Bachelor's project

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Solheim, Sondre

Mooring of Floating Offshore Wind Turbines

A review of the mooring designs and the installation vessels for floating offshore wind turbines.

Bachelor's project in Nautical Science
Supervisor: Terje Fiskerstrand
Co-supervisor: Eirik Klokkersund

June 2021

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SOLSTAD OFFSHORE

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Preface

This bachelor thesis is written in conjunction with the completion of the studies of Nautical Science, Department of Ocean Operations and Civil Engineering at NTNU Aalesund. The problems to be addressed are composed by the authors in close collaboration with Solstad Offshore.

We would like to thank Kai Roger Nilsen in Deep Sea Mooring and Henning Støylen at OTS for providing valuable information from the industry. We would also like to thank Karl Henning Halse at NTNU for giving us valuable insight in the technical extent. Numerous others have contributed with their help, and they are not forgotten.

We would also like to thank our supervisor Terje Fiskerstrand at NTNU, for always answering our questions immediately.

Finally, our most sincere gratitude goes to our supervisor at Solstad Offshore, Eirik Klokkersund. Eirik has always been supportive and constantly providing us with the required information. Without him, this bachelor thesis would not have been possible.

The content in this thesis is of the author's account.

Sammendrag

Målet med denne oppgaven var å undersøke hvilke instanser som er ansvarlige for å regulere offshore vind i Norge. Deretter forklarer oppgaven hvilke design for fortøyningssystemene som er tilgjengelige for flytende vindmøller i Norge. Til slutt foreslår oppgaven modifikasjoner som kan gjøres på ankerhåndteringsfartøyene til Solstad Offshore for at de skal være utrustet for installasjon av fortøyningssystemer for flytende vindmøller.

Oppgaven undersøker regelverket for offshore vind i Norge, både med hensyn på søknadsprosessen for å få konsesjon, og med hensyn på hvilke etater som er ansvarlige for tilsyn av flytende vindmøller. Informasjonen var innhentet gjennom studier av lover, forskrifter og regelverk for flytende vindmøller i Norge i dag. Olje- og Energidepartementet har det overordnede ansvaret for offshore vind i Norge. Ansvaret er videre delegert til Petroleumstilsynet, som har ansvar for tilsyn med næringen. Norges vassdrags- og energidirektorat er assisterer Olje- og energidepartementet med faglige råd gjennom søknadsbehandlingen. Norges vassdrags- og energidirektorat er også ansvarlige for å godkjenne den prosjektspesifikke detaljplanen for vindkraftverket. Klasseselskapene har tilsyn med og godkjenner vindmøllene på oppdrag fra forsikringsselskapene, men dette ansvaret er ikke lovfestet.

Oppgaven presenterer design av forankringssystemer for flytende vindmøller. Informasjonen om forankringsdesign var innhentet gjennom møter med fagpersoner i næringen og gjennom studier av eksisterende litteratur og forskning på området. Designene av forankringssystemene er hovedsakelig basert på design som er brukt i olje- og gassnæringen. Oppgaven beskriver hovedkategoriene av design, materialer brukt i førtøyningslinene og ankertypene som blir brukt. Slakkline forankring baserer seg på slakke fortøyningsliner, og har et stort fotavtrykk. Slakkline forankring gir store posisjonsforskyvninger, men derimot lav strekkspenning i fortøyningslinene. Stramline forankring baserer seg på stramme fortøyningsliner, og de motvirkende kreftene baserer seg på elastisiteten i materialet som er brukt i fortøyningslinen. Posisjonsforskyvningen i et stramline forankringssystem er mindre, men strekkspenningen i fortøyningslinen er høyere enn for et slakkline forankringssystem. Egenskapene til materialene brukt i fortøyningslinene og ankertypene er valgt for å gi ønskede egenskaper i fortøyningssystemet. Kostnader er også avgjørende for designet av forankringssystemet.

Oppgaven foreslår modifikasjoner til Normand Drott for at fartøyet skal passe for installasjon av forankringssystemer for flytende vindmøller. Forslagene er basert på informasjon fra rederiet,

Solstad Offshore. Utstyret som håndterer kjetting må modifiseres for å passe større kjettingdimensjoner. Et reaksjonsanker må brukes for å oppnå den påkrevde oppstrammingen av ankeret.

Abstract

The aim of this thesis was to investigate who is the licencing authorities for offshore wind in Norway. Then, this thesis explains which mooring configurations that are available for floating offshore wind turbines. Lastly, this thesis suggests how Solstad Offshore could modify their AHTS vessels to fit for installation of mooring systems for floating offshore wind turbines.

The thesis studies the regulations for offshore wind in Norway, both on the process of applying for a license and which authorities are responsible for supervision and inspection of floating offshore wind farms. The information was gathered by studying the current laws and regulations for offshore wind in Norway. The Ministry of Petroleum and Energy has the overall responsibility and has delegated the supervision to the Petroleum Safety Authority Norway. The Norwegian Water Resource and Energy Directorate assists the Ministry of Petroleum and Energy with professional advice during the application process. The Norwegian Water Resource and Energy Directorate are also responsible for approving the project specific detailed plan. The classification societies approve the wind farm on behalf of the insurance companies and are not required by the law.

The thesis presents the mooring designs for floating offshore wind turbines. The information of mooring designs was collected through meetings with industry professionals as well as reading literature and research papers of the topics. The mooring designs are mainly based on designs developed in the oil and gas industry. This thesis describes the main categories of mooring designs, mooring line materials and relevant anchor types. The catenary design utilises slack mooring lines with a large footprint. The offset of the catenary design is large, and the tension is lower. The taut mooring configuration utilises taut mooring lines, and the resisting forces rely on the elastic stiffness of the mooring line. The offset in a taut mooring system is smaller, and the tension is higher than for a catenary system. The properties of mooring line materials and anchors are chosen to get the desired properties of the mooring configuration. The mooring design is also subject to cost.

The thesis suggests modifications for Normand Drott to make the vessel fit for the installation of moorings for floating offshore wind turbines. The suggestions are based on information from the vessel owner, Solstad Offshore. The chain handling equipment must be modified to fit for larger chain diameters. A reaction anchor can be used to circumvent the problem of the high required proof tension.

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Abbreviations

AH – Anchor Handling

AHC – Active Heave Compensated

AHTS – Anchor Handling Tug Supply

ALS – Accidental Limit State

BP – Bollard Pull

CSV – Construction Support Vessel

DEA – Drag Embedment Anchor

DP – Dynamic Positioning

FLS – Fatigue Limit State

FOW – Floating Offshore Wind

FOWF – Floating Offshore Wind Farm

FOWT – Floating Offshore Wind Turbine

HMPE – High Modulus Polyethylene

LCOE – Levelized Cost OF Electricity

LTM – Long Term Mooring

MBL – Minimum Breaking Load

MODU – Mobile Offshore Drilling Unit

MPE – Ministry of Petroleum and Energy

N. Drott – Normand Drott

N. Prosper – Normand Prosper

NVE – Norwegian Water Resource and Energy Directorate

O&G – Oil and Gas

PS – Port Side

PSA – Petroleum Safety Authority

PSCR – Project Specific Consequence Review

PSDP – Project Specific Detailed Plan

PSR – Project Specific Review

ROV – Remotely Operated Vehicle

SHW – Special Handling Winch

SOFF – Solstad Offshore

STB – Starboard Side

TLP – Tension Leg Platform

ULS – Ultimate Limit State

VLA – Vertical Load Anchors

WLL – Working Load Limit

WTG – Wind Turbine Generator

WWC – Wind, Wave, Current

1 Introduction

The size and number of offshore wind farms have faced considerable growth since 2010. From 2010 to 2020, the global offshore wind capacity has grown by 29 GW, a tenfold increase since 2010 (GWEC, 2010, GWEC, 2020). The wind farms are being built further from shore and in deeper waters (GWEC, 2020). Floating Offshore Wind (FOW) is expected to grow by 6.2 GW over the next ten years. Norway is expected to be a significant producer of offshore floating wind, with 1.88 GW of floating wind farms to be installed in the next ten years (GWEC, 2020). The Norwegian part of the North Sea is well suited for FOW due to deep waters and strong winds (NVE, 2010).

The technology for Floating Offshore Wind Turbines (FOWT) is less developed than for bottom fixed turbines. To this date, there are 65.7 MW of FOW power in operation (GWEC, 2020). For FOWTs, the mooring system must be optimised due to the large quantities of units and large environmental forces acting upon the units. The mooring systems utilised for mooring FOWTs to date, are mainly based on designs developed by the Oil and Gas (O&G) industry. This presents a new market for use of vessels originally built for installation of mooring systems for O&G installations. The trend of FOWTs moorings is that the dimensions will be larger than the typical O&G mooring designs. Therefore, the existing mooring installation vessels will not be able to meet the future demand, and must be adapted for the coming requirements (Solstad Offshore, 2021).

For FOW, the regulations and the distribution of responsibilities between the various ministries in Norway are still under development. This thesis addresses the current regulations and the process of applying for a licence to construct and operate a Floating Offshore Wind Farm (FOWF) in Norway.

This thesis is written in collaboration with Solstad Offshore (SOFF), which has a potential client with specific plans for Utsira Nord. Therefore, Utsira Nord is chosen as the focus in this thesis. The client plans to install 40 semi-submersible FOWTs, using chain catenary moorings and Drag Embedment Anchors (DEAs). As a result of this, SOFF is facing challenges meeting the requirements for future installations of FOWTs. On the background of this, the assignment of this thesis is to clarify the following questions:

- Why is there a need for such large chains and high proof tension?

- What can SOFF do to make the vessels fit for installation of the desired chain and proof tension?

To clarify these questions, the following problems to be addressed are composed:

- Who is the licensing authority for offshore wind farms?
- Which mooring designs are suitable for mooring of floating offshore wind turbines in Norway?
- What can Solstad Offshore do to make their vessels comply with the future requirements for mooring of floating offshore wind turbines?

First, the thesis will describe the licencing authorities and the requirements for FOW in Norway. Further on, the mooring designs for FOWTs will be described. Then, the thesis presents suggestions on how the Anchor Handling Tug Supply (AHTS) fleet of SOFF could be adapted to meet future demands.

The arrangement of the thesis is according to the IMRAD-model. Following this introduction, the thesis is divided into the sections induction, method, results, discussion, and conclusion. The section of induction introduces the previous work on the subject. The section of the method will explain how the information is collected. After that, the technical terms are explained in the section of the results. Then, the problems to be addressed are discussed in the section of the discussion.

