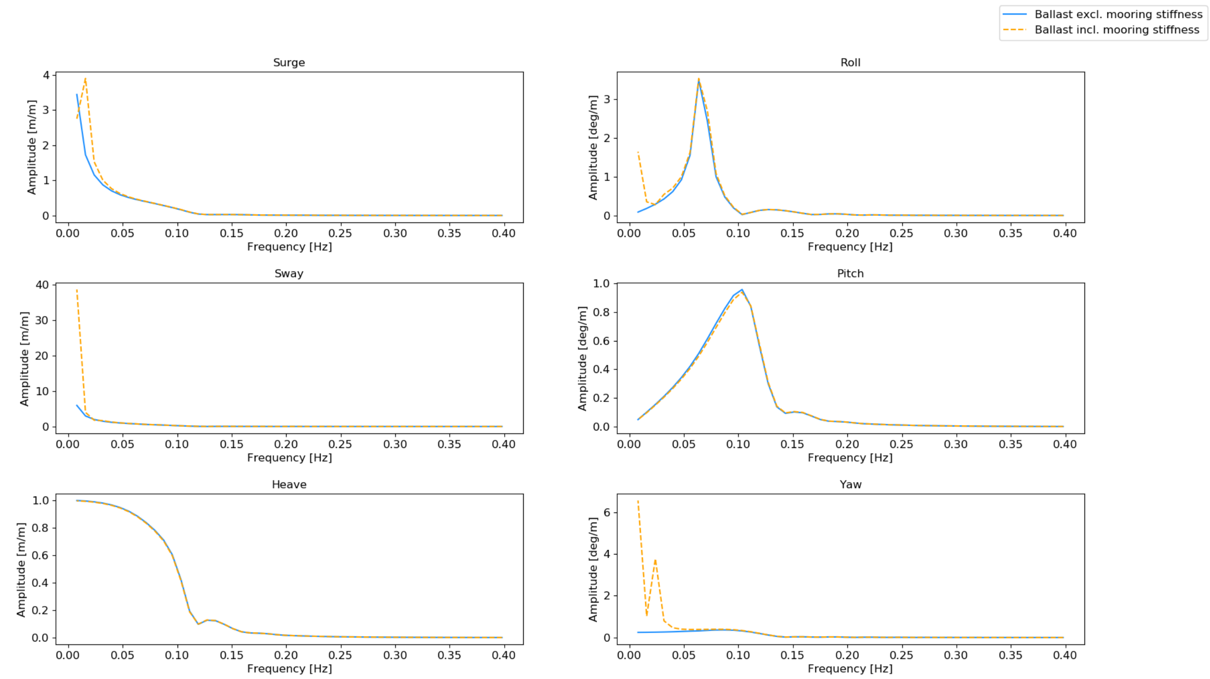


Figure E.10: Influence of mooring stiffness on displacement RAOs for a vessel heading of 60°.

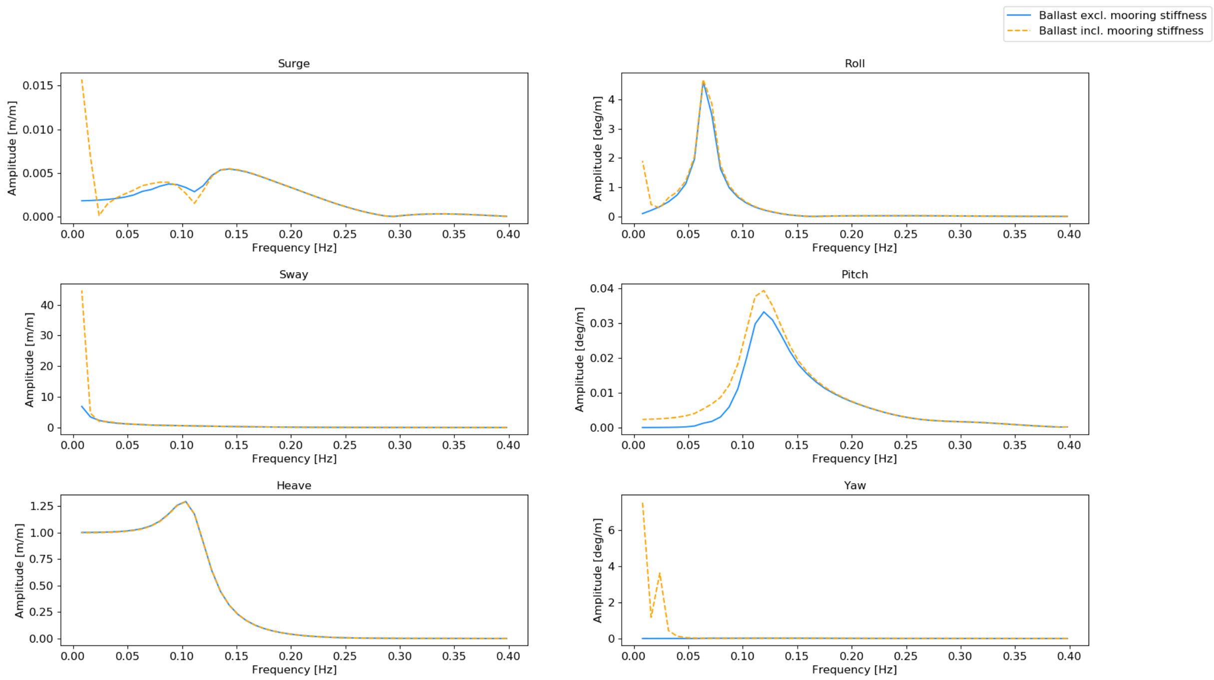


Figure E.11: Influence of mooring stiffness on displacement RAOs for a vessel heading of 90°.

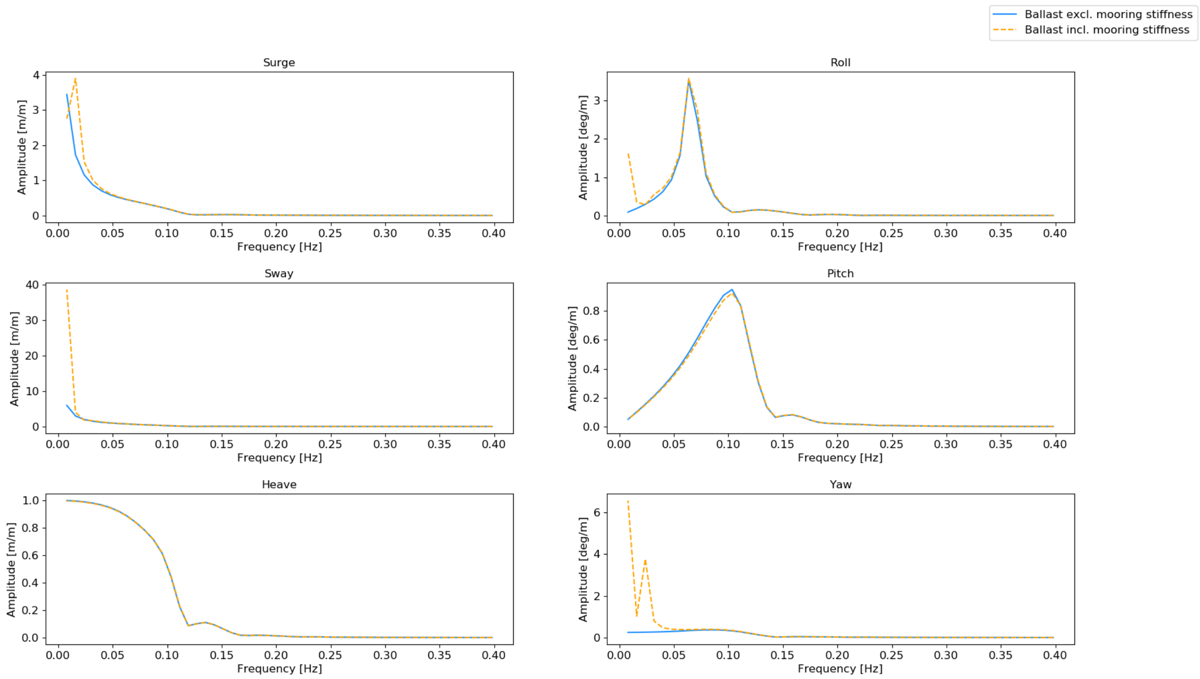


Figure E.12: Influence of mooring stiffness on displacement RAOs for a vessel heading of 120°.

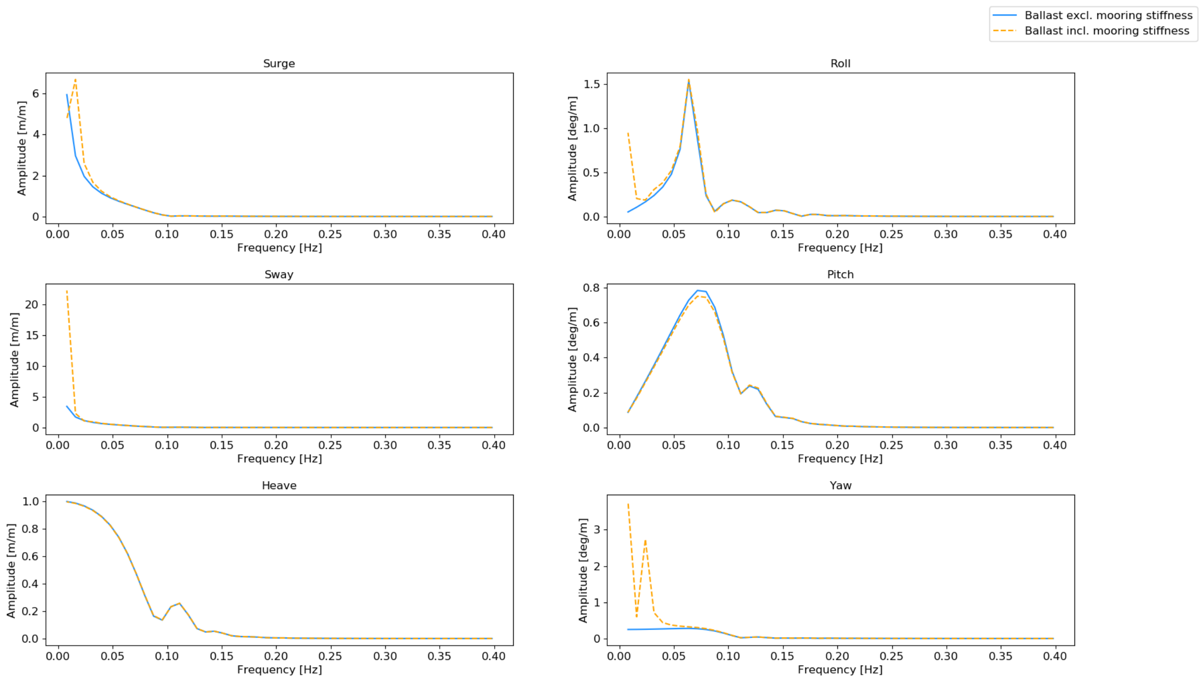


Figure E.13: Influence of mooring stiffness on displacement RAOs for a vessel heading of 150°.

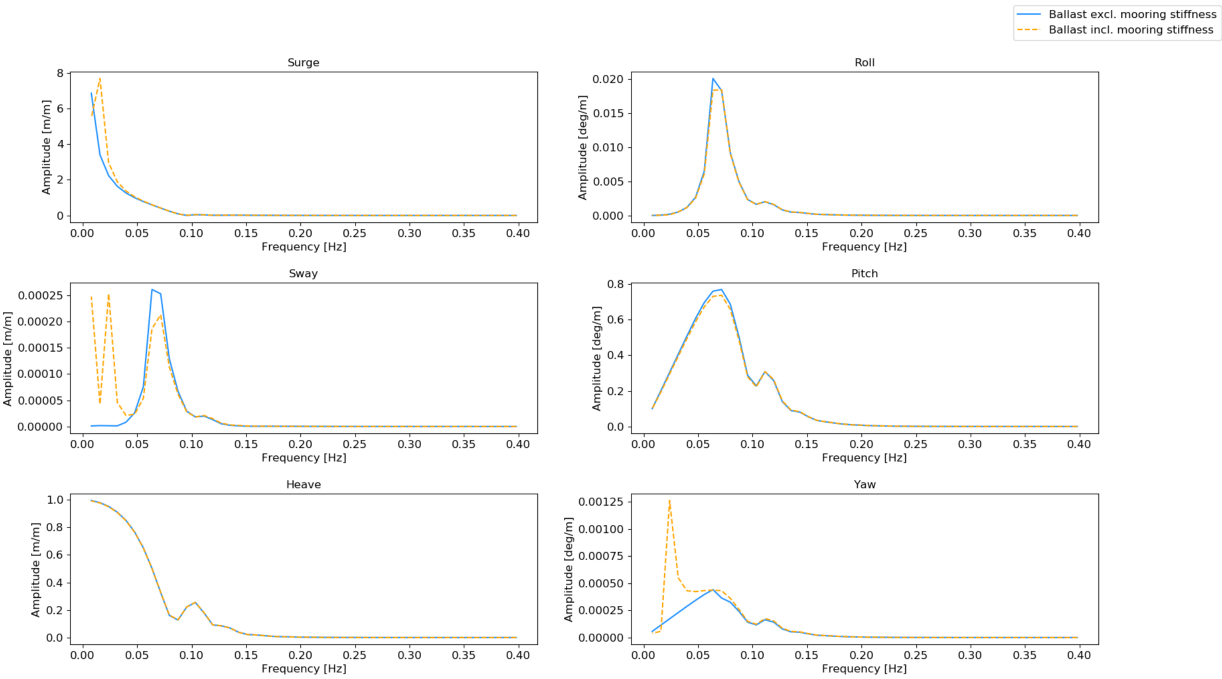


Figure E.14: Influence of mooring stiffness on displacement RAOs for a vessel heading of 180°.

E.3 First order wave load RAOs

This section shows the 1^{st} order wave load RAOs for the different load cases resulting from the diffraction analysis in figures E.15 till E.21. The wind turbine placement is in this case on the vessel's center line (design 3), as explained in section 9.5.3.