2 Induction

2.1 Previous Work

The research on mooring of FOWTs are based on simulations, prototypes, and demonstrator projects. The experience of installing mooring configurations in a great magnitude are lacking. The research focuses on simplification of traditional mooring configurations. Mainly, the research focused on catenary mooring configurations. The research on mooring systems in general, especially on moorings for the O&G industry are extensive. However, some of the technology from the O&G industry can not be adapted due to differing costs, and especially the total number of mooring lines for each structure.

Xu et al. (2020) performed a mooring analysis for the mooring of a FOWT in shallow waters, ranging from 50-80 metres. The study recommended a catenary mooring configuration using all chain with additional clump weights and buoys. The analysis also recommended a mooring configuration using taut moorings with pure synthetic fibre rope.

Campanile et al. (2018) focused on the mooring design of a semi-submersible FOWT in deeper waters. The paper investigated the mooring design in two different sites. One near the Troll field in the North Sea, water depth 200-350 metres. The other site was near Dogger Bank in the southern North Sea, with water depths 50-80 metres. The paper concluded that a 6-line mooring configuration was preferable to a 9-line configuration due to lower costs. The 3-line configuration was assumed to be non-redundant. The paper also recommended not using wire ropes in FOWT moorings due to the need for larger footprint to get the desired catenary shape. Differing from O&G structures, the large mooring footprint could overlap between mooring lines from other FOWTs. A larger footprint could lead to larger spacing between each FOWT. The author assessed larger spacing as not favourable.

Nordvik and Larsen (2019) investigated the marine operation of installing suction anchors and torpedo anchors, simulating the weather state and installation procedure of the anchor types. The thesis concluded that installing a suction anchor is weather dependent, especially in the phase of lifting the anchor from the deck and lowering it through the splash zone. The limit for installation of the suction anchor was set to 2 metres in the North Sea. From the marine operations point of view, the thesis recommended a torpedo anchor, due to less weather dependent installation. The weather limit for the installation of a torpedo anchor was set to 5 metres in the North Sea. The thesis did not investigate the installation of DEAs, nor different mooring designs.

Borlet et al. (2016) investigated alternative mooring designs for the Hywind Demo SPAR turbine at 130 metres water depth. The study showed that by replacing the chain moorings with fibre rope and buoys, the cost and weight could be reduced by 70% and 60%, respectively. The mooring configuration using fibre rope and buoys had the same restoring properties and horizontal footprint as the original chain catenary mooring.

However, no research exists on the installation of larger mooring configurations, as the mooring configurations to date are mainly smaller due to smaller demonstration turbines. This thesis will investigate which modifications are available and needed for a Norwegian AHTS vessel to fit for installing large mooring systems for FOWTs.

Available mooring designs for FOWTs are compared with mooring designs for the O&G industry. The designs are compared to understand why the anchor systems are planned with larger dimensions than those for Mobile Offshore Drilling Units (MODUs) or permanent structures in the O&G industry. As the vessels of SOFF are built for the O&G industry, suggestions on how the vessels could be fitted for installation of FOWT moorings are presented.

3 Method

The thesis was written as a qualitative study. The information was mainly collected by studies of existing literature and consecutive conversations with professionals within the industry. The O&G industry has experience of mooring floating structures in the North Sea. Therefore, relevant research and experience were transferred from the moorings in the O&G industry to the mooring of FOWTs.

In collaboration with SOFF, parts of the data were collected through meetings and e-mail correspondence with the AHTS department. The information can be verified by contacting the AHTS department in SOFF. SOFF has operated AHTS vessels since the start of the 1970s. After the merger between SOFF, Farstad Shipping, Rem Offshore, and Deep Sea Supply, the combined experience with Farstad Shipping has contributed to the development of the AHTS vessels of today (Solstad Offshore, 2021). Based on this experience, the authors considered the information from SOFF as credible and relevant for the thesis.

When data was collected from companies with commercial motives, prudence was shown to ensure that the information was objective. Especially when the information was collected by reading promotional fact sheets or other information published on the companies' websites, prudence was shown to ensure that the information was objective. If it was discovered deviation between the sources, additional research was carried out to verify the facts. If the facts could not be verified, the source was rejected.

Standards, recommended practices, and other publications from classification societies were studied to understand the procedures and regulations. Some of these publications are both applied for the O&G industry and the FOW industry. The authors have evaluated the relevant publications for the O&G industry and verified that the information and requirements were relevant for mooring systems in the FOW industry.

The mooring systems shall be designed according to standards of the classification societies, such as DNV. For this thesis, the DNV standards and recommended practices are used as a basis. The DNV publications are verified as high-quality publications. Publications from other classification societies were also reviewed. The differences between the publications were minor, therefore DNV was chosen as the primary source.

Some information was kept confidential by the companies. When the thesis was written, the authors were permitted to provide the essence in a general point of view or censor the company name or other sensitive information. To present the whole picture, the authors evaluated to generalise the data rather than exclude it.

When the sources were written in Norwegian, such as the laws, the relevant text from the law was translated and cited to give the reader an understanding of the context. But the translations are not official, and the cited laws must be read in their original format to be valid.

Data collected through personal communications with companies and people, the sources are referred to as the company or person name, and the year of the communication. This includes the following conversations:

- Solstad Offshore, regular communications with Vessel Manager AHTS & PSV Eirik Klokkersund during the work of this thesis, communications using E-mail, and digital meetings. Shown in text as (Solstad Offshore, 2021).
- DNV, communications via E-mails 10.03.2021 with Acting Head of Department-Renewable Projects Offshore Nordics & Benelux, Marte Aaberg Midtsund. Shown in text as (DNV, 2021).
- Karl Henning Halse, Pro-decan Bachelor, Department of Ocean Operations and Civil Engineering NTNU. Meeting 10.03.2021 regarding technical terms in mooring systems. Shown in text as (Halse, 2021)
- Kai Roger Nilsen, Director of Engineering, Deep Sea Mooring. Communications via E-mails, and meeting 15.04.21. Shown in text as (Nilsen, 2021).
- Offshore Trawl Supply (OTS), communications with Henning Støylen, Product Development & Project Engineer, via E-mail 12.05.21. Regarding mooring line data. Shown in text as (OTS, 2021).

The authors are certified Able-Bodied Seamen with experience from offshore vessels, one of them has experience from AHTS vessels. Therefore, personal experience is included where applicable.

4 Theory

4.1 Introduction to Floating Offshore Wind

FOWFs are still only at a pilot phase, and additional cost reductions are needed to compete with bottom fixed turbines. The maximum depth for bottom fixed Wind Turbine Generators (WTGs) are approximately 60 metres (European Wind Energy Association, 2013). FOWFs creates a potential for deeper waters with stronger and more consistent winds than in shallow waters. According to GWEC (2020), 80% of the global wind energy resources are in waters deeper than 60 metres. For example, Hywind Scotland achieved a record in average capacity in Scotland. During twelve months, the average capacity was 57.1%, compared to the average in UK, which was 40%. (Equinor, 2021). The capacity factor is the ratio of produced energy and the maximum capacity of the wind farm over a given period.

SOFF’s client has drafted a FOWF at Utsira Nord. The FOWF will be used as a basis for this thesis. Utsira Nord is located 22 km off Utsira island. The average depth is 267 metres. The maximum allowed capacity is 1,500 MW (Ministry of Petroleum and Energy, 2020). The client’s draft contains 40 semi-submersible FOWTs. The planned mooring configuration is all chain catenary moorings, using DEAs. The chain size is expected to be 180 mm (Solstad Offshore, 2021).

4.1.1 Status of Floating Offshore Wind

According to GWEC (2020), there are 65.7 MW of installed FOW capacity globally to date. Compared to bottom fixed offshore wind, which is 31,900 MW. Most FOW projects are installed in Europe, with 71% of the global installations (Rystad Energy, 2021). The Levelized Cost Of Electricity (LCOE) is still high for FOW. For Hywind Scotland, the LCOE is 200-240 EUR/MWh, compared to bottom-fixed offshore wind farms, which are 110-140 EUR/MWh. The exact LCOE varies from different sources collected by Rystad Energy (2021), but the values still reflect the development and costs. When the size of FOWFs increases and the FOWF’s are deployed at a commercial scale, the LCOE is expected to be reduced towards 2030 and could be competitive with bottom fixed wind farms by 2030, as seen in Figure 1 (Rystad Energy, 2021).

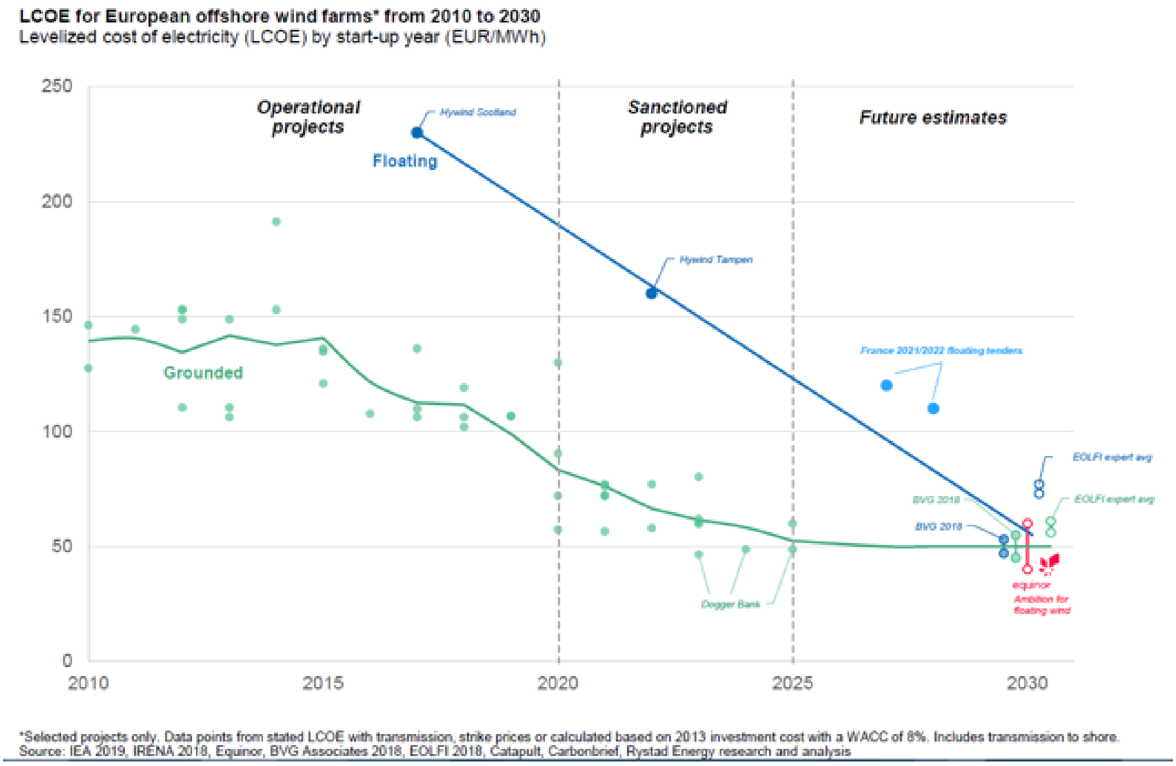


Figure 1 – Expected reduction in LCOE for bottom fixed and floating wind farms by 2030 (Rystad Energy, 2021).

4.1.2 Outlook of Floating Offshore Wind

By 2030, the expected installed capacity of FOW is 6,000 MW. The Asia Pacific area, excluding China, is expected to grow significantly within the FOW market. By 2030, the area is expected to surpass the expected installed FOW capacity in Europe (Rystad Energy, 2021). Rystad Energy (2021) predicts the FOW to have a small but increasing role in the offshore wind energy mix with a 5% share of the installed capacity by 2030. There are seven countries within Europe with specific plans to build FOWFs within the decade. These countries are France, UK, Portugal, Italy, Spain, Norway, and Sweden (WindEUROPE, 2021).

For Norway, FOW has potential due to the deep waters and strong winds. The experience from the O&G industry could contribute to the development of the FOW industry. The water depths on the Norwegian continental shelf are mostly deeper than 60 metres, as seen in Figure 2. The average wind speeds are high on the Norwegian continental shelf, especially in deeper waters, as shown in Figure 3 (NVE, 2010).

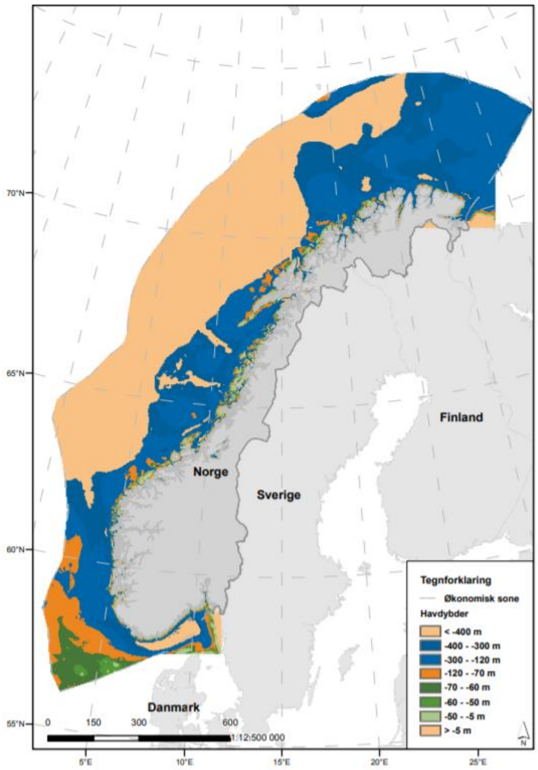


Figure 2 – Water depths in the Norwegian Economical Zone (NVE, 2010)

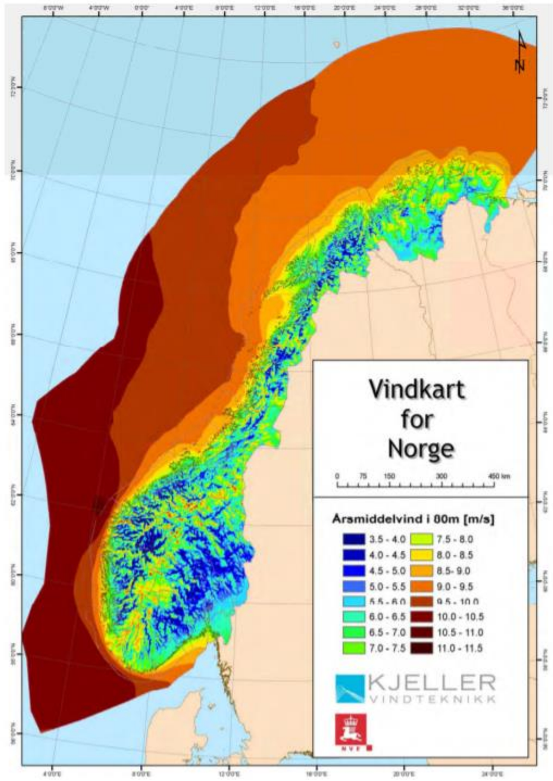


Figure 3 – Chart of wind resources in Norway (NVE, 2009)

4.2 Licensing Authorities

For the offshore wind industry in Norway, the regulations are still under development. The overall responsibility is with the Ministry of Petroleum and Energy (MPE), which delegates parts of the responsibility to the Norwegian Water Resource and Energy Directorate (NVE) and the Norwegian Petroleum Safety Authority (PSA). MPE is responsible for handling applications for a license to construct and operate an offshore wind farm in Norway in cooperation with NVE. The distribution of responsibility and the process of applying for a license are described further in this chapter.

4.2.1 Ministry of Petroleum and Energy

The Norwegian MPE is responsible for ensuring a coordinated and integrated energy policy. The primary objective is to ensure that the energy resources of Norway are utilised in the best possible way, both for the environment and to ensure high value creation (Ministry of Petroleum and Energy, 2013). MPE is responsible for managing the Norwegian energy resources by creating rules and regulations to control the production of energy. MPE is also managing the licenses for both petroleum fields and offshore wind farms. The Norwegian MPE has the jurisdiction of wind energy on the Norwegian continental shelf.

Award of Licence

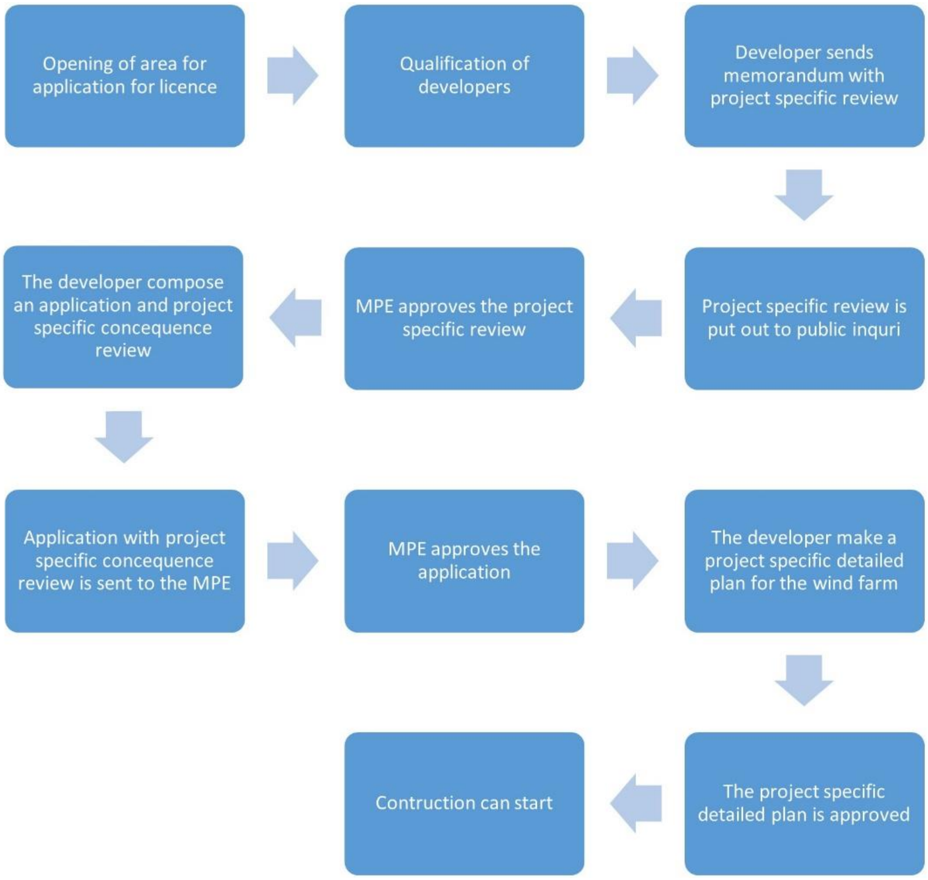


Figure 4 – Process of application of licence (Havenergilovforskrifta, 2020, Author's illustration, 2021, Havenergilova, 2010).

The process of applying for a license of constructing an offshore wind farm in Norway starts with the government opening an area for the use of energy production. The Norwegian Havenergilova (2010) § 1-2 provides that all renewable energy production outside the baseline shall only occur after the government has opened an area for energy production. The MPE will decide who gets licenced to commence construction and operation of an energy production plant. The opening of areas for FOW will be according to Havenergilova (2010) § 2-2.

The developer must comply with and be qualified according to the Havenergilova (2010) § 3-5 before applying for a licence. If the developer is qualified, the developer must send a memorandum to the MPE with a proposition of a Project Specific Review (PSR). The memorandum must be according to Havenergilova (2010) § 3-3 and the Norwegian Havenergilovforskrifta (2020) chapter 2 § 7. The procedure of the PSR must be according to Havenergilova (2010) § 4-1 and Havenergilovforskrifta (2020) ch. 2 § 4. The MPE decided that all memorandums, including a PSR, are imposed a fee to get processed (NVE, 2019).

The developer must perform a Project Specific Consequence Review (PSCR) of the proposed area. The PSCR must be according to Havenergilova (2010) § 4-1 and Havenergilovforskrifta (2020) ch. 2 § 6. The MPE allocates the licence and approving of the PSCR according to Havenergilova (2010) § 3-1, § 3-2 and Havenergilovforskrifta (2020) § 8.

The developer must also send a Project Specific Detailed Plan (PSDP). The PSDP shall be according to Havenergilova (2010) § 3-2 and Havenergilovforskrifta (2020) ch. 2 § 9. When all is processed, the NVE will decide to approve or reject the detailed plan and give a justification.

MPE has announced that a guide for offshore wind in Norway will be launched in conjunction with the white paper on the long-term value creation from Norwegian energy resources. The white paper is expected to be published 11th of June 2021, which is after this thesis is submitted (Olje- og energidepartementet, 2021). The information provided in this thesis is only preliminary and based on published information in press releases, laws, and regulations. The guide is expected to clarify the process of applying for a licence and the basis for approval or denial (Ministry of Petroleum and Energy, 2021).