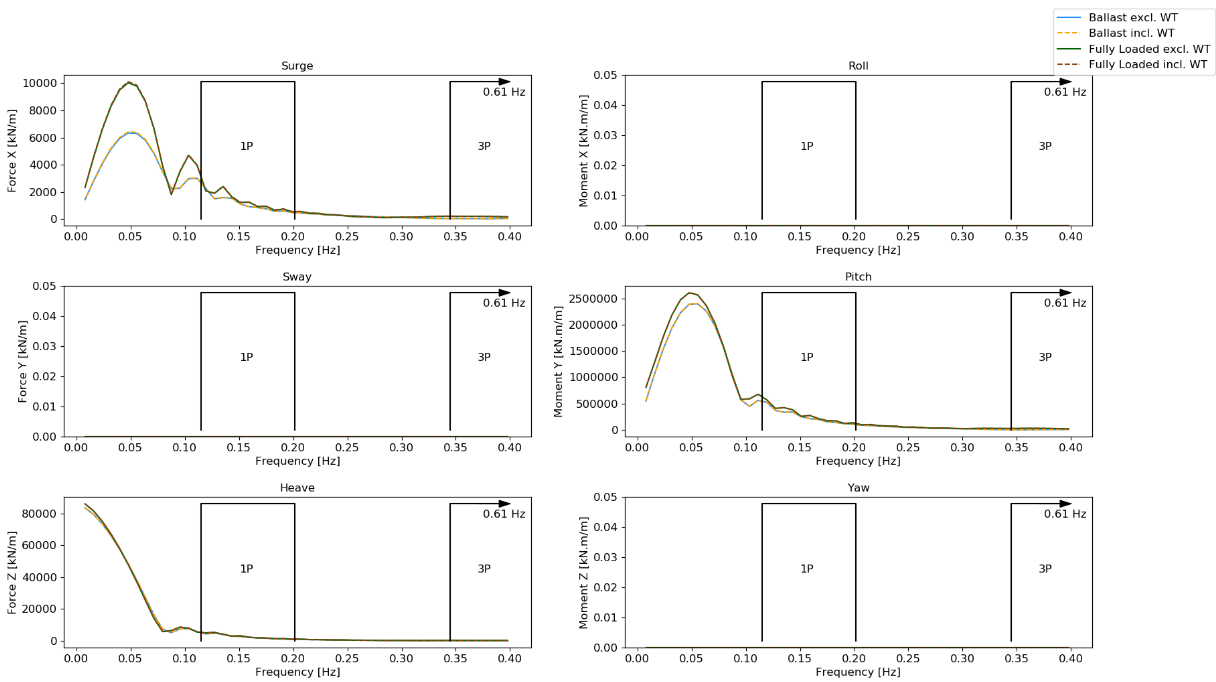


Figure E.15: Wave load RAOs for 6DoF for a vessel heading of 0°.

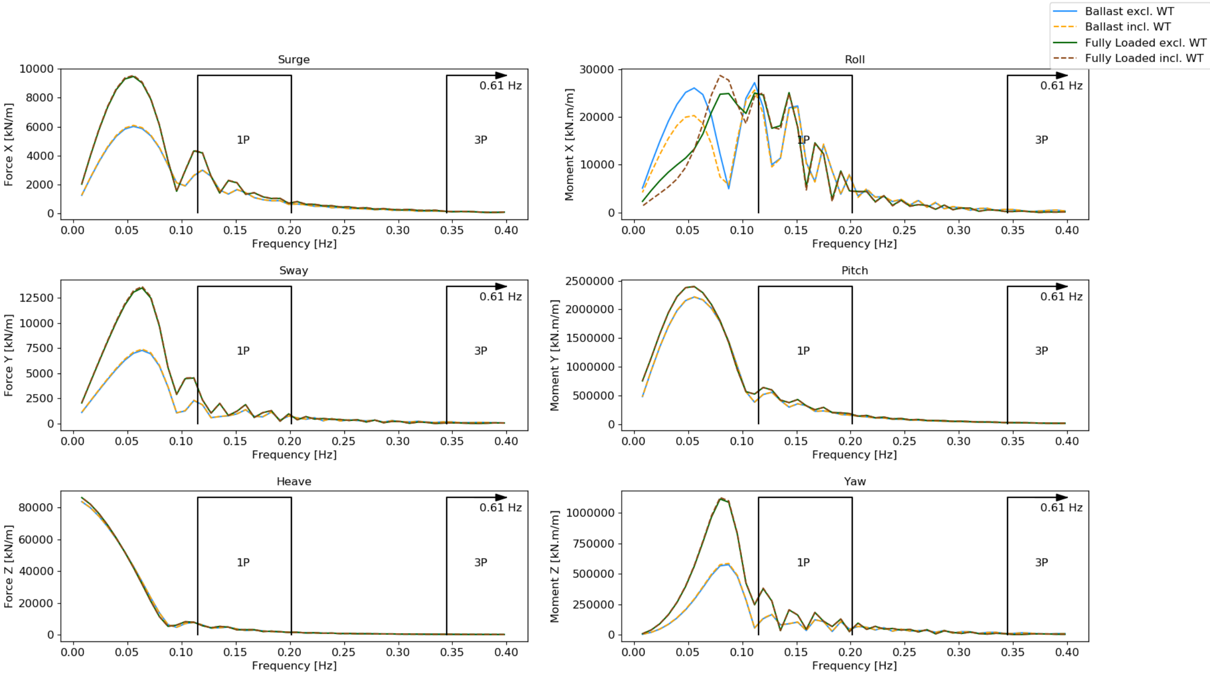


Figure E.16: Wave load RAOs for 6DoF for a vessel heading of 30°.

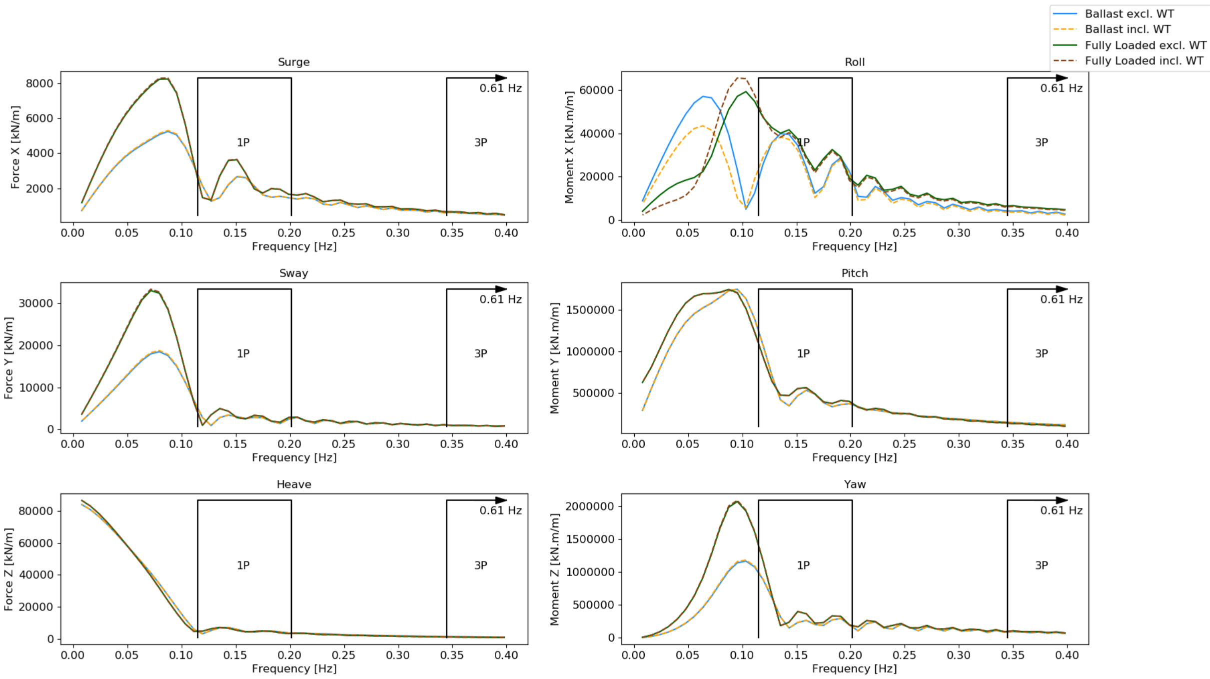


Figure E.17: Wave load RAOs for 6DoF for a vessel heading of 60°.

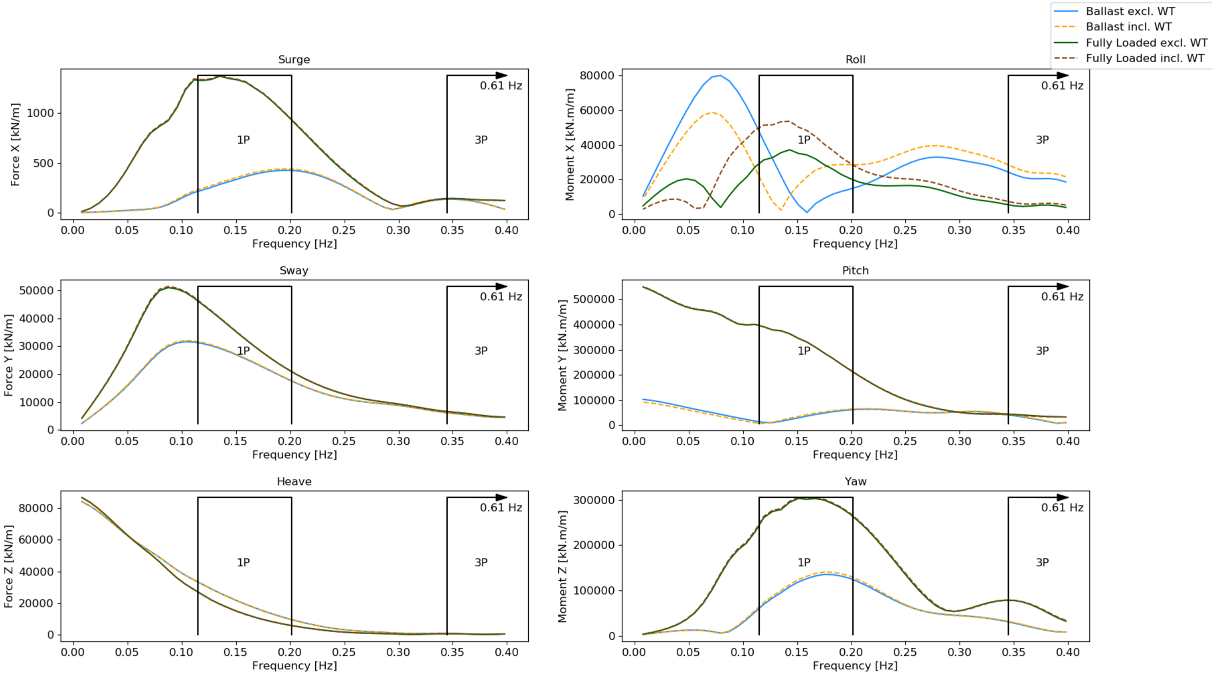


Figure E.18: Wave load RAOs for 6DoF for a vessel heading of 90°.

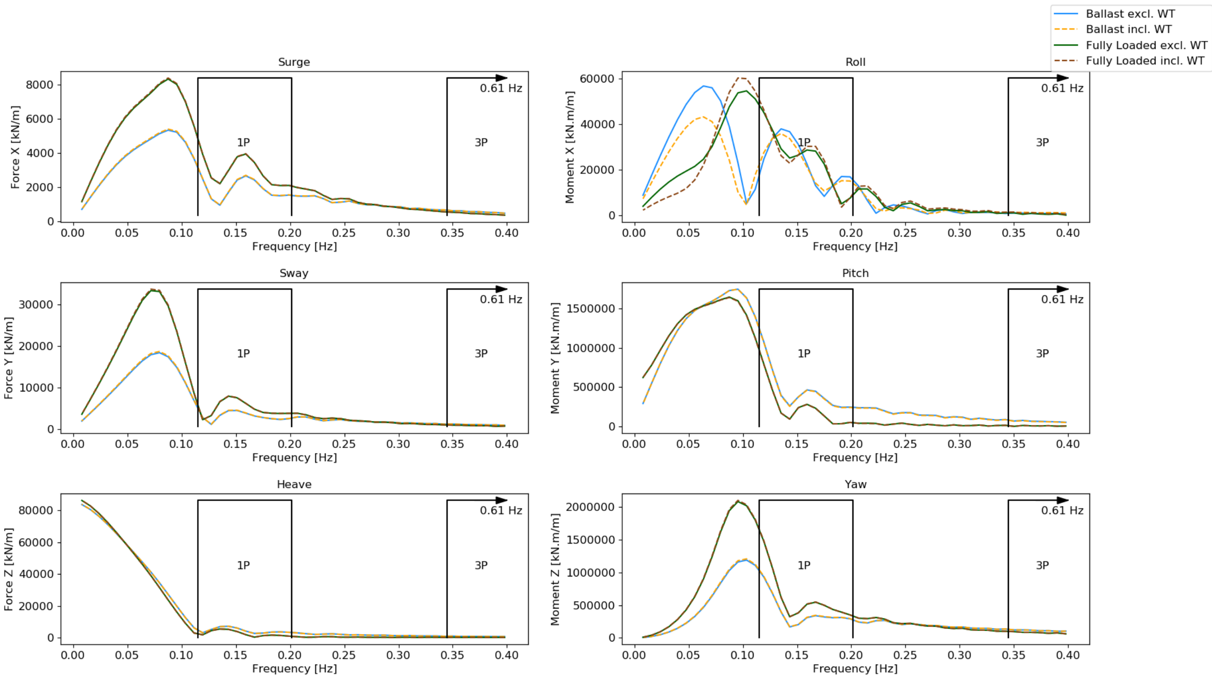


Figure E.19: Wave load RAOs for 6DoF for a vessel heading of 120°.