4.2.2 Classification Societies

Classification societies were historically created for the ship insurance companies. The classification of ships and other units done by a classification society, such as DNV, ensures the insurance companies that a ship follows class rules (Jensen-Eriksen, 2015). Aside from providing classification for ships, they also provide services such as guidelines, recommended practices, and standards for the mooring of FOWTs.

DNV has published standards and recommended practices relevant to the anchoring of FOWTs, such as DNVGL-RP-E301 Design and installation of fluke anchors (DNV, 2019a) and DNVGL-ST-0119 Floating wind turbine structures (DNV, 2018a). Another classification society, Bureau Veritas, has published the NI 572 Classification and Certification of Floating Offshore Wind Turbines (Bureau Veritas, 2019) document with specific guidance and recommended practices for FOWTs. UK based Lloyds Register also provides services for classification and guidelines for FOW (Lloyds Register, 2021). Countries like Denmark and Germany require certification of FOWTs by law, where classification societies like DNV and Bureau Veritas provide such services. For Norway, requirements of classification of FOWTs are under consideration by the PSA (DNV, 2021).

4.2.3 Design Limits

When designing the mooring system for any floating unit, design limits are used to ensure that the construction can withstand the expected environmental forces, and forces acting upon the system in a damaged condition. Design limits and the safety factors to be used, are dependent on the mooring design and materials. The design limits and safety factors are provided by standards and recommendations set by the classification societies.

Ultimate Limit State

Ultimate Limit State (ULS) is in the case of FOWTs the total limit for failure or collapse of all or part of a structure due to loss of structural stiffness or exceedance of load-carrying capacity. Examples of ULS are overturning, capsizing, yielding and buckling (DNV, 2018a). The primary objective of the ULS design is to ensure that the mooring system stays intact, i.e. to guard against occurrence of a line failure or occurrence of continuous anchor drag (DNV, 2019a, DNV, 2018a). Design against the ULS is intended to ensure that the anchor with its geotechnical anchor resistance can withstand the loads arising in an intact station keeping system under extreme environmental conditions (DNV, 2018a). Some of the environmental loads that need to be calculated for the ULS is the steady wind and current loads, mean wave drift forces, wave loads and slow varying wave drift forces (USTUTT, 2016). For mooring of FOWTs, environmental conditions with a 50-year return period are used when designing against the ULS (DNV, 2018a).

Accidental Limit State

Accidental Limit State (ALS) is, in the case of FOWT, survival conditions in a damaged condition or the presence of nonlinear environmental conditions (DNV, 2018a). For mooring of a FOWT, the design against the ALS is intended to ensure that the anchor can withstand the loads arising in an intact station keeping system under accidental load conditions. Also, the design shall ensure that the damaged mooring configuration retains an adequate capacity if one mooring line, one tendon or one anchor should accidentally fail for reasons outside the designers control (DNV, 2018a).

Fatigue Limit State

Fatigue Limit State (FLS) is a limit state on the repetitions of actions that causes fatigue. For the mooring system of a FOWT, such actions are environmental loads such as Wind, Wave, and Current (WWC) (Bureau Veritas, 2019). Also, when considering the FLS on a FOWT mooring system, the corrosion on the different components needs to be considered. When designing for FLS, a S-N curve is used to illustrate different materials number of cycles to failure. N is the number of loading cycles, and S is the stress range. Fatigue life should be higher than the expected field service time multiplied by a safety factor. In Figure 5, this is illustrated with different types of wire rope and chain. For chain, this curve is intended to be applicable in sea water and for the wire rope types, it is assumed that the rope is protected from sea water corrosion (DNV, 2020).

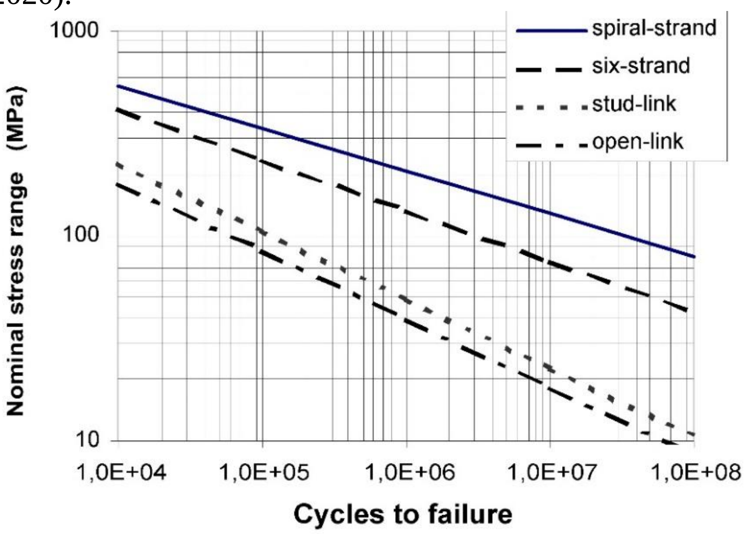


Figure 5 – Mooring line fatigue curve (DNV, 2020).

4.2.4 Redundancy

For mooring of a FOWT, the number of lines and types of anchors used will determine the redundancy of the station keeping system. DNV defines redundancy in ST-0119 Floating Wind Turbine Structures as; “The ability of a component or system to maintain or restore its function after a failure of a member or connection has occurred” (DNV, 2018a, p. 25). For example, a redundant station keeping system reduces the risk in the event of a single line failure. The level of redundancy within a station-keeping system is assessed in the ALS. A non-redundant station keeping system can be a 3-line catenary system using drag anchors, where if one line breaks, the direction of load will change, which can cause the remaining anchors to fail (USTUTT, 2016). A FOWT using a Tension Leg Platform (TLP) mooring system where a loss of a tendon will cause the structure to capsize will not be redundant and shall be designed for consequence class 2 (DNV, 2018a).

4.2.5 Consequence Classes

Consequence Class 1

Consequence class 1 is the lower class, where it is unlikely that a failure within a mooring system leads to loss of life, collision with other structures in the area and other environmental impacts (DNV, 2018a). If a complete failure of the mooring system does not harm other structures, it is in conjunction with consequence class 1. According to DNV ST-0119 Floating Wind Turbine Structures, the station keeping system of a FOWT shall generally be designed to consequence class 1 (DNV, 2018a).

Consequence Class 2

Consequence class 2 is the higher class, where a failure of the station keeping system will lead to unacceptable consequences of the types mentioned in consequence class 1. The station keeping system of a FOWT needs to be designed for consequence class 2 if it is not redundant (DNV, 2018a).

4.3 Floating Offshore Wind Turbine Terminology

A FOWT mainly consists of a WTG mounted on a floating platform connected to a mooring configuration. The WTG design is not included in this thesis. For both floating platform and mooring configuration designs, there are three main categories. The main floating platform categories is Semi-submersible, spar, and TLP. Regarding mooring configuration design, the main categories are catenary, taut and TLP. The TLP design are only described in brief in this thesis as it is not relevant for the AHTS vessels of SOFF. In this chapter, the platform and mooring configuration designs are described.

4.3.1 Floating Platforms

The FOWT is exposed to environmental loads such as WWC, which will lead to pitch, roll, and heave movement in the FOWT. The platform design shall ensure the righting moment and reduce the pitch, roll, and heave movement of the turbine.

The design of floating platforms for the wind turbines is based on designs used in the O&G industry. FOWT platforms are constructed in three different general designs, depending on the technology used to achieve stability of the structure. The design of the platform can vary within the categories. The designs which are deployed on a large scale is the spar-platform and semi-submersible platform. For example, the spar platform is installed in Hywind Scotland, and the semi-submersible platform is installed in Windfloat Atlantic (Principle Power, n.d, Equinor, n.d-b). TLP for FOWTs are under development but not yet tested on a large scale. TLP is a proven technology in the O&G industry. For example, the Heidrun platform in the North Sea is a TLP (Equinor, n.d-a, Lie, 2021).

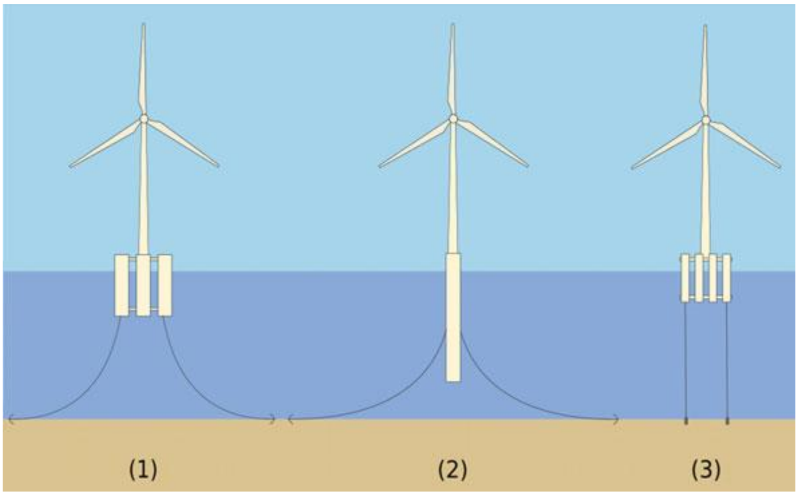


Figure 6 – Floater main categories; (1) Semi-submersible, (2) Spar, (3) TLP (Castro-Santos and Diaz-Casas, 2016).

Differing from the O&G industry, FOWTs is meant to be installed as relatively small structures of a great magnitude, which is a driving factor in the design of FOWT platforms (Castro-Santos and Diaz-Casas, 2016). There is also a need for easy installation, and it should be possible to disconnect the mooring lines and tow the turbine to shore if there is a need for more extensive repairs.

Semi-Submersible Platform

The semi-submersible platform ((1) in Figure 6) is a shallow draft, buoyancy stabilised platform with a large horizontal footprint (Castro-Santos and Diaz-Casas, 2016). The semi-submersible platform is moored using catenary or taut mooring lines. The advantage of a shallow draft design is that it simplifies the construction due to the possibility to construct the entire turbine at a standard depth quayside. The semi-submersible platform can be equipped with an active ballast system to reduce the movement of the structure. For example, the semi-submersible platform is installed at the Windfloat Atlantic FOWF by Principle Power, as shown in Figure 7 (Principle Power, n.d).

Figure 7 – Windfloat Atlantic semi-submersible platform (Principle Power, 2020).

Spar platform

The spar-type ((2) in Figure 6) floating platform is a cylindrical, deep draft, ballast stabilised platform. The stability is caused by the centre of gravity is lower than the centre of buoyancy. The ballast is positioned in the lower part of the cylinder and reduces the pitch and roll movements. The draft is in the magnitude of 80-90 metres, which will eliminate the heave movement (Equinor, n.d-c). Therefore, the spar type platform is best suited for wind farms deeper than 100 metres and requires deep water installation facilities (Castro-Santos and Diaz-Casas, 2016). Spar platforms are suitable for both taut and catenary mooring configurations. Spar platforms are installed in Hywind Scotland and are planned for Hywind Tampen as seen in Figure 8 (Equinor, n.d-b, Equinor, n.d-c).

Figure 8 – Hywind Scotland spar-type platform (Equinor, 2017).

Tension leg platform

TLP ((3) in Figure 6) is a tension leg stabilised floating platform, where the platform is moored using taut tendons. The tendons will provide stability for the platform and reduce the movements (Pelastar, n.d). The TLP requires anchors which can withstand high vertical tension, such as suction anchors or Vertical Load Anchors (VLA) (Vryhof, 2018). The TLP is well suited for deeper waters as the tendons is connected vertically to seabed, reducing the need for long mooring lines. TLP installation requires special installation vessels that can provide the platform with stability and connect the tendons. Special vessels are also required if the FOWT should be towed to port for service. If a tendon fails, the stability will be reduced, and there is a risk of capsizing (Castro-Santos and Diaz-Casas, 2016, DNV, 2018a). The TLP wind turbine is not yet demonstrated in full scale, and the knowledge is therefore based on calculations and small-scale tests, as well as experience transfer from the O&G industry.

Figure 9 – GICON and Glosten TLP type (GICON and Glosten, n.d).

Other Floater Types

There are other conceptual and prototype designs of FOWTs under development. One example is the Pivotbuoy as shown in Figure 11, which is a concept focusing on reducing the cost of FOWTs. The Pivotbuoy will utilise single point mooring and weather-vaning. The prototype turbine is expected to be deployed off the Canary Islands in 2021 (Pivotbuoy, n.d.). The Damping Pool prototype, shown in Figure 10, is developed by BW Ideol (n.d.-b)The Damping Pool is deployed as Floatgen and Hibiki demonstrators outside France and Japan, respectively. The Damping Pool offers reduced wave movements as well as shallow draft (BW Ideol, n.d.-b). The other conceptual designs are not described further in this thesis.

Figure 10 – BW Ideol Damping Pool (BW Ideol, n.d.-a).

Figure 11 – Pivotbuoy (Pivotbuoy, n.d.).

4.3.2 Current Floating Offshore Wind Farms

In the table below, some of the FOWFs currently in operation or under construction in the North Sea are presented. These FOWFs are installed or is to be installed at different water depths, and features FOWTs with different turbine sizes, floater types and mooring designs. Due to differences in WWC conditions and water depth, these are not directly comparable. Although they are selected to show the different configurations of the available catenary mooring designs.

	Hywind Scotland (5 FOWT's)	**Hywind Tampen (11 FOWT's)**	**Kincardine (6 FOWT's)**
Location	Buchan deep, Scotland, North Sea	Tampen Area, North Sea	Aberdeen Bay, Scotland, North Sea
Turbine effect	6 MW	8 MW	9.5 MW & 2 MW
Turbine height (surface to blade tip)	175 m	190 m	190 m
Rotor diameter	154 m	167 m	164 m

Floater type & material	Spar buoy, steel	Spar buoy, concrete	Triangular semi-submersible, steel
Floater draft	~78 m	~90 m	~25m
Water depth	95-129 m	260-300 m	60-80 m
Mooring lines per turbine	3	3	4
Mooring line type & size	132 mm bridle chain + 147 mm 4S stud-less chain	80 mm Spiral strand bridle + 124 mm R3	Chain: 76 mm + 152 mm + 82 mm, + 52.5 t clump weights
Anchor type, anchors to turbine ratio	Suction anchor 300 tonnes, 3 anchors per turbine	Shared suction anchors, 1.73 anchors per turbine	4 DEAs, 12 t pr turbine

Table 1 – Floating wind farm comparison (Equinor, n.d-b, Equinor, 2019b, Equinor, n.d-c, Equinor, 2019a, 4C Offshore, 2021, Vestas, 2021, NS Energy, 2021)

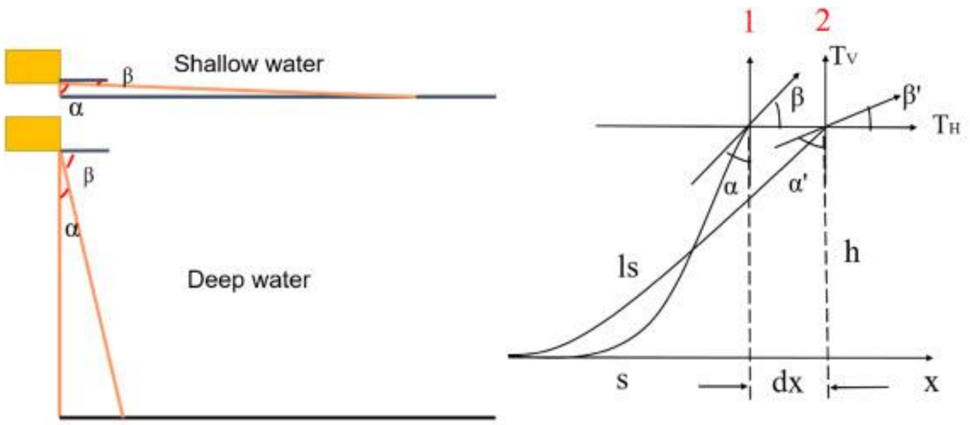
4.4 Mooring Configuration

All FOWTs need a mooring system to ensure that the FOWT stays in its determined position. The mooring lines are connected to the floater. The connection points are depending on the design of the floater. Normally, there are three to four mooring lines per FOWT (Equinor, 2019a, Principle Power, n.d, Equinor, n.d-b). The mooring lines for FOWTs are made by either spiral strand wire rope, chain, synthetic fibre rope or a combination of these materials. The main role of the mooring system is to control the surge, sway and yaw movement and ensure that the position offset of the FOWT is within its limits (Xu et al., 2021). For some floater designs, a bridle is used to control the yaw movement (Andersen et al., 2016) A bridle is multiple mooring lines connected at a given angle. In addition, in some floater designs, the mooring system provides the righting moment, such as TLP moorings (Kai-Tung et al., 2019).

The design of FOWT mooring systems allows the turbine to have a given offset from its equilibrium position. For example, the turbines in Hywind Tampen are permitted to move within a radius of 100 metres from their equilibrium position (Equinor, 2019a). The permitted offset is to ensure some slack in the movement of the turbine and to avoid extreme snap loads and tension in the mooring system, which can result in fatigue damage. For FOWTs the limiting factor for offset, is the electrical export cable (Nilsen, 2021). When designing a mooring system, there is always a compromise between line tension and turbine offset (Nilsen, 2021). The stiffness of the mooring configuration controls the offset and is given by the geometric and elastic stiffness of the chosen configuration and material (Xu et al., 2021).

4.4.1 Catenary Mooring

The principle of a catenary mooring system is that the catenary shape, weight, and stiffness of the suspended mooring line shall provide a soft and strong resistance to movements. The resisting and restoring effects of the mooring system will be mobilised by the geometric and elastic stiffness of the mooring configuration. The principle of the catenary mooring shape is that a loaded mooring line will resist the movement by mobilising resistance through tightening of the suspended part of the mooring line. The resistance increases as the part of the mooring line lying on the seabed is lifted. Therefore, the weight of the mooring line is important to mobilise resistance. The weight is either gained by the mooring line itself or by using clump weights attached to the mooring line (Halse, 2021).



(a) Mooring line catenary shape in shallow and deep water (b) Influence of x-offset on the top angles

Figure 12 (a) and (b) – Catenary mooring shape (Xu et al., 2021).

The characteristics of the catenary mooring configuration are different in shallow and deep waters. When the line is under tension, the angle (β in Figure 12) between the mooring line at the fairlead and the water line will decrease while the mooring line at the seabed is lifted. This reaction will cause a resilient effect and reduce the movement of the FOWT. The magnitude of the resilient effect is given by the geometric and elastic stiffness of the mooring configuration and the suspended mooring line (Xu et al., 2021).

Figure 12 (a) shows the difference in angle β between deep and shallow water loaded catenary moorings. The shallow water configuration has less catenary shape and potential to tighten and decrease the movement than the deep-water configuration, where the catenary shape is steep. The steeper catenary shape has better resilient effects because the angle β is larger at the initial position. To ensure that the catenary shape of the mooring line is retained and to achieve the same pre-tension and resistance in shallow water, the weight and length of the mooring line must be greater. The weight of the mooring line can be increased either by installing bigger chains or by the use of clump weights (Xu et al., 2021). The mooring line should be long enough to avoid being totally lifted from the seabed when using DEAs.

Figure 12 (b) shows position 1 before the FOWT is affected by an external force. Position 2 is when the FOWT has been affected by an external force, and the mooring line has mobilised its resistance by decreasing angle β and lifting the mooring line from the seabed (Xu et al., 2021).

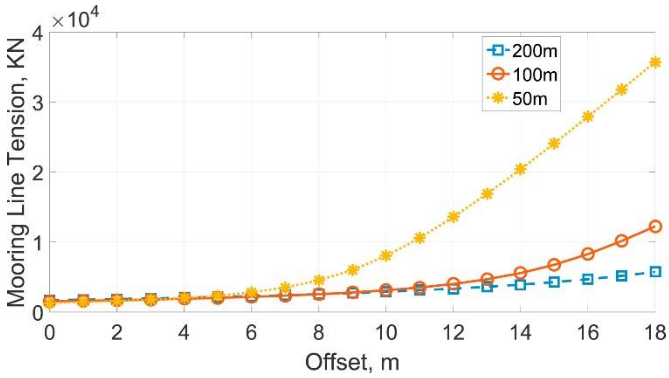


Figure 13 – Offset and tension in deep and shallow water (Xu et al., 2021).

Xu et al. (2021) has compared the mooring configuration for a specific semi-submersible FOWT. As seen in Figure 13, the mooring line tension increases faster in shallow water than in deep water with increasing horizontal offset.

4.4.2 Taut Mooring

In a taut mooring system, the mooring lines are permanently suspended. This gives a constant uplifting force on the anchors, meaning normal DEAs cannot be used. In the Handbook of Offshore Engineering (Subrata, 2005), a taut mooring system is defined as: "One in which the anchor loads have an uplift component for all load conditions, i.e. the anchor chain or wire never lies on the seabed" (Subrata, 2005, p. 544). Therefore, anchors that can withstand both vertical and horizontal forces need to be used for a taut mooring system. Examples of such are suction anchors and VLAs.