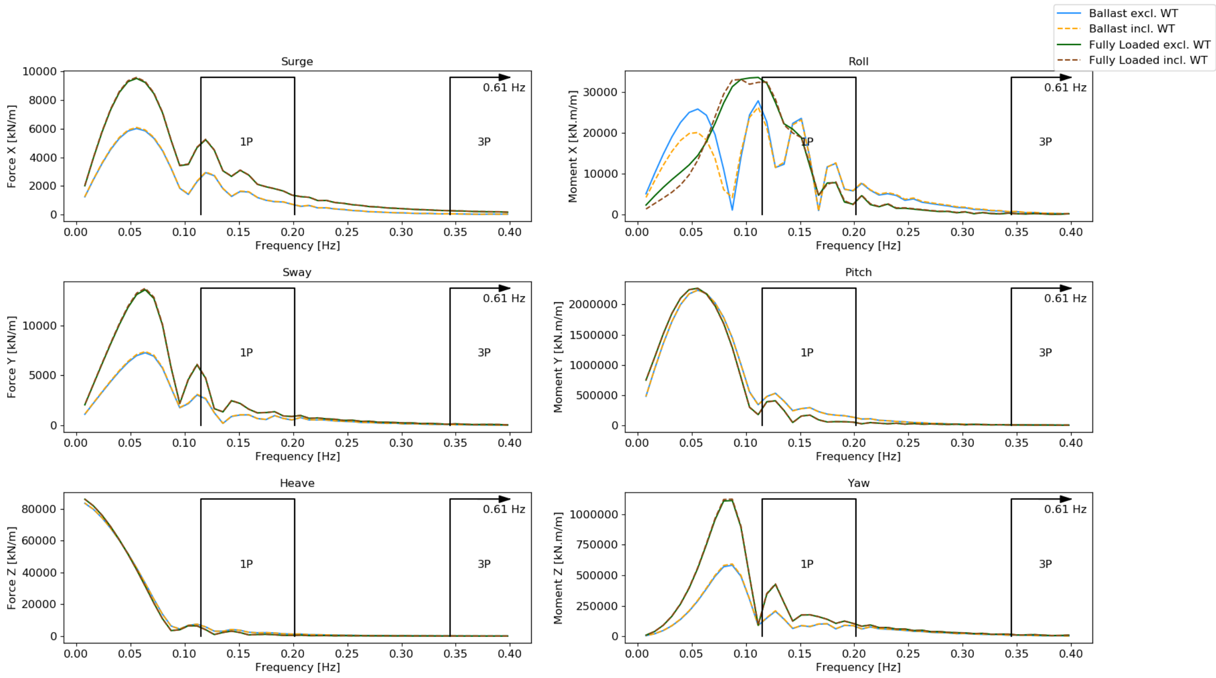


Figure E.20: Wave load RAOs for 6DoF for a vessel heading of 150°.

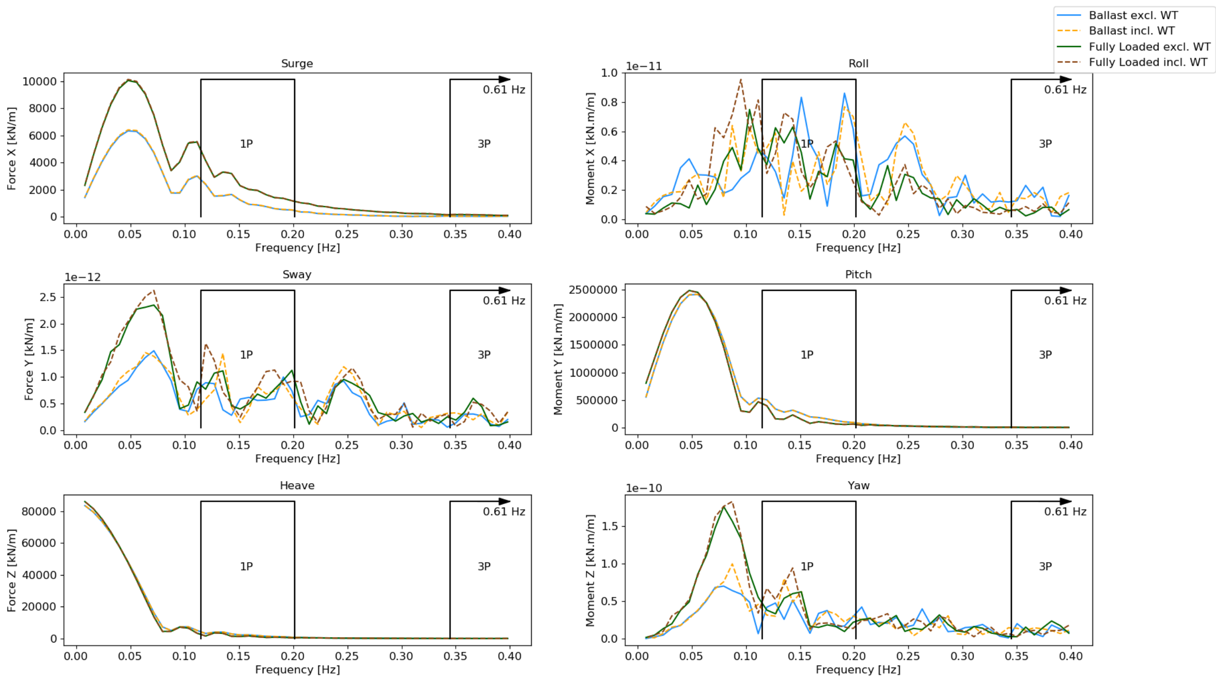


Figure E.21: Wave load RAOs for 6DoF for a vessel heading of 180°.

E.4 Added mass and damping

This section shows the added mass and damping for the different load cases resulting from the diffraction analysis in figures E.22 till E.25. The wind turbine placement is in this case on the vessel's center line (design 3), as explained in section 9.5.3.

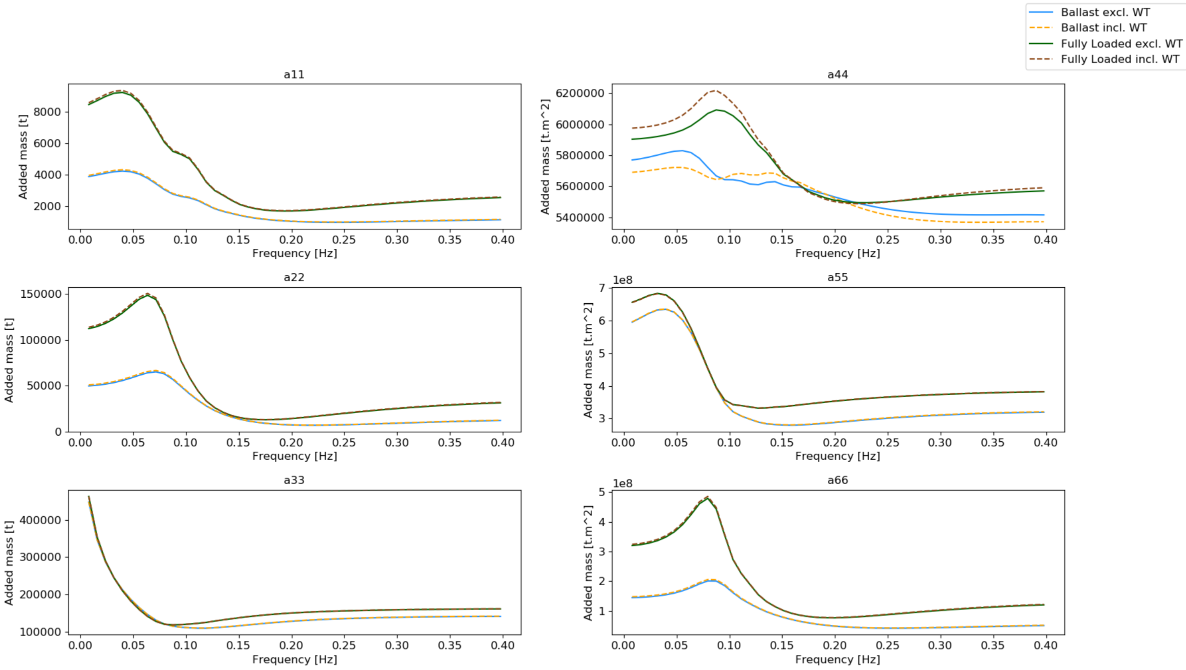


Figure E.22: Frequency dependent added mass: matrix diagonal terms.

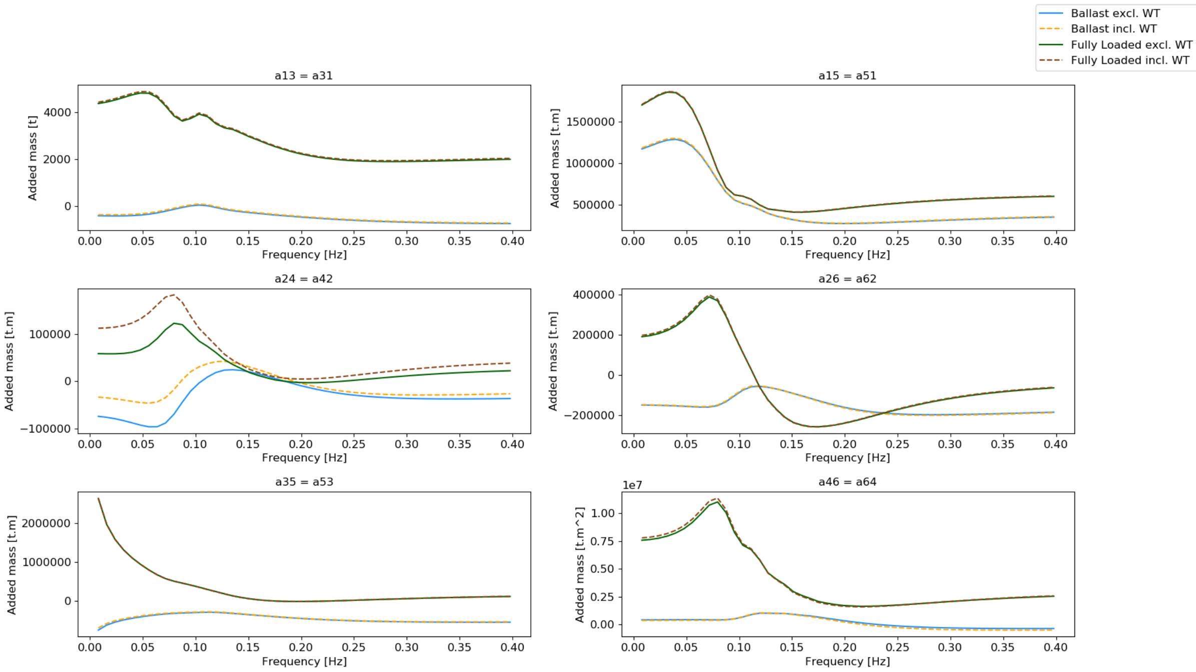


Figure E.23: Frequency dependent added mass: matrix off-diagonal terms.

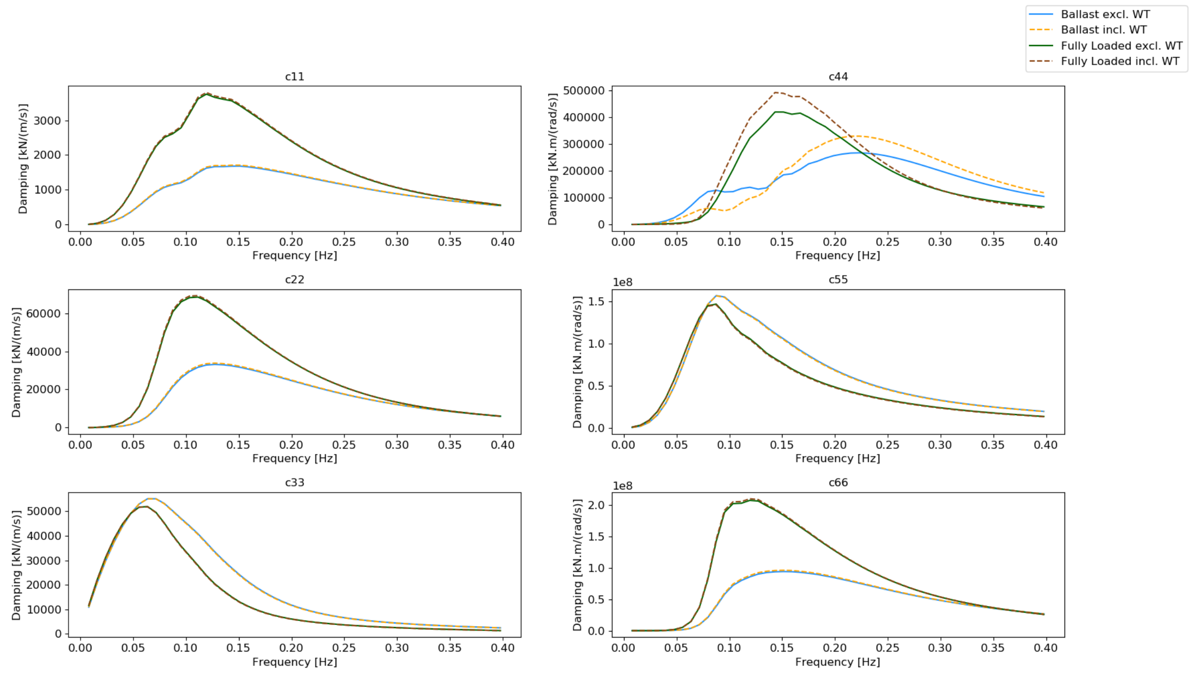


Figure E.24: Frequency dependent damping: matrix diagonal terms.

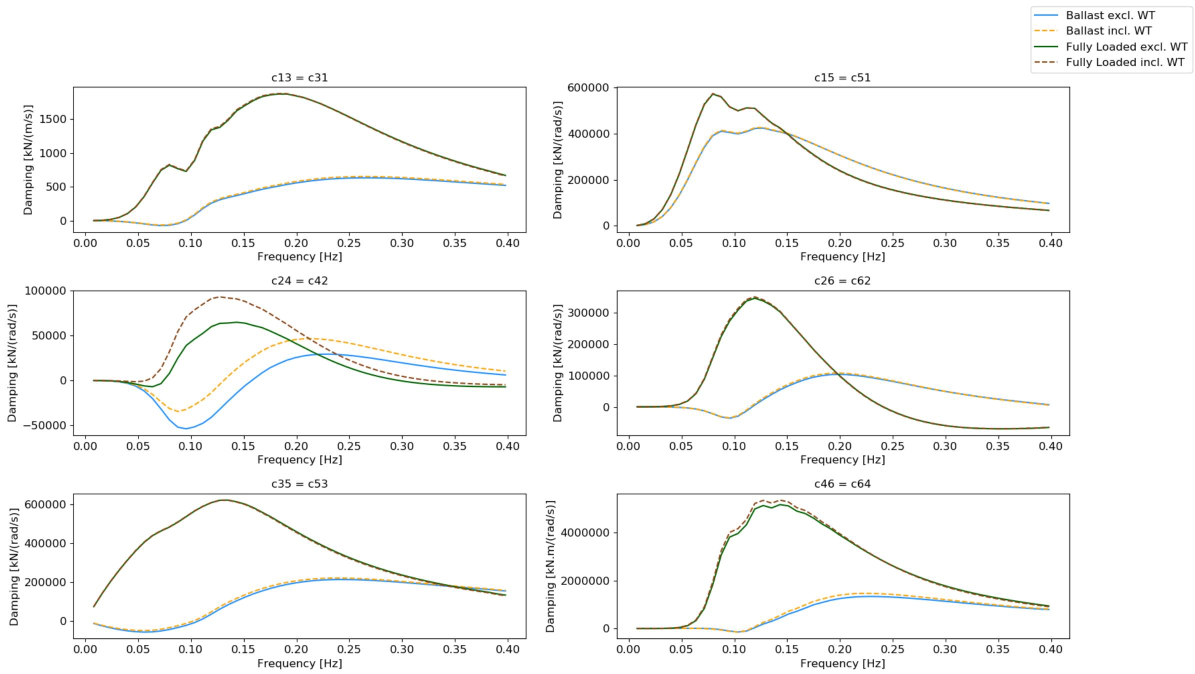


Figure E.25: Frequency dependent damping: matrix off-diagonal terms.

E.5 Verification: comparison to old RAOs

For verification of the diffraction analysis, a comparison is made between the displacement RAOs for load case Ballast, as presented in appendix E.1 and earlier computed displacement RAOs of the Haewene Brim for load case Ballast originating from Haewene Brim's RAO report [130][28].

The displacement RAOs are verified, and not the 1^{st} order wave load RAOs, added mass and damping due to the data's availability. An assumption is therefore made that in case the displacement RAOs are verified, the 1^{st} order wave load RAOs, added mass, and damping originating from the same diffraction analysis, are also correct.

The goal of the comparison is to show a close match between the old RAOs, and the computed RAOs. However, there is a difference in the input parameters for the vessel in Ballast condition, due to adjustments made to the vessel in time. The old Ballast case is based on the vessel properties in 2013, while the new Ballast case properties used for the computation are updated in 2021. The vessel properties for both cases are shown in table E.1. Due to the difference in load case parameters, small differences in the displacement RAOs are expected.

Property	Haewene Brim vessel	
Length overall [m]	253.505	
Length between perpendicular [m]	233	
Breadth [m]	42	
Depth moulded [m]	23.2	
Load case	Ballast old	Ballast new
Draft mean [m]	10.60	10.45
Draft fore [m]	8.46	8.51
Draft aft [m]	12.73	12.38
Trim by stern [m]	-	3.87
Displacement mass [t]	82824	81192.00
Displacement volume [m^3]	80809.90	79211.71
LCG (from APP) [m]	116.01	116.86
VCG (w.r.t. baseline) [m]	12.96	12.96
TCG (from CL) [m]	0	0.12
Free surface correction [m]	0.04	0.054
Kxx [m]	17.1	17.1
Kyy [m]	62.4	63.1
Kzz [m]	64.7	63.7
Kxy [m]	-	1.2
Kxz [m]	-	3.7
Kyz [m]	-	1.8
Added roll damping	6%	6%

Table E.1: Difference between old and new Ballast load case parameters.

Figures E.26 up to E.32 show the comparison of the old displacement RAOs and computed new displacement RAOs for different vessel headings. As expected there are several differences observed.

[28]Reference coming from Bluewater's Meridian database (not publicly accessible).

The observations are:

- For a vessel heading of 0° and 180° differences are observed between the old and new RAOs. For both of these vessel headings, the RAO amplitude for the old RAOs sway, roll, and yaw is equal to 0. For the new RAOs, this is not the case. This can be explained through the coupling term of K_{xy}, as a result of the TCG positioned off the center line of the vessel. In the case of the TCG on the center line of the vessel, the situation is fully symmetric with respect to the x-axis of the vessel. Therefore no resulting term in the y-direction occurs due to waves in the x-direction. For the new RAOs, the situation is not fully symmetric, resulting in a response in y-direction due to waves in x-direction, as indicated by the coupling term K_{xy}. The TCG off the center line also causes the roll of the vessel. Due to the sway-roll-yaw coupling, this effect also influences the yaw RAO. Since for the new Ballast case, the TCG is only 0.12 meters off the center line of the vessel, the amplitude for the sway, roll, and yaw RAOs is negligibly small.

- For a wave heading of 90° the differences that stand out are in the RAOs for surge and yaw. It is expected that similar to the 0° and 180° RAOs, the coupling term K_{xy} causes this difference in the surge. However, it is common that in this case, the RAO for the surge is not equal to zero, due to the lack of symmetry between the forward and the aft of the vessel. Again due to the sway-roll-yaw coupling an effect in the yaw is observed, but only with a small amplitude.

- Besides the above-mentioned differences, the comparison of the old and new RAOs shows similar shapes and peak frequencies between the two. In some cases, a small amplitude difference is observed, which can be devoted to the difference in load case properties, such as the vessel's weight, COG position, and draft. The effects explained above related to the surge-sway coupling (K_{xy}) are not visible in the figures of the other wave headings, due to their negligible small amplitude difference in comparison to the total amplitude of surge and sway in these directions.

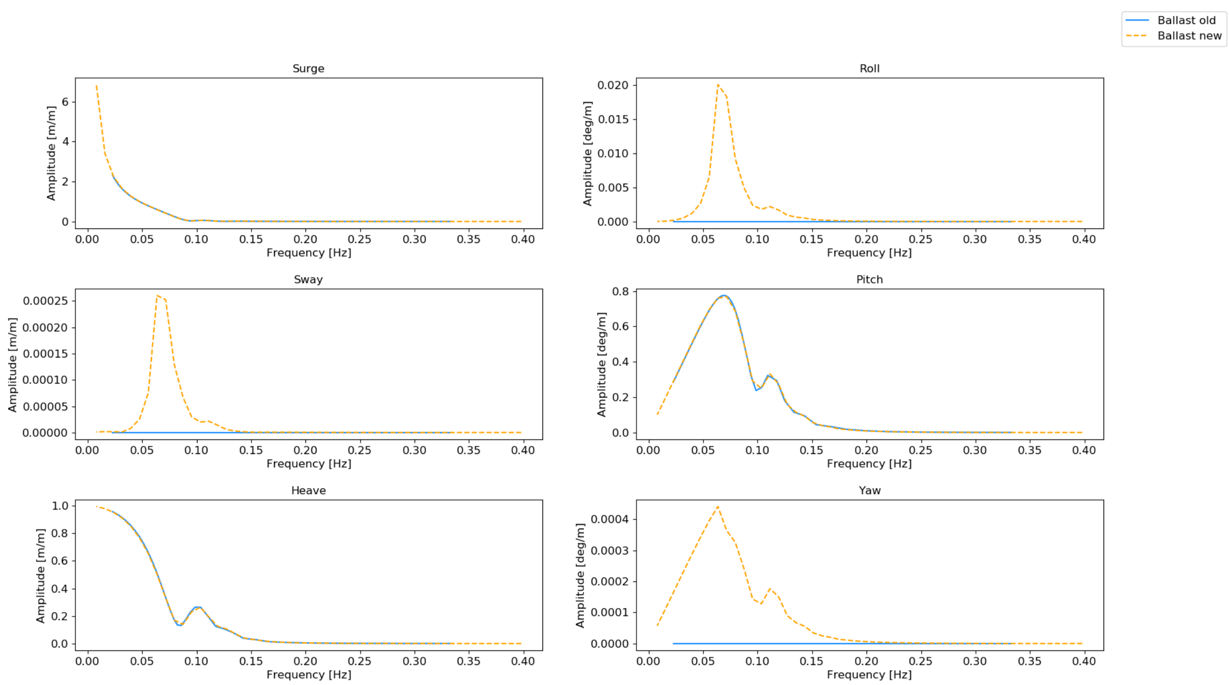


Figure E.26: Verification of RAOs load case Ballast, vessel heading 0°.

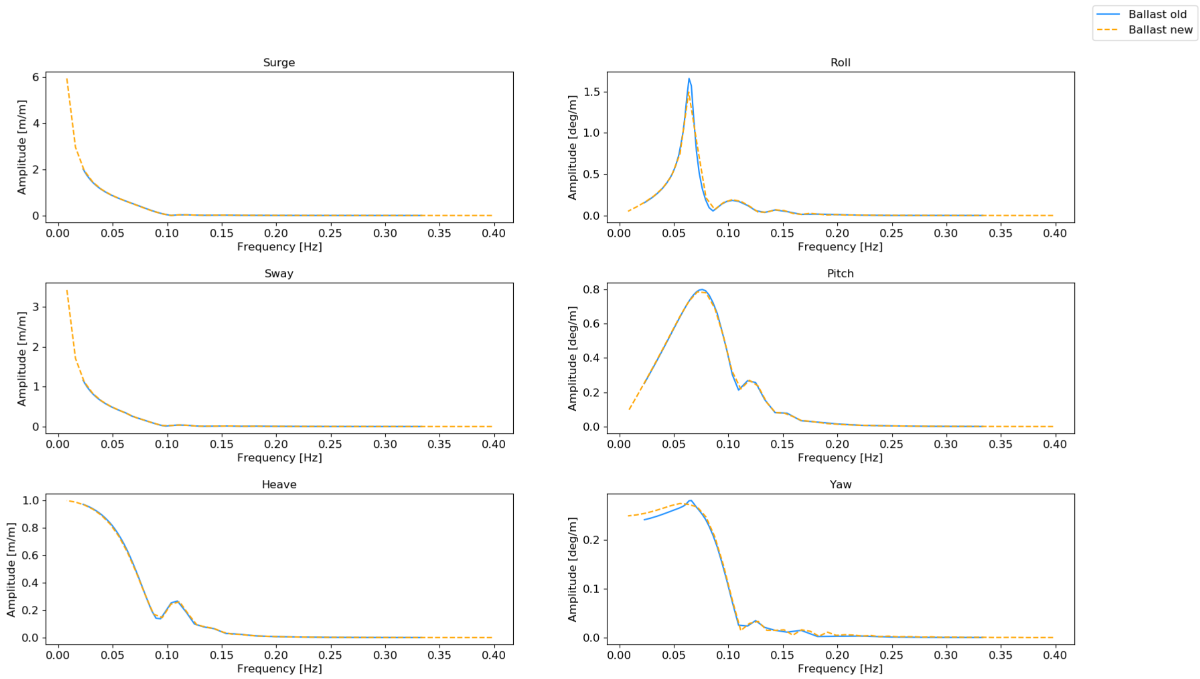


Figure E.27: Verification of RAOs load case Ballast, vessel heading 30°.

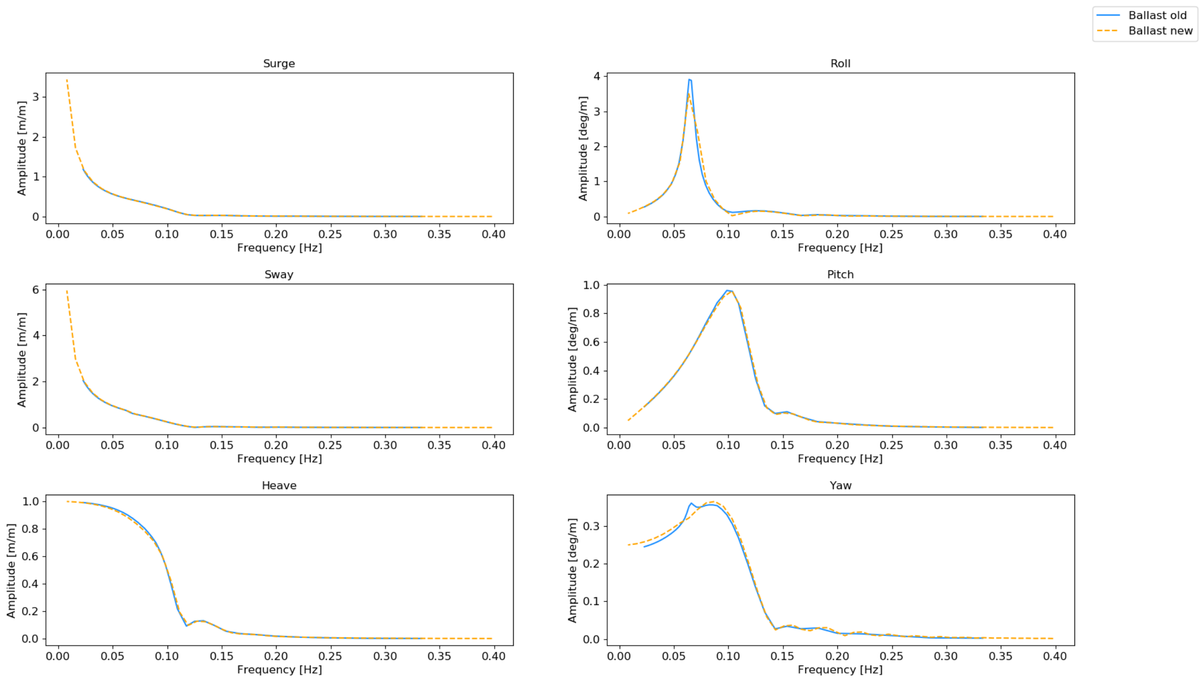


Figure E.28: Verification of RAOs load case Ballast, vessel heading 60°.

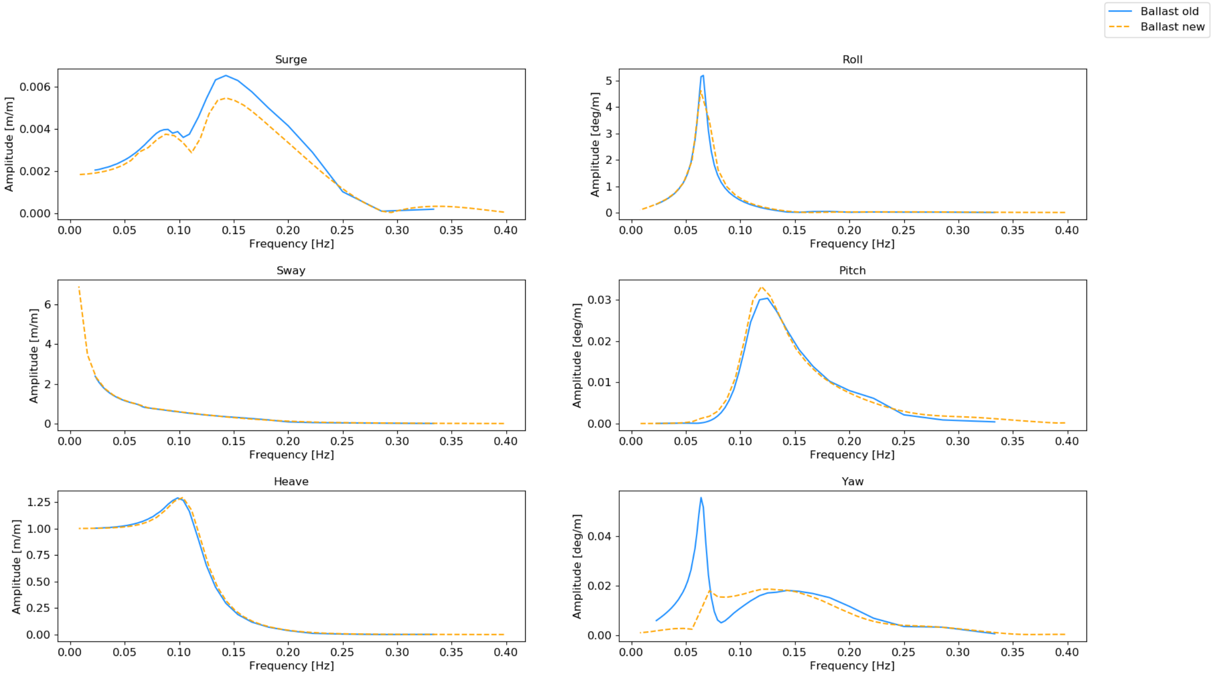


Figure E.29: Verification of RAOs load case Ballast, vessel heading 90°.