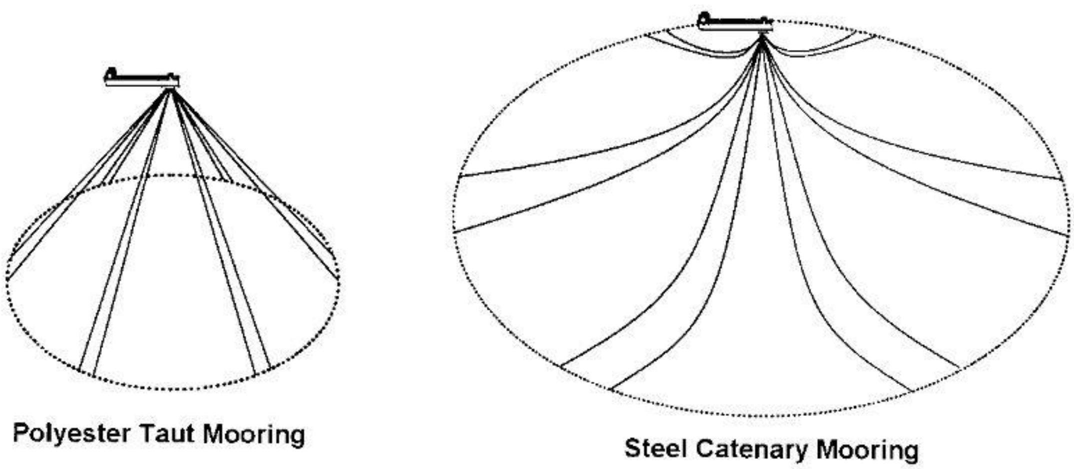


Figure 14 – Taut mooring vs. catenary mooring (Subrata, 2005).

A taut mooring system relies on the elastic stiffness of the mooring lines, where the stretch in the lines create the restoring forces of the floating unit (Subrata, 2005). Mooring lines with great elastic properties, such as synthetic fibre rope, are therefore advantageous. The length of the lines in a taut mooring system is normally 1.5 times the depth (Subrata, 2005). This ratio between mooring line length and depth creates a normal angle of 60° of the taut mooring line relative to the sea floor (Lie, 2021). Due to the reliance on elastic stiffness in the mooring line material, the construction of a taut mooring system has a relatively small footprint on the sea floor. As the elastic stiffness of a synthetic fibre rope increases with length, taut mooring systems are mainly used in calmer seas and deeper waters ranging between 1,000 and 3,000 metres, such as those found in Brazilian waters (Lie, 2021).

4.4.3 Clump Weight

Clump weights are attached to the mooring line to achieve the desired geometric stiffness in the mooring configuration. The clump weight is usually attached at the touchdown point of the mooring line to achieve additional restoring forces when the structure reaches a certain horizontal offset. Clump weights can be made by several compositions, for example, added chains. This is done by adding multiple smaller parallel chains connected to a coupling plate, larger bottom chain or attached weight blocks on the chain, as seen in Figure 15. Clump weights are used at the Kincardine FOWF, as seen in Figure 16. The clump weights will be lifted from the seabed several times, which cause abrasion to the clump weights. Some clump weight configurations suffer from damage due to abrasion (Kai-Tung et al., 2019).

Niccolo et al. (2020) investigated the effect of clump weights installed in various positions and mass on the OC3 Hywind spar buoy turbine. The study showed that installing a 2-tonne clump weight in the mooring line 50 metres from the turbine centre line. The configuration could increase the restoring forces of the mooring system without increasing the overall line tension.

Figure 15 – Single shell cast clump weights added to chain (Kai-Tung et al., 2019).

Figure 16 – Kincardine clump weights (FMCG, n.d.).

4.4.4 Buoy

Buoys can be attached to the mooring line to give clearance to subsea structures, but additional geometric stiffness can also be achieved. The buoy will reduce the weight of the line supported by the structure. For FOWTs, buoys have not yet been used in a deployed mooring system (Xu et al., 2021).

Xu et al. (2021) investigated the ULS in eight different load cases with the OC4 semi-submersible turbine. The study compared various mooring configurations utilising buoys and clump weights in shallow water, comparing to the already installed OC4 semi-submersible turbine installed in a water depth of 200 metres. The study showed promising results for a combination of buoys and clump weights, as seen in Figure 17, configuration IV. The configuration showed a reduction in the extreme tension in the mooring lines, as well as reduced horizontal offset.

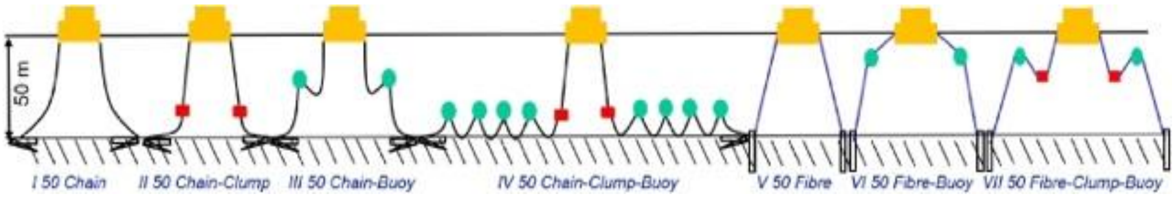


Figure 17 – Mooring configurations investigated by (Xu et al., 2021).
Green = Buoy, Red = Clump weight, Black = Chain, Blue = Synthetic fibre rope

4.5 Mooring line components

For all mooring configurations, the composition of components gives the characteristics. The mooring line material provides the elastic and geometric stiffness of the mooring design. Often, the mooring configuration consists of multiple sizes of the mooring line. For example, larger chains on the seabed increase the geometric stiffness, and smaller chain in the suspended part reduces the tension. Multiple mooring line materials can also be used in combination, for example, a combination of wire rope and chain to reduce the overall weight of the mooring line. To connect all components, connectors are used. The connectors are differing between permanent and temporary moorings due to fatigue. In this chapter, the mooring line materials and their properties, as well as the mooring line connectors, are described.

4.5.1 Chain

Chain is a relatively strong and cheap material used as a mooring line when mooring floating structures (Klingan, 2016). Chains are available in a wide range of designs, sizes, and qualities. The chain size is described as the diameter of the steel bar. The size used for offshore moorings ranges from 70-200 mm (Kai-Tung et al., 2019). Common for all mooring chains, it is compounded of multiple oval steel links welded and connected inside each other. The chain is heavy and is suited for catenary mooring configurations. Chain is a durable material that can stand rough handling and long-time abrasion with the seabed (Castro-Santos and Diaz-Casas, 2016, Kai-Tung et al., 2019).

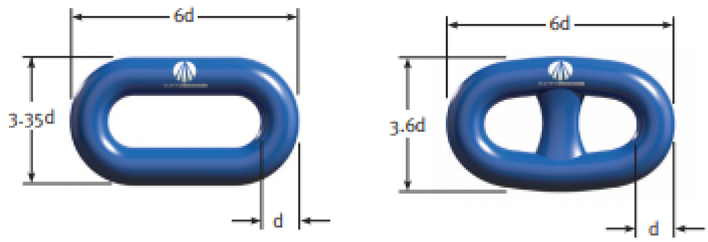


Figure 18 – Stud-less and Stud-link chain (InterMoor, n.d-b, InterMoor, n.d-a).

A chain made for mooring of floating structures is either a stud-less chain or stud-link chain. As seen in Figure 18, the stud-link chain has a stud installed inside the link to prevent the chain from tangling. A stud-link chain is 9% heavier than a stud-less chain (InterMoor, n.d-b, InterMoor, n.d-a). A stud-less chain does not have the stud inserted, and there is a higher risk for tangling when handling the chain. The stud-less chain is lighter and cheaper than the stud-link chain due to the reduction of material. In permanent mooring configurations, the stud-less chain is preferred because the chain is not supposed to be handled during its service time, such as the stud-link used in temporary mooring systems.

Offshore mooring chains are designed and manufactured according to classification societies standards, such as DNVGL-OS-E302 Offshore mooring chain (DNV, 2018c). The standard provides six quality grades given by the Minimum Breaking Load (MBL) to chain diameter ratio, as seen in Figure 19 (IACS, 2016, Kai-Tung et al., 2019). The given grades are R3, R3S, R4, R4S, R5, and R6, where R6 is the highest quality graded by DNV to date. R7 quality is under development (Castro-Santos and Diaz-Casas, 2016, DNV, 2018c).

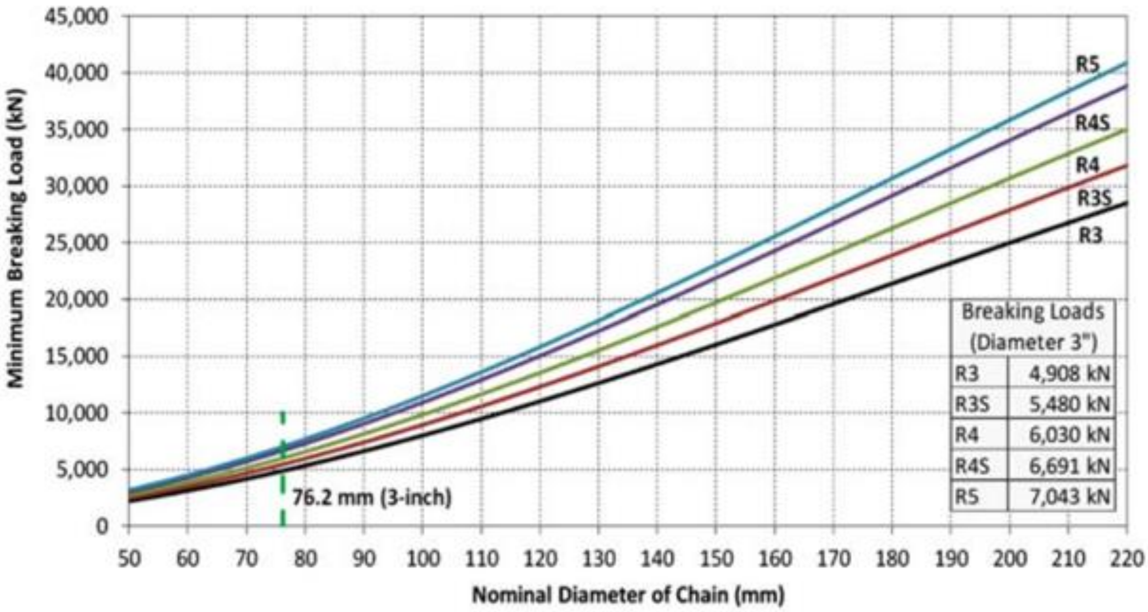


Figure 19 – Breaking strength for different chain grades (Kai-Tung et al., 2019).