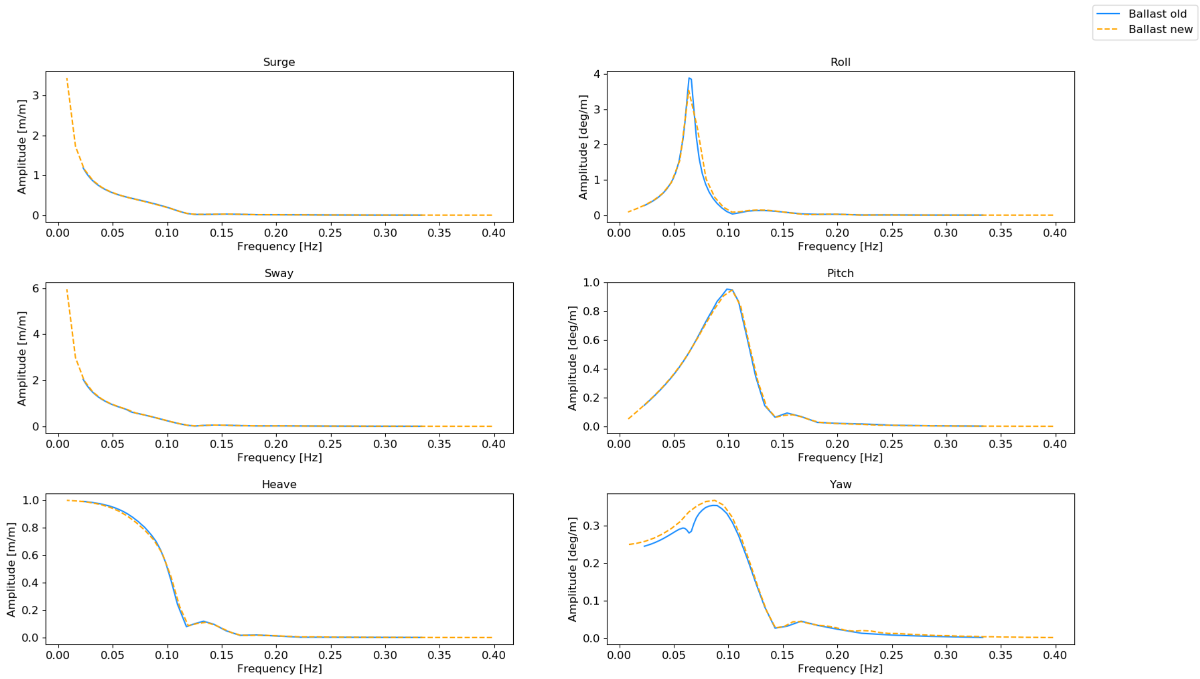


Figure E.30: Verification of RAOs load case Ballast, vessel heading 120°.

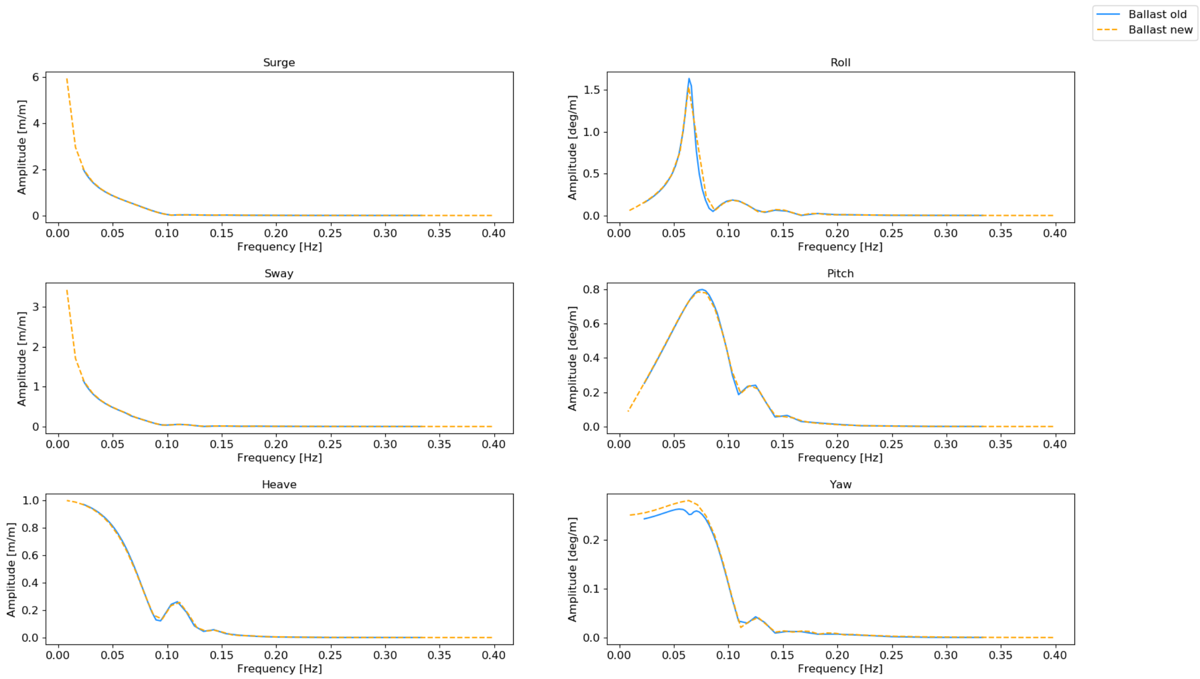


Figure E.31: Verification of RAOs load case Ballast, vessel heading 150°.

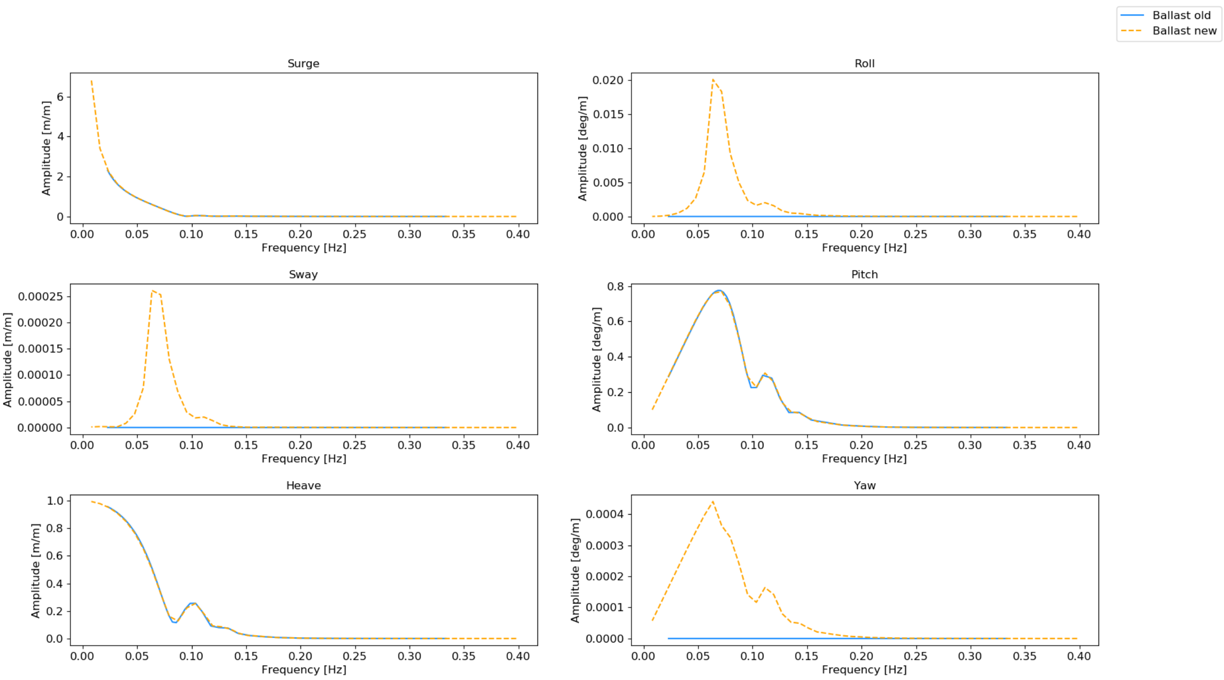


Figure E.32: Verification of RAOs load case Ballast, vessel heading 180°.

E.6 Intermediate load cases

For the motion analysis, two different load cases are considered, namely Ballast and Fully Loaded. This section discusses the expectation of the vessel's motions in case of intermediate load cases.

From the displacement RAOs, as presented in appendix E.1 can be observed that the influence of the wind turbine is most significant in the roll RAO. For every wave heading the addition of the wind turbine causes the peak frequency of the roll RAO to shift to the lower frequencies. This is a result due to the decreasing GM in the case of the wind turbine addition.

That a lower GM causes lower roll peak frequencies, is also occurring when considering the intermediate load cases. To show this, the old displacement RAOs of the Haewene Brim from [130][29] are taken into consideration. The displacement mass and GM, including and excluding free surface correction, of the different load cases, are shown in table E.2.

Load case	Displacement mass	GM solid	GM corrected
Ballast	82824	6.20	6.16
Intermediate 30% cargo	88154	6.76	4.96
Intermediate 50% cargo	90215	5.40	2.52
Intermediate 70% cargo	100863	4.38	1.45
Fully loaded	119366	2.62	2.22

Table E.2: Overview of old load cases Haewene Brim.

Figure E.33 shows an example of the old RAOs of the Haewene Brim for the 6 DoF of the vessel for its different old load cases, with a vessel heading of 150°. As can be observed the roll RAO is the only RAO in which significant peak-frequency changes occur. The peak frequency of the roll increases with an increasing GM.

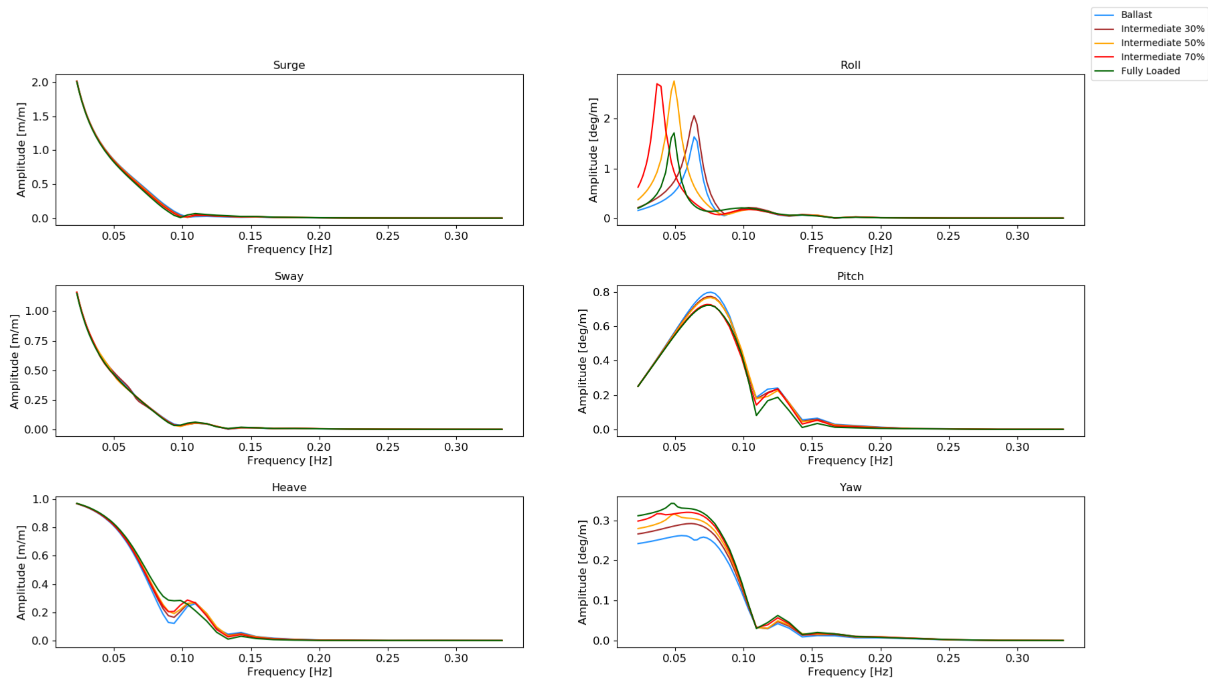


Figure E.33: Example of old displacement RAOs for multiple vessel load cases, vessel heading 150°.

[29]Reference coming from Bluewater's Meridian database (not publicly accessible).

The expectation is that when the intermediate load cases are considered including the wind turbine, this will cause the vertical center of gravity of the vessel to shift up, resulting in a lower value for GM, similar to what is observed for the Ballast and Fully Loaded load case as shown in section 9.2. A lower GM causes the peak frequency of the roll RAO to shift to the lower frequencies, away from the wind turbine's 1P frequency range. Depending on the wave-loading conditions, it can occur that an intermediate load case is governing. However, for the hydrodynamic loading, it is favorable that the GM decreases due to the addition of the wind turbine since an increasing GM causes shorter roll periods which are considered uncomfortable for personnel on board the vessel [131].

Figure E.34 shows how the roll RAOs relate to the considered JONSWAP-spectra, as explained in section 9.5, and the 1P frequency range of the wind turbine. For the sea-states that have been taken into consideration in the motion analysis, the addition of the wind turbine resulting in lower roll peak frequencies would cause the RAO to shift away from the JONSWAP-spectra and 1P frequency range of the wind turbine, which is expected to be favorable for the system's motions.

However, from the motion analysis results, it was also observed that the wind loading has a significant influence on the vessel's dynamic roll behavior. In that case, the lower value of GM is not favorable, since that will result in a less steep slope of the righting moment curve resulting in larger roll angles compared to a loading condition with a higher value of GM, possibly leading to a governing and critical combination, especially when wind comes from the side of the vessel. Because of this balance between the hydrodynamic and aerodynamic loading effects, it will be required to eventually evaluate also the different intermediate loading conditions.

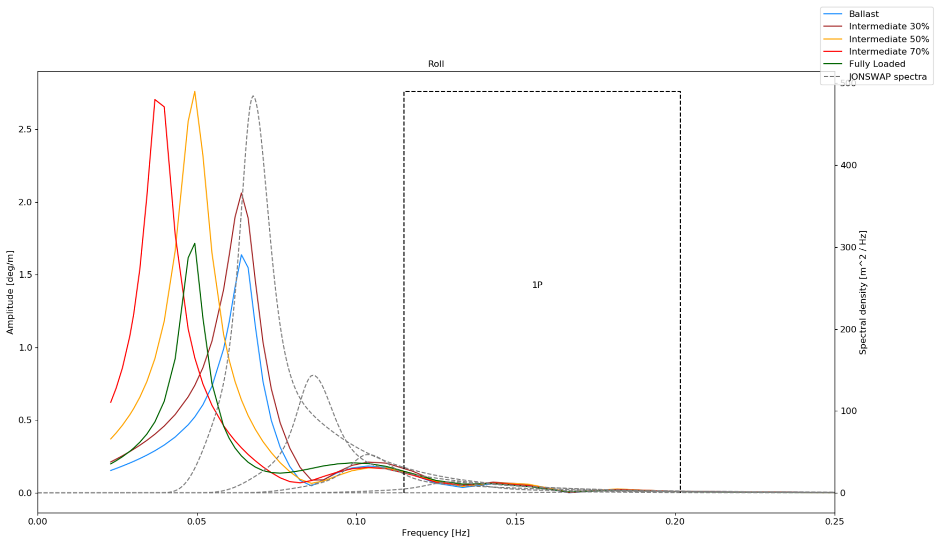


Figure E.34: Roll RAO for a vessel heading of 150°, JONSWAP wave-spectra, and 1P frequency range.

F Wind turbine model validation

The wind turbine model that is used in OrcaFlex is validated by reproducing the results of the Wind Turbine Validation Report of Orcina Project 1405 [84]. Several deviations are later made to this model to capture different phenomena and adjust to the required configuration. These changes are further explained in chapter 9. In this appendix, the OrcaFlex input from the Wind Turbine Validation Report is explained, and the results are shown, where a comparison is made with results from FAST as reported by NREL in [47]. The version of OrcaFlex used is version 11.2c.

F.1 Model input

The validation report [84] describes two different cases, namely a Land-Based system and the OC3 Hywind System. As a start, the K01 5MW spar FOWT model is downloaded from Orcina's website [132]. Since the application requires the turbine to be placed on an FPSO, the effect and validation of the spar platform are not included. Therefore, the validation is only shown for the Land-Based system as shown in figure F.1. The model is adjusted to the settings of the Land-Based System, which match the properties of the NREL 5 MW reference turbine as described by Jonkman in [47]. The model uses the Blade-Element Momentum (BEM) theory to model the forces onto the turbine. The steady-state response of the system is obtained and evaluated against the FAST results given in [47].

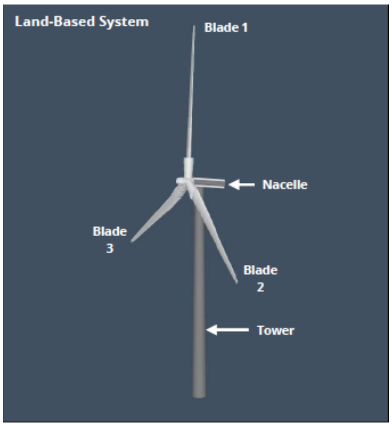


Figure F.1: Land-Based System [84]

F.1.1 Environmental conditions and simulation settings

The environmental conditions are fully described by wind loading. Within the operational wind speed range of the NREL 5 MW, 23 different load cases are evaluated where a uniform wind speed is applied to the model. The environmental conditions are shown in table F.1.

Wind type	Time history (speed)
Wind direction	0°(parallel to rotor axis)
Load cases	23
Lowest wind speed	3 m/s
Highest wind speed	25 m/s
Increments	1 m/s
Density air	1.225 kg/m^3
Kinematic viscosity air	15·10^{-6} m^2/s

Table F.1: Environmental conditions [84]

The model is simulated in the implicit time domain. For each load case, the same duration, build-up phase, and time-step is used, which are shown in table F.2.

Simulation type	Implicit time domain
Duration	500 s
Build-up phase	50 s
Time step	0.1 s

Table F.2: Simulation settings [84]

The wind speed increases linearly from 0 towards the uniform wind speed during the build-up phase and remains constant during the duration of the simulation, as can be seen in figure F.2 for a wind speed of 13 m/s.

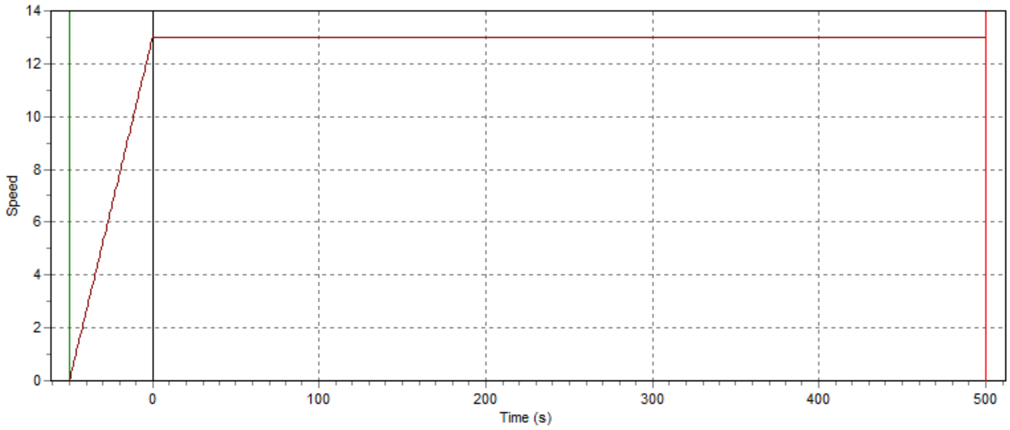


Figure F.2: Wind speed during simulation, example 13 m/s.

F.1.2 Generator, hub, and nacelle

The generator and hub are specified using OrcaFlex 'turbine' object. Its properties are shown in table F.3. The center of mass is positioned at the center of the rotor. The generator control is determined by specified torque, using an external function. This is further explained in section F.1.5.

Generator	Capacity	5 MW
	Cut-in wind speed	3 m/s
	Rated wind speed	11.4 m/s
	Cut-out wind speed	25 m/s
	Rotor diameter	126 m
	Initial rotor angle	0 deg
	Gear ratio	97:1
	Inertia about high-speed shaft	0.534 te.m^2
	Rated rotor speed	12.1 rpm
	Rated generator speed	1173.7 rpm
Hub	Diameter (H)	3.000 m
	Mass	56.78 te
	Axial moment of inertia	115.926 te.m^2
	Transverse moment of inertia	0 te.m^2
	Main shaft stiffness	Infinity kN.m/deg
	Horizontal offset (over-hang) from yaw-axis (B)	5.000 m
	Offset from yaw-axis (C)	5.019 m
	Offset from rotor bearing (D)	1.912 m

Table F.3: Generator & Hub properties [84].

The nacelle is implemented into the model using a '6D buoy' object. Its properties are shown in table F.4. A detailed overview of the hub and nacelle is given in figure F.3. The indicators shown in the figure are assigned in tables F.3 and F.4 to the corresponding values.

Mass	240 te
Dimensions (l x b x h)	14.285 x 2.286 x 3.500
Drag (x,y,z)	8.0, 50.0, 32.7
Drag coefficient (along x,y,z)	1, 1.2, 1.2
Inertia (x,y,z)	350.024 te.m^2, 5409.87 te.m^2, 2607.89 te.m^2
Main shaft tilt (G)	5°
Yaw bearing vertical offset to main shaft (A)	1.963 m
Center of mass horizontal offset (E)	1.900 m
Center of mass vertical offset (F)	1.750

Table F.4: Nacelle properties [84].

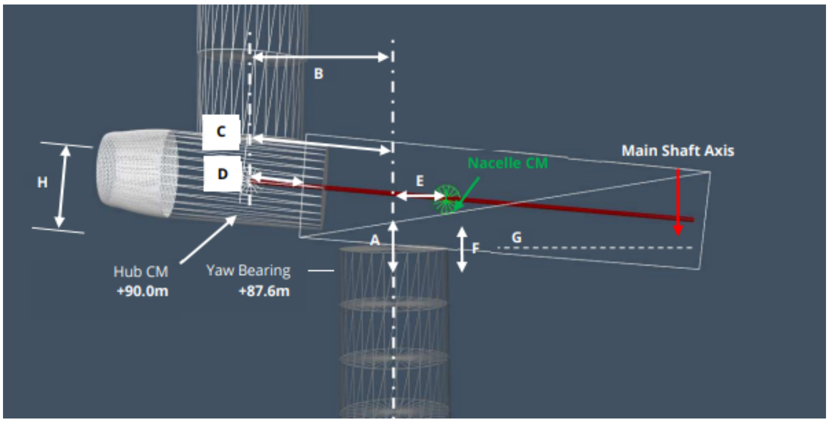


Figure F.3: Detailed overview of the hub and nacelle [84].

F.1.3 Blades

The turbine consists of three blades. The blades are modeled as part of the turbine object. The overall blade properties are shown in table F.5.

Length	61.5 m
Mass	17.740 te
Pre-cone angle	2.5°
Initial pitch	0°
Material	Glass fibre

Table F.5: Overall blade properties [84].

Each blade is divided into 17 sections, each with a specified section length and constructed from a particular wing type. Each section is assigned a node with certain inertia, where the space between the nodes is massless segments. The used wing types and their data originate from Appendix B by Jonkman in [47]. The wing types provide different coefficients for drag, lift, and moment for different incidence angles of the blade. Further structural properties, geometry, and inertia of the blades are taken from Jonkman's description of the NREL 5 MW in [47]. The blade pitch control is described using an external function, which is further explained in section F.1.5.

Section No.	Section length [m]	Cumulative length [m]	Number of segments	Wing type
1	2.733	2.733	1	Cylinder1
2	2.733	5.467	1	Cylinder1
3	2.733	8.200	1	Cylinder2
4	4.100	12.300	1	DU40
5	4.100	16.400	1	DU35
6	4.100	20.500	1	DU35
7	4.100	24.600	1	DU30
8	4.100	28.700	1	DU25
9	4.100	32.800	1	DU25
10	4.100	36.900	1	DU21
11	4.100	41.000	1	DU21
12	4.100	45.100	1	NACA64
13	4.100	49.200	1	NACA64
14	4.100	53.300	1	NACA64
15	2.733	56.033	1	NACA64
16	2.733	58.767	1	NACA64
17	2.733	61.500	1	NACA64

Table F.6: Blade section properties [84]

F.1.4 Tower

In OrcaFlex the tower is represented by a line object with a line type of homogeneous pipe. The properties of the tower are shown in table F.7. The tower diameter and wall thickness are linearly interpolated between the tower's top and bottom. To match the results from FAST, wind loading onto the tower is neglected. The model does not take into account the influence that the tower has on the inflow of the turbine or the blade-to-tower interaction [84].

Mass	347.46 te
Length	87.6 m
Diameter top	3.87 m
Diameter bottom	6 m
Wall thickness top	25 mm
Wall thickness bottom	35 mm
Material density	8.50 te/m^3
Center of mass height	38.148 m
Young's Modulus	210 GPa
Shear Modulus	80.8 GPa
Poisson ratio	0.3
Added mass coefficient	1
Drag coefficient	1.2

Table F.7: Tower dimension and properties [84]

F.1.5 Control system

In OrcaFlex the wind turbine control system is represented by two external Python control functions. One controls the blade pitch of the wind turbine, and the other controls the generator torque. These functions are based on Jonkman's description of the blade pitch and generator torque control as provided in [47]. The activity of a certain controller depends on the wind speed. Three different regions are defined of which the properties are shown in table F.8. During the transition phase, both controllers are active where the transition from full generator torque control to full blade pitch control is made.

Region	Active controller	Wind speed range
1	Generator torque	3-11 m/s
2	Transition phase	11-12 m/s
3	Blade pitch	12-25 m/s

Table F.8: Controller type per wind speed [84].

In OrcaFlex the behavior of these controllers can be adjusted based on certain tags. The tags given to the model are shown in table F.9. The high value for the natural angular frequency (ActuatorOmega) of 188 rad/s together with the damping ratio (ActuatorGamma) of 2% are assigned to neglect the blade pitch actuator dynamic effects which are not modeled in FAST [84].

FloatingSystem	False
UseActuator	True
ActuatorOmega	188.0
ActuatorGamma	0.02

Table F.9: Tags for external functions [84]

Generator torque controller

The goal of the generator torque controller is to capture the maximum amount of power in case the wind is below the rated wind speed. Its response is fully determined based on the generator speed. This is described by the graph shown in figure F.4 where the line of the variable-speed controller shows the used control system behavior in different regions. The behavior is captured in a Python function and used as input for OrcaFlex.

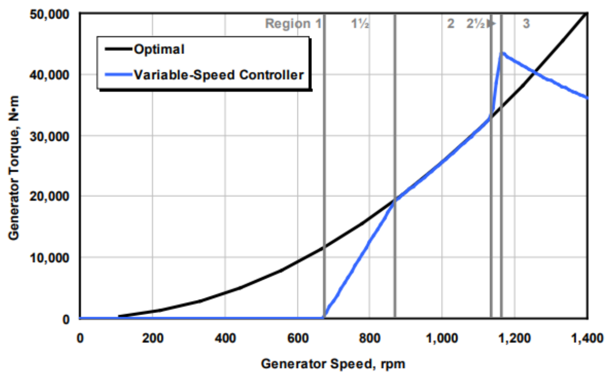


Figure F.4: Torque controller [47].