According to IACS (2016), DNV (2018c), the manufacturer shall proof load each length of the chain to a given load. The proof load of the stud-link chain is higher than the stud-less chain. For example, the proof load of a 116 mm R5 quality stud-link chain is 11,727 kN. The proof load of a 116 mm R5 stud-less chain is 10,418 kN. However, the MBL is the same for both, which is 14,950 kN (InterMoor, n.d-b, InterMoor, n.d-a). When designing the mooring system, the required proof load should be set higher than the expected maximum load of the chain with an appropriate safety factor (DNV, 2018a). The appropriate safety factors are given in Figure 20, according to the load, consequence class and limit state.

Limit state	Load factor	Consequence class	
		1	2
ULS	γ_{mean}	1.3	1.5
ULS	γ_{dyn}	1.75	2.2
ALS	γ_{mean}	1.00	1.00
ALS	γ_{dyn}	1.10	1.25

Figure 20 – Partial Safety factor for mooring lines (DNV, 2018a).

In catenary mooring configurations, the chain contributes significantly to the resisting and restoring forces because of its high weight and seabed friction (Vryhof, 2018). The chain has a high weight. For example, a 180 mm R5 stud-less chain has a weight of 649 kg/m (InterMoor, n.d-b). The weight could be both a positive, but also a limiting factor of the chain. In deep waters, the weight of the chain will cause a high pre-tension in the mooring line and reduce the available deadweight of the floater (Castro-Santos and Diaz-Casas, 2016). When using all chain catenary configuration in deep water greater than 300 metres, the high weight will cause the catenary shape to dip. The dip causes a steep angle from the structure to the seabed, and the catenary effect of the mooring line will be reduced, causing less restoring force in the system (Kai-Tung et al., 2019). In shallow water, the mooring line often consists of an all chain arrangement, where the weight of the chain is utilised to increase the restoring forces of the mooring configuration. In addition, in some cases, additional clump weights are attached at the line touchdown point to increase the restoring forces, as described in 4.4.3 (Kai-Tung et al., 2019).

As seen in Figure 18, the volume displaced by a chain is relatively high compared to other line materials. For example, a 180 mm stud-less chain link has a length of 1,008 mm and a width of 603 mm, which cause problems for handling on board vessels (Solstad Offshore, 2021, InterMoor, n.d-b).

The required diameter of the chain is found by calculating the required strength and weight of the mooring line. Further on, the required diameter is increased to account for the safety factor, corrosion and wear, as seen in Figure 21 (Lie, 2021).

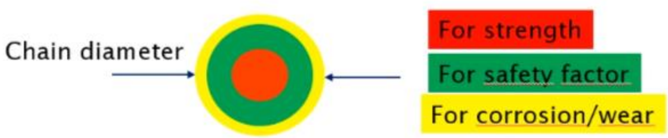


Figure 21 – Chain diameter contribution (Lie, 2021).

Figure 22 – Loose stud in chain (Author's photo).

DNV fatigue curve is shown in Figure 23. The S-N curve shows that the stud-link chain has better fatigue performance than the stud-less chain (DNV, 2020). However, after a given time, experience has shown that the stud can separate from the chain ring, as shown in Figure 22. Stress will increase at the stud footprint and reduce fatigue resistance (Kai-Tung et al., 2019).

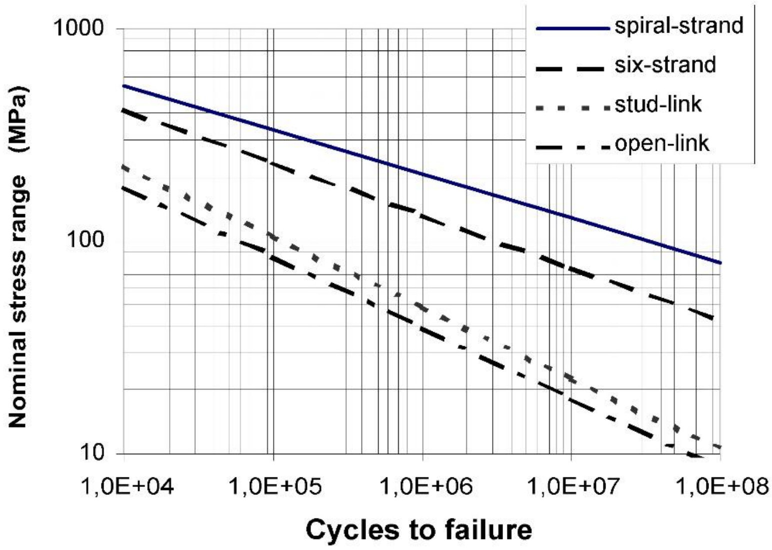


Figure 23 – Mooring line fatigue curve (DNV, 2020).

The stiffness of a mooring system using chain is given by the geometric stiffness of the shape and the elastic stiffness of the chain. The elastic stiffness of the chain is high. For example, a 116 mm stud-less chain has an elastic modulus of 56 GPa (DNV, 2020). Geometric stiffness in a catenary mooring system with all-chain is given by the weight and catenary shape of the mooring line. If the chain is heavy, the catenary shape will be steep, and the mooring system will have a high geometric stiffness (Halse, 2021, Kai-Tung et al., 2019).

4.5.2 Wire Rope

A wire rope is a rope made up of multiple strands of wound metal. Each strand consists of metal wires, often steel wound into a helix. For use in mooring arrangements, there are normally two different types of steel wire rope; spiral strand and six-strand wire rope. Figure 24 illustrates different wire rope arrangements used in mooring systems. The different steel wire rope constructions offer characteristics and areas of use. A six-strand wire rope is common in temporary moorings for MODUs due to its flexibility and easier handling. There are different classes of six-strand wire rope, depending on the number of wires in each strand. Examples of common classes are 6x19 IWRC and 6x36 IWRC. A 6x19 IWRC steel wire rope features six strands, with 19 smaller strands in each strand. IWRC means Independent Wire Rope Core which sits in the centre of a six-strand steel wire rope offering support for the outer wire strands. A six-strand steel wire rope is prone to rotational torque under stretching, causing twisting of mooring line (DNV, 2015). More wires in each strand offer greater fatigue life and flexibility at the expense of poorer abrasion (Subrata, 2005).

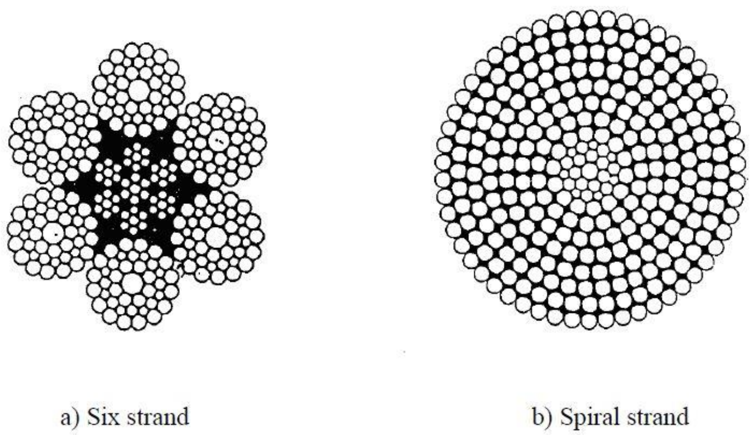


Figure 24 – Wire rope construction (DNV, 2015).

A spiral strand steel wire rope, as seen in Figure 24, is steel wires wound into a helix, featuring multiple layers. These layers are often wound in opposite directions, also called contra-lay, offering great torque balance (Chaplin, 2001). Therefore, a spiral strand wire used for mooring is designed not to rotate under load caused by stretching (Lie, 2021). A spiral strand wire offers good corrosion resistance as water ingress is less likely due to the compact structure and construction of the wire rope (DNV, 2015).

Spiral strand wire rope can also be half-locked or full-locked. As shown in Figure 25, a half-locked wire rope features shaped and round wires in the outer layer. A full-locked wire rope, as shown in Figure 26, features z-shaped wires in the outer layer. This construction creates a uniform surface and increases corrosion resistance by blocking the water.

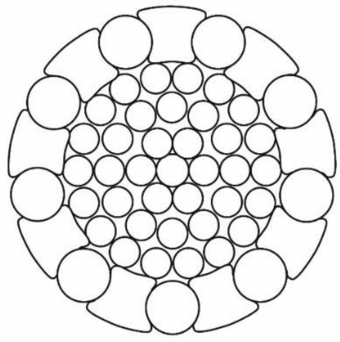


Figure 25 – Half-locked spiral strand wire rope (Teufelberger).

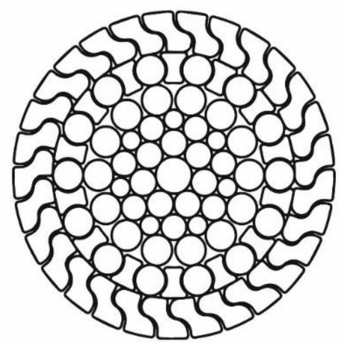


Figure 26 – Full-locked spiral strand wire rope (Teufelberger).

The uniform surface of a spiral strand wire rope also makes it possible to cover the wire rope with a sheathing, such as a plastic socket. Such a plastic socket also often features an axial stripe to monitor the rotational twist of the wire rope (DNV, 2015). DNVs standard DNVGL-OS-E304 Offshore moorings steel wire ropes (DNV, 2015) defines that a wire rope used for mooring is protected against corrosion when its fatigue life approaches that in air. The protection is normally done by:

- “Sacrificial coating of wires, such as galvanisation.
- Application of a blocking compound on each layer of the strand during stranding, which strongly adheres to the wire surface.
- Sheathing with a plastic socket, preventing ingress of water, and flushing of the blocking compound.”