Blade-pitch controller

A brief explanation of the blade-pitch controller is given. For more details, Jonkman [47] can be consulted. The computations are included in external functions implemented in OrcaFlex by using Python. The blade-pitch controller controls the generator speed in case the wind speed is above the rated wind speed, which occurs in region 3 of the generator torque controller. The blade pitch angles are computed using gain-scheduled proportional-integral control which assesses the speed error [47]. The speed error is the difference between the filtered generator speed and the rated generator speed. It is based on a single-degree-of-freedom model of a wind turbine, where the degree of freedom is the angular rotation of the shaft. The equation of motion for this degree of freedom can eventually be described by formula F.1 which is derived by Jonkman in [47]. Dot notation is used to indicate a time derivative.

$$\underbrace{\left[I_{Drivetrain}+\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_D\right]}_{M_\varphi}\ddot{\varphi}+\underbrace{\left[\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_P-\frac{P_0}{\Omega_0^2}\right]}_{C_\varphi}\dot{\varphi}+\underbrace{\left[\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_I\right]}_{K_\varphi}\varphi=0 \tag{F.1}$$

The parameters in the equation of motion are described in table F.10.

φ	Shaft angular rotation
θ	Full-span rotor-collective blade-pitch angle
P	Mechanical power
P_0	Rated mechanical power
Ω_0	Rated rotor speed
N_{Gear}	Gearbox ratio
$I_{Drivetrain}$	Drivetrain inertia cast to low-speed shaft
K_D	Derivative gain
K_P	Proportional gain
K_I	Integral gain

Table F.10: Definition of parameters in EoM.

To ignore the negative damping resulting from the generator torque controller, which is not modeled in FAST, the derivative gain is equal to zero. For the proportional gain and integral gain, the expressions in formulas F.2 and F.3 are found.

$$K_P=\frac{2I_{Drivetrain}\Omega_0\zeta_\varphi\omega_{\varphi n}}{N_{Gear}\left(-\frac{\partial P}{\partial \theta}\right)} \tag{F.2}$$

$$K_I=\frac{I_{Drivetrain}\Omega_0\omega_{\varphi n}^2}{N_{Gear}\left(-\frac{\partial P}{\partial \theta}\right)} \tag{F.3}$$

Here $\omega_{\varphi n}$ is the natural frequency of the system and ζ_φ is the system's damping ratio. Due to the linear behavior of the pitch sensitivity, as is shown in figure F.5, it is possible to rewrite the expression for the gains. These expressions are shown in equations F.4 and F.5.

$$K_P(\theta)=\frac{2I_{Drivetrain}\Omega_0\zeta_\varphi\omega_{\varphi n}}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta=0)\right]}GK(\theta) \tag{F.4}$$

$$K_I(\theta)=\frac{I_{Drivetrain}\Omega_0\omega_{\varphi n}^2}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta=0)\right]}GK(\theta) \tag{F.5}$$

Here $GK(\theta)$ is the gain-correction factor of which the expression is shown in formula F.6.

$$GK(\theta)=\frac{1}{1+\frac{\theta}{\theta_K}} \tag{F.6}$$

As can be seen, the gain-correction factor depends on the blade-pitch angle. Solving the system results in the eventual values of the blade pitch. The initial conditions that are used are for $K_P(\theta = 0°) = 0.01882681$ and for $K_I(\theta = 0°) = 0.008068634$. The values that are found for the different gains and the gain-correction factor in relation to different blade-pitch angles are shown in figure F.6. Eventually, the blade pitch can be found using formula F.7.

$$\Delta\theta = K_P N_{Gear} \Delta\Omega + K_I \int_0^t N_{Gear} \Delta\Omega dt + K_D N_{Gear} \Delta\dot{\Omega} \tag{F.7}$$

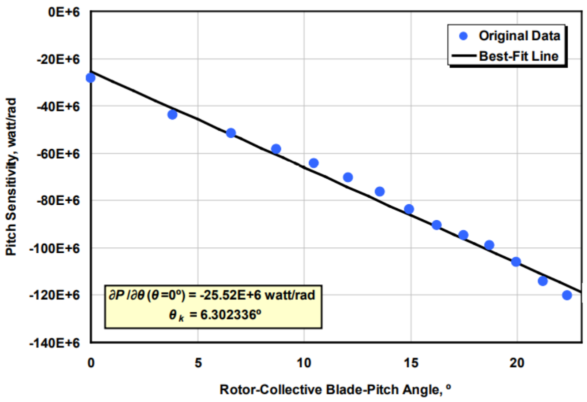


Figure F.5: Pitch sensitivity [47].

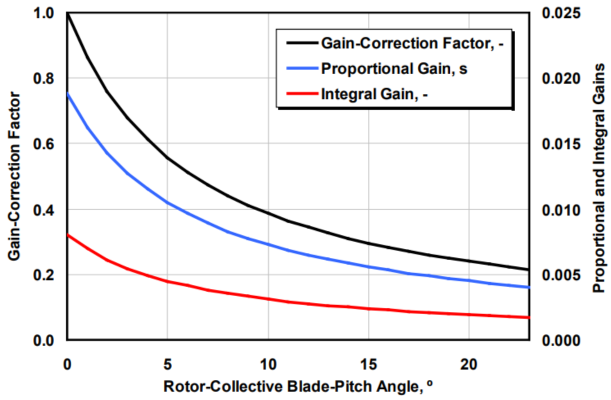


Figure F.6: Gain scheduling values [47]

F.2 Model results

The results that are obtained by running multiple implicit time domain simulations for the different wind speeds in OrcaFlex are plotted against the results from FAST, similar to how the results are plotted in [84]. First, the graphical results are shown, followed by the data in table form. The black line represents the results gathered from Jonkman in [47] using FAST. The red dashed line shows the computed results using OrcaFlex.

F.2.1 Graphical results

Rotor results

The results related to the rotor are shown in figures F.7 till F.10. As can be seen, the results obtained in OrcaFlex match the results from FAST by Jonkman [47] closely, similar to the results shown in Orcina's validation report [84].

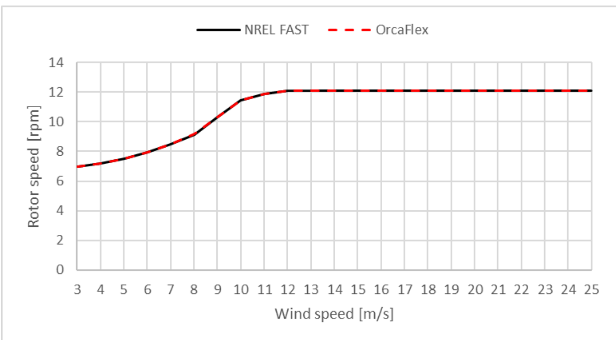


Figure F.7: Rotor speed comparison.

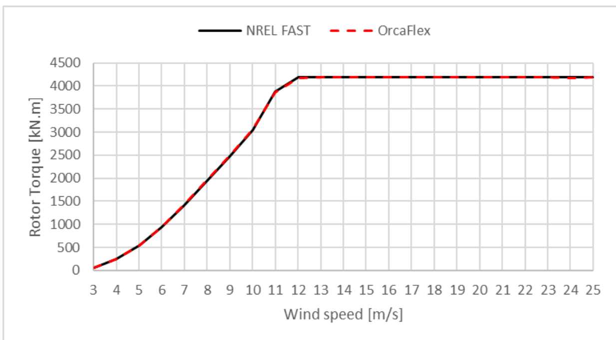


Figure F.8: Rotor torque comparison.

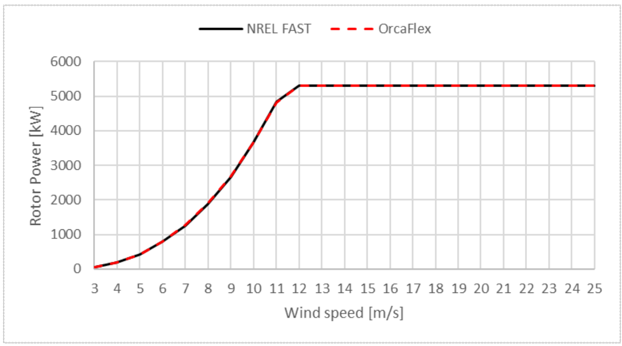


Figure F.9: Rotor power comparison.

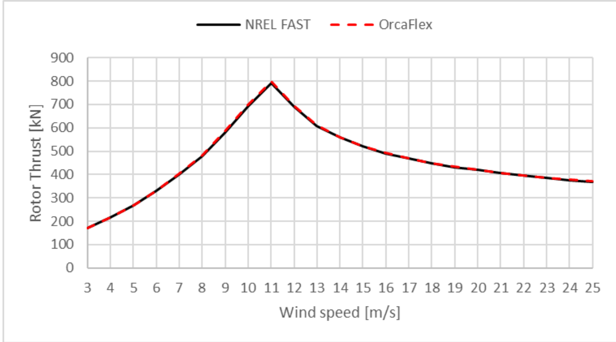


Figure F.10: Rotor thrust comparison.

Generator results

The results related to the generator are shown in figures F.11 till F.13. Again a close match with the FAST results is obtained. When it comes to the generator power, it should be noted that in OrcaFlex the mechanical-to-electrical losses are not taken into consideration, while this is taken into account in FAST. Therefore a user-defined result parameter is defined in OrcaFlex taking into account the FAST found generator efficiency of 94.4%, which results in a close agreement between the OrcaFlex and FAST results as can be seen in figure F.13.

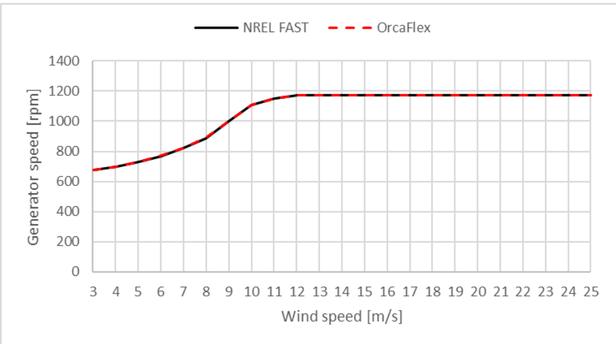


Figure F.11: Generator speed comparison.

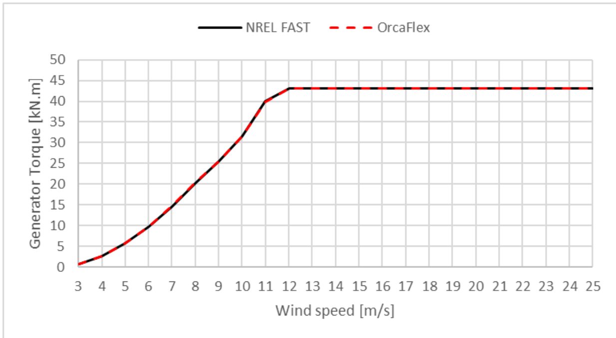


Figure F.12: Generator torque comparison.

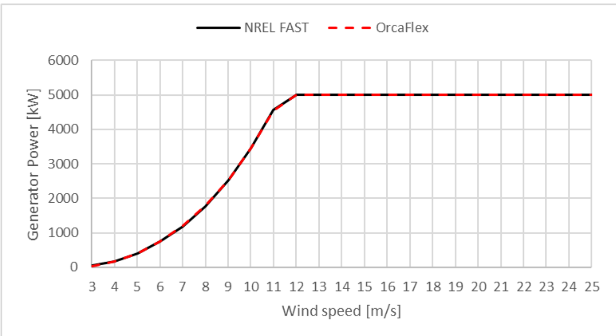


Figure F.13: Generator power comparison.

Blade results

The results related to the blades are shown in figures F.14 till F.17. The following figures also show a green dashed line showing OrcaFlex default results. The difference between the two OrcaFlex results is due to a change in the settings for the torsional and axial stiffness properties of the blades, similar to what is done in Orcina's validation report [84]. The OrcaFlex default results (green dashed line) model both axial and torsional degrees of freedom, while for the OrcaFlex results (red dashed line) these degrees of freedom are neglected by assigning high stiffness values for these degrees of freedom of

1*10^9 kN.m and 1*10^9 kN.m^2 and respectively. This is to better match the results from FAST where these phenomena are not modeled. The impact of this change is minimal on the rotor and generator results shown previously, which is the reason that the green dashed line is not included in these figures.

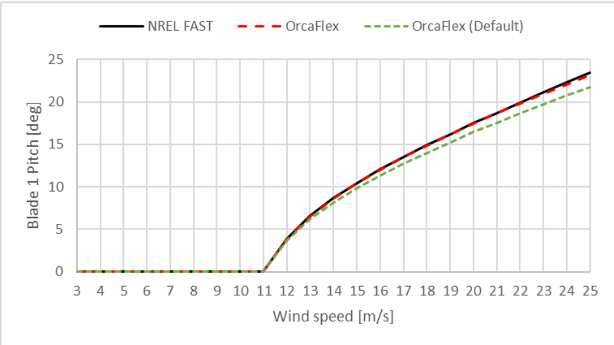


Figure F.14: Blade 1 pitch comparison.

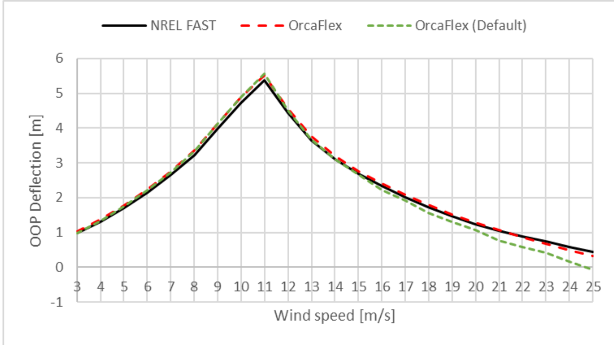


Figure F.15: Average out-of-plane tip deflection blade 1 comparison.

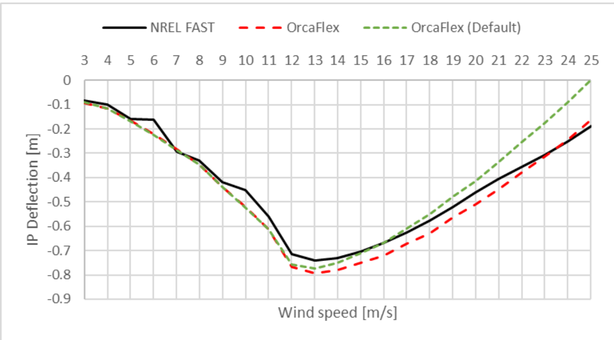


Figure F.16: Average in-plane tip deflection blade 1 comparison.

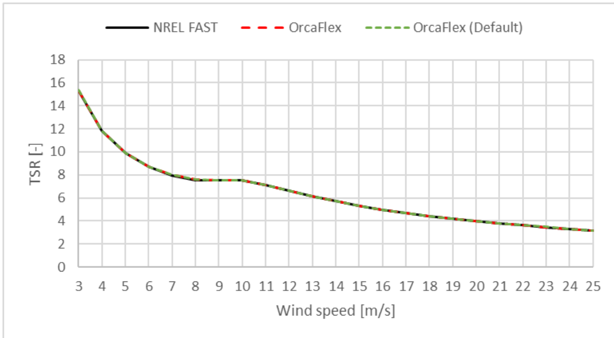


Figure F.17: TSR comparison.

Tower results

The results related to the tower are shown in figures F.18 and F.19.

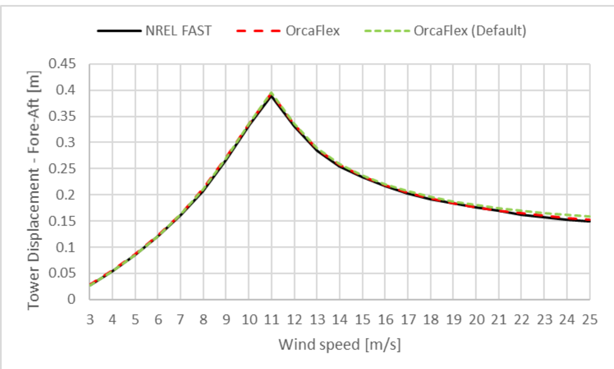


Figure F.18: Average fore-aft deflection tower top comparison.

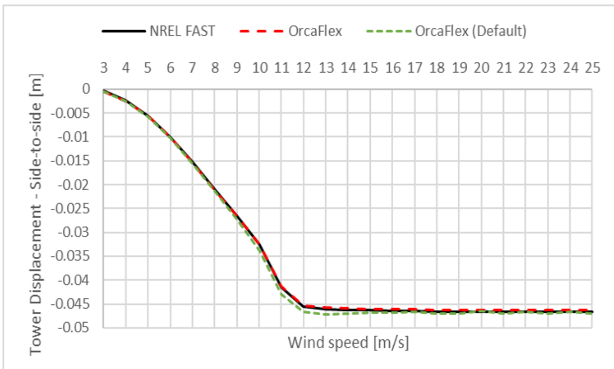


Figure F.19: Average side-to-side deflection tower top comparison.

F.2.2 Tables with computed values

The values used to determine the graphical results are shown in tables F.11 until F.13.

Wind speed	GenSpeed	RotPwr	GenPwr	RotThrust	RotTorq	RotSpeed	BldPitch1	GenTq	TSR	OoPDefl1	IPDefl1	TTDspFA	TTDspSS
(m/s)	(rpm)	(kW)	(kW)	(kN)	(kN·m)	(rpm)	(deg)	(kN·m)	(-)	(m)	(m)	(m)	(m)
3	676.3	42.9	40.5	171.7	58.8	6.972	0	0.606	15.316	0.989	-0.082	0.0278	-0.0004
4	696.7	188.2	177.7	215.9	250.2	7.183	0	2.58	11.835	1.3159	-0.0993	0.054	-0.0024
5	728.1	427.9	403.9	268.9	544.3	7.506	0	5.611	9.895	1.7103	-0.1588	0.0852	-0.0056
6	770.3	781.3	737.6	330.3	939.5	7.942	0	9.686	8.724	2.1517	-0.1635	0.1214	-0.01
7	821.4	1257.6	1187.2	398.6	1418.1	8.469	0	14.62	7.974	2.6592	-0.2925	0.1615	-0.0152
8	888.1	1876.2	1771.1	478	1956.9	9.156	0	20.174	7.543	3.2292	-0.3295	0.208	-0.021
9	998.7	2668	2518.6	579.2	2474.5	10.296	0	25.51	7.54	3.966	-0.4173	0.2669	-0.0265
10	1109	3653	3448.4	691.5	3051.1	11.431	0	31.455	7.535	4.7325	-0.4516	0.3322	-0.0326
11	1153.3	4833.2	4562.5	790.6	3881.3	11.89	0	40.014	7.125	5.3692	-0.561	0.3901	-0.0416
12	1173.9	5296.6	5000	690	4180.1	12.1	3.823	43.094	6.646	4.4382	-0.7149	0.3319	-0.0456
13	1173.8	5296.6	5000	608.4	4180.1	12.1	6.602	43.094	6.135	3.6501	-0.7404	0.2844	-0.046
14	1173.8	5296.6	5000	557.9	4180.1	12.1	8.668	43.094	5.697	3.1155	-0.7307	0.255	-0.0462
15	1173.8	5296.6	5000	520.5	4180.1	12.1	10.45	43.094	5.317	2.688	-0.7051	0.2333	-0.0463
16	1173.8	5296.6	5000	491.2	4180.1	12.1	12.055	43.094	4.984	2.3278	-0.6693	0.2165	-0.0464
17	1173.8	5296.6	5000	467.7	4180.1	12.1	13.536	43.094	4.691	2.0138	-0.6259	0.203	-0.0465
18	1173.8	5296.6	5000	448.4	4180.1	12.1	14.92	43.094	4.431	1.7327	-0.5759	0.1921	-0.0466
19	1173.8	5296.6	5000	432.3	4180.1	12.1	16.226	43.094	4.197	1.4765	-0.5203	0.1832	-0.0467
20	1173.8	5296.7	5000	418.8	4180.1	12.1	17.473	43.094	3.988	1.2452	-0.4616	0.1758	-0.0467
21	1173.8	5296.6	5000	406.7	4180.1	12.1	18.699	43.094	3.798	1.043	-0.4042	0.1691	-0.0467
22	1173.8	5296.7	5000	395.3	4180.1	12.1	19.941	43.094	3.625	0.8829	-0.3563	0.1625	-0.0467
23	1173.9	5296.6	5000	385.1	4180.1	12.1	21.177	43.094	3.467	0.7387	-0.3082	0.1568	-0.0467
24	1173.9	5296.6	5000	376.7	4180.1	12.1	22.347	43.094	3.323	0.5904	-0.2514	0.1525	-0.0467
25	1173.9	5296.7	5000	369.3	4180.1	12.1	23.469	43.094	3.19	0.4404	-0.1875	0.1487	-0.0466

Table F.11: NREL FAST results.

Wind speed	GenSpeed	RotPwr	GenPwr	RotThrust	RotTorq	RotSpeed	BldPitch1	GenTq	TSR	OoPDefl1	IPDefl1	TTDspFA	TTDspSS
(m/s)	(rpm)	(kW)	(kW)	(kN)	(kN·m)	(rpm)	(deg)	(kN·m)	(-)	(m)	(m)	(m)	(m)
3	676.1	42.0	39.7	171.9	57.6	7.0	0	0.594	15.330	1.0308	-0.0927	0.0288	-0.0004
4	696.8	188.8	178.3	216.3	251.0	7.2	0	2.588	11.848	1.3700	-0.1169	0.0549	-0.0025
5	728.3	429.4	405.3	269.5	546.1	7.5	0	5.629	9.910	1.7707	-0.1647	0.0861	-0.0057
6	770.8	785.4	741.4	331.7	943.9	7.9	0	9.730	8.739	2.2392	-0.2221	0.1227	-0.0100
7	822.6	1269.2	1198.2	402.6	1429.1	8.5	0	14.734	7.994	2.7661	-0.2834	0.1642	-0.0153
8	890.7	1892.6	1786.4	484.1	1968.2	9.2	0	20.289	7.572	3.3667	-0.3463	0.2119	-0.0211
9	1000.4	2681.6	2531.4	586.2	2482.9	10.3	0	25.596	7.560	4.1171	-0.4396	0.2712	-0.0266
10	1109.3	3655.8	3451.1	698.8	3052.7	11.4	0	31.471	7.545	4.8958	-0.5216	0.3366	-0.0326
11	1153.0	4808.3	4539.3	797.0	3862.9	11.9	0	39.826	7.129	5.5271	-0.6130	0.3943	-0.0414
12	1173.6	5295.2	4999.7	694.0	4179.2	12.1	3.798	43.094	6.652	4.5587	-0.7678	0.3348	-0.0454
13	1173.7	5296.6	5000.1	612.0	4179.9	12.1	6.543	43.093	6.141	3.7599	-0.7937	0.2870	-0.0458
14	1173.7	5296.2	5000.0	560.2	4179.8	12.1	8.621	43.093	5.703	3.2064	-0.7809	0.2570	-0.0460
15	1173.7	5296.5	4999.9	522.4	4180.1	12.1	10.402	43.094	5.322	2.7675	-0.7502	0.2351	-0.0461
16	1173.7	5296.4	4999.9	492.7	4180.0	12.1	12.007	43.094	4.989	2.3991	-0.7220	0.2181	-0.0461
17	1173.7	5296.1	4999.9	468.8	4179.8	12.1	13.488	43.093	4.696	2.0734	-0.6702	0.2044	-0.0462
18	1173.7	5296.0	5000.0	449.2	4179.4	12.1	14.872	43.092	4.435	1.7853	-0.6275	0.1933	-0.0462
19	1173.7	5297.0	5000.1	432.9	4180.4	12.1	16.177	43.094	4.201	1.5206	-0.5632	0.1842	-0.0462
20	1173.6	5296.1	4999.8	419.0	4179.9	121	17.426	43.094	3.992	1.2819	-0.5092	0.1766	-0.0462
21	1173.7	5297.2	5000.1	407.1	4180.4	12.1	18.634	43.093	3.801	1.0679	-0.4486	0.1701	-0.0462
22	1173.6	5295.9	4999.8	396.7	4179.8	12.1	19.802	43.094	3.628	0.8671	-0.3780	0.1646	-0.0462
23	1173.7	5296.1	5000.0	387.3	4179.6	12.1	20.928	43.093	3.471	0.6748	-0.3128	0.1600	-0.0462
24	1173.7	5295.6	5000.0	379.2	4179.1	12.1	22.015	43.092	3.326	0.4922	-0.2433	0.1561	-0.0462
25	1173.7	5297.4	5000.1	371.4	4180.7	12.1	23.119	43.094	3.193	0.3155	-0.1613	0.1522	-0.0462

Table F.12: OrcaFlex results.

Wind speed	GenSpeed	RotPwr	GenPwr	RotThrust	RotTorq	RotSpeed	BldPitch1	GenTq	TSR	OoPDefl1	IPDefl1	TTDspFA	TTDspSS
(m/s)	(rpm)	(kW)	(kW)	(kN)	(kN·m)	(rpm)	(deg)	(kN·m)	(-)	(m)	(m)	(m)	(m)
3	676.7	45.9	43.3	168.8	62.9	7.0	0	0.647	15.346	0.9877	-0.0900	0.0269	-0.0004
4	697.3	192.3	181.6	213.5	255.5	7.2	0	2.635	11.857	1.3325	-0.1166	0.0532	-0.0026
5	728.8	432.8	408.6	266.9	550.1	7.5	0	5.672	9.912	1.7395	-0.1693	0.0846	-0.0058
6	771.1	788.4	744.2	329.5	947.0	7.9	0	9.763	8.740	2.2168	-0.2247	0.1214	-0.0101
7	822.8	1270.5	1199.4	400.7	1430.4	8.5	0	14.747	8.002	2.7427	-0.2853	0.1631	-0.0154
8	890.7	1893.0	1786.8	482.5	1968.6	9.2	0	20.292	7.576	3.3419	-0.3465	0.2111	-0.0214
9	1000.4	2681.7	2531.6	584.3	2482.9	10.3	0	25.598	7.554	4.1093	-0.4393	0.2704	-0.0273
10	1109.2	3654.9	3450.2	697.0	3052.3	11.4	0	31.466	7.549	4.8844	-0.5237	0.3362	-0.0338
11	1152.8	4801.4	4532.7	797.8	3857.9	11.9	0	39.774	7.116	5.5671	-0.6138	0.3955	-0.0429
12	1173.6	5296.1	4999.7	694.4	4180.0	12.1	3.615	43.095	6.660	4.5049	-0.7580	0.3360	-0.0467
13	1173.7	5296.0	5000.0	612.5	4179.4	12.1	6.190	43.092	6.150	3.6659	-0.7724	0.2883	-0.0471
14	1173.7	5296.7	5000.0	561.3	4180.2	12.1	8.152	43.094	5.710	3.1047	-0.7519	0.2585	-0.0469
15	1173.7	5296.9	5000.0	524.0	4180.3	12.1	9.831	43.094	5.313	2.6553	-0.7101	0.2369	-0.0469
16	1173.7	5296.7	4999.9	494.8	4180.3	12.1	11.335	43.094	4.995	2.2217	-0.6693	0.2203	-0.0467
17	1173.6	5296.2	4999.8	471.6	4180.0	12.1	12.714	43.094	4.692	1.9160	-0.6079	0.2072	-0.0466
18	1173.7	5295.1	4999.9	452.8	4178.9	12.1	14.007	43.092	4.440	1.5574	-0.5509	0.1966	-0.0469
19	1173.8	5297.7	5000.2	437.3	4180.7	12.1	15.241	43.093	4.195	1.3094	-0.4785	0.1877	-0.0470
20	1173.6	5297.6	4999.9	423.9	4181.2	12.1	16.426	43.096	3.997	1.0601	-0.4142	0.1804	-0.0464
21	1173.7	5296.3	5000.0	412.5	4179.7	12.1	17.562	43.092	3.801	0.7658	-0.3370	0.1744	-0.0470
22	1173.6	5296.9	4999.9	402.5	4180.6	12.1	18.655	43.096	3.624	0.5836	-0.2536	0.1694	-0.0466
23	1173.7	5295.4	4999.9	393.8	4179.1	12.1	19.714	43.092	3.474	0.4116	-0.1749	0.1652	-0.0470
24	1173.7	5295.3	4999.8	386.0	4179.2	12.1	20.743	43.094	3.329	0.1479	-0.0904	0.1615	-0.0466
25	1173.8	5298.7	5000.4	379.8	4181.4	12.1	21.746	43.093	3.191	-0.0775	0.0012	0.1585	-0.0469

Table F.13: OrcaFlex default results.