  (DNV, 2015, p. 11)

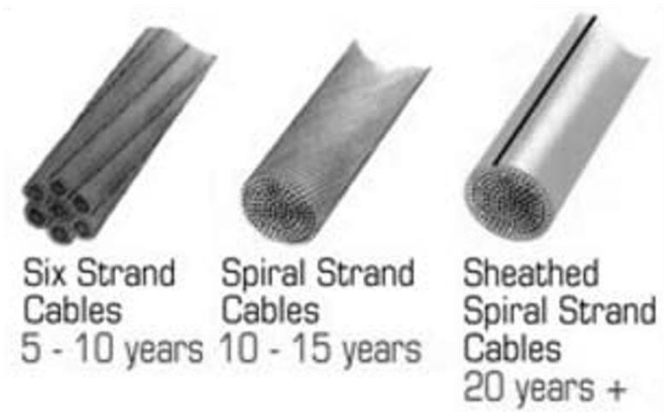


Figure 27 – Wire rope longevity (Subrata, 2005).

A steel wire rope is often used in MODU moorings as a middle piece between sections of chain. A steel wire rope is not suitable for laying on the sea floor due to excessive bending (DNV, 2020). A representative sheathed spiral strand wire rope with a diameter of 120 mm features a minimum breaking force of 14,720 kN, and a submerged weight of 61.4 kg/m (Bridon Bekaert, 2018).

DNVs standard DNVGL-OS-E301 Position mooring (DNV, 2020) provides the types of wire rope to be used in an offshore mooring, according to field design life and the possibility of replacing wire rope segments, as seen in Figure 28.

Field design life(years)	*Possibilities for replacement of wire rope segments*	
	Yes	*No*
< 8	A/B/C	A/B/C
8 – 15	A/B/C	A/B
> 15	A/B	A
A) Half locked coil/full locked coil/spiral rope with plastic sheathing. B) Half locked coil/full locked coil/spiral rope without plastic sheathing. C) Stranded rope.		

Figure 28 – Choice of seel wire rope construction (DNV, 2020).

4.5.3 Synthetic Fibre Rope

Synthetic fibre ropes are often used in deep-water moorings to reduce the weight and length of the mooring line, and therefore the total mooring cost (Subrata, 2005). Synthetic fibre ropes can be manufactured from a range of synthetic yarn materials, such as Aramid, High Modulus Polyethylene (HMPE), Liquid Crystal Polymer, Polyamide (nylon) or Polyester (DNV, 2018b). The synthetic fibre ropes are composed as shown in Figure 29. The properties of a synthetic fibre rope are complex and advanced. Synthetic fibre ropes are light and elastic. For example, a Polyester rope from OTS with a MBL of 14,710 kN has a diameter of 211 mm. The weight of the polyester in air is 33 kg/m. The length of the polyester rope will increase when loaded. The polyester will extend in length by 8% when exposed to 50% of MBL (OTS, 2021). Another synthetic fibre rope, Dextron (HMPE), delivered by OTS with a MBL of 14,710 kN has a diameter of 166 mm. The weight of the Dextron in air is 14 kg/m (OTS, 2021). Synthetic fibre ropes have high strength to weight ratios and some compositions have neutral buoyancy in seawater (Weller et al., 2015).

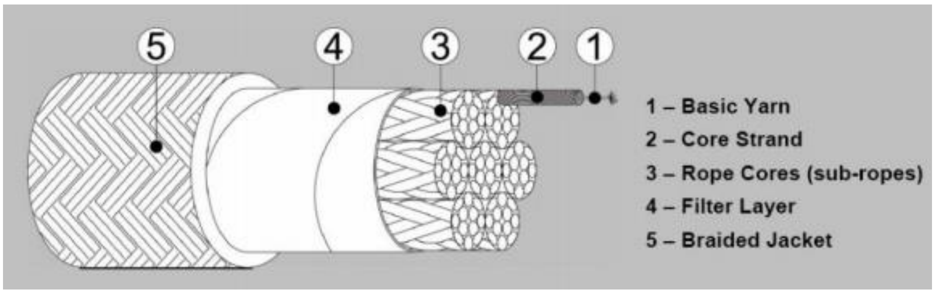


Figure 29 – Composition of a fibre rope (Hole and Larsen, 2018).

The stiffness of the synthetic fibre ropes is not constant but varies with the load range and the mean load. Furthermore, the stiffness varies with age (Subrata, 2005). When synthetic fibre ropes are used, the structure becomes more ideal, and the load will be shared equally on the rope cores. This will result in increased MBL and stiffness (OTS, 2021). The synthetic fibre is vulnerable to heat which can cause the rope components to melt. Greater dimensions and certain lay types are more vulnerable to heat (Weller et al., 2015). The synthetic fibre rope has good fatigue performance and does not suffer from corrosive problems. However, the synthetic fibre rope is vulnerable to sharp objects and gnawing (Weller et al., 2015). Sand can penetrate the braided jacket and damage the rope. A special sheathing is used for polyester ropes created for touching the seabed, in addition to the sand filter.

DNV Standard DNVGL-OS-E301 Position mooring (DNV, 2020), DNVGL-OS-E303 Offshore fibre ropes (DNV, 2018b), and DNVGL-RP-E305 Design testing and analysis of offshore fibre ropes (DNV, 2019b) are standards and recommended practices for synthetic fibre ropes used for offshore mooring. There are also additional standards which covers other aspects of the synthetic fibre ropes used offshore.

4.5.4 Mooring Line Connectors

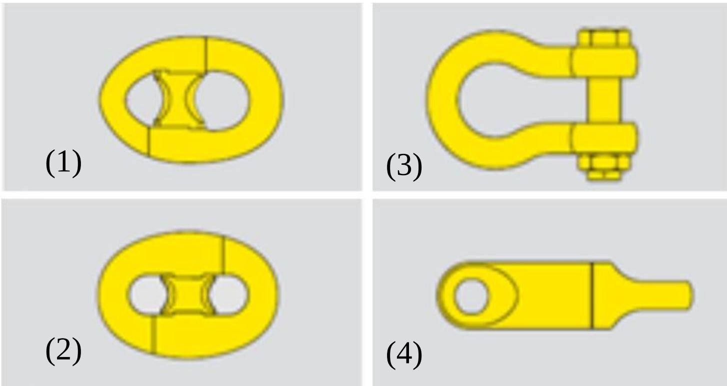


Figure 30 – Mooring line connectors; (1) Trident anchor shackle, (2) Kenter shackle, (3) Shackle, (4) Mooring swivel (Vryhof, 2018).

Connectors are used to connect the components in a mooring line. This could be two different chain sizes, a wire socket to a chain link or from chain to a synthetic fibre rope. Figure 30 illustrates common mooring line connectors. In permanent mooring systems, there are restrictions on which components that can be used. According to DNVGL-OS-E301 Position mooring (DNV, 2020), it is normally not permitted to use trident anchor shackles (1), Kenter shackles (2), ordinary shackles (3), or swivels (4) due to their poor fatigue qualities. Swivels can be used if they are qualified with respect to functionality, structure strength and fatigue. Kenter shackles are accepted in temporary mooring systems (DNV, 2020). DNVGL-OS-E301 Position mooring (DNV, 2020) recommended that connectors in permanent mooring systems are purpose made elements such as coupling plates, Long Term Mooring (LTM) D-shackles, and H-shackles. Other types of connectors may be accepted in permanent mooring systems if their fatigue life is documented (DNV, 2020).

Figure 31 – Kenter shackle connected to socket (Author's photo).

Figure 32 – Trident anchor shackle (Author's photo).

Figure 33 – Shackle (Author's photo).

Figure 34 – Mooring swivel (Author's photo).

As shown in Figure 31 and (2) in Figure 30, the Kenter shackle is used to connect two chains of the same dimension. This is the connector that is the most used for MODU moorings. The Kenter shackle has equal length and diameter as the equivalent chain size. Another type of Kenter shackle is a fast lock Kenter shackle (Vryhof, 2018).

The Trident anchor shackle, as shown in Figure 32 and (1) in Figure 30, is only used in Norway (Vryhof, 2018). The Trident anchor shackle design is based on the same principal as the Kenter shackle. This connector is used to connect chains of different dimensions (Vryhof, 2018).

As shown in Figure 33 and (3) in Figure 30, the shackle is a universal connector and consists of a bow which is closed by a pin. The shackle is available in different types and sizes. The shackles can both be used in permanent and temporary moorings, but special LTM shackles are required in permanent moorings (Vryhof, 2018, DNV, 2020).

As shown in Figure 34 and (4) in Figure 30, the mooring swivel is used to compensate twist in the mooring line. This component is often placed a few links from the anchor in the bottom chain (Vryhof, 2018).

Figure 35 – Coupling plate (Lie, 2021).

Figure 36 – In-line tensioner (Vryhof).

As shown in Figure 35, the coupling plate is often used in permanent moorings and is also used when parallel tensioning a mooring line. A shackle is used to connect the mooring line to the coupling plate.

The in-line tensioner is shown in Figure 36. It is a component that makes it possible to adjust tension and length of the mooring lines after it is connected. This component can be inserted in the mooring line and makes it possible for less advanced vessels to adjust the tension in the mooring line using its onboard winch. A chain stopper mechanism is used to lock the mooring line when the desired tension is reached. The inline tensioner will be mounted in the mooring line, and therefore the fatigue life must exceed the mooring line fatigue (Vryhof, 2018). The in-line tensioner are used in moorings of FOWTs, because the FOWT does normally not have winches on board (Nilsen, 2021).

4.6 Anchor Types

The chosen anchor type depends on the mooring configuration due to the different properties of each anchor type. The anchor type is also subject to the soil type. For example, the soil type on the Norwegian continental shelf is mostly clay. Therefore, suction anchors and DEAs are the most used anchors on the Norwegian continental shelf (Lie, 2021). Suction anchors and DEAs are chosen as the focus in this thesis as the most relevant anchor types for FOW in Norway. The anchor type selected is also a factor to decide the installation cost due to differing vessel requirements and hardware costs. In this chapter, suction anchors and DEAs are described together with the alternative configurations and installation of the anchors.

4.6.1 Suction Anchor

The suction anchor consists of a circular skirt designed to be submerged into the seabed with the help of suction. The structure and size of the suction anchor are decided by the soil and expected load. The diameter is normally 4 to 6 metres. The pad eye for connection of mooring line is located on the side of the skirt and is partly submerged together with the skirt. The suction anchor is normally installed by a Construction Support Vessel (CSV), using its Active Heave Compensated (AHC) crane. The procedure of penetrating the suction anchor is shown in Figure 38. The weight of the suction anchor makes it partly self-penetrating. A Remotely Operated Vehicle (ROV) operated suction device is connected to a valve on the top of the structure to penetrate further. The suction device will remove trapped seawater inside the skirt and create a negative pressure inside the skirt. Clay soils are relatively impermeable, and therefore the negative pressure inside the skirt will initiate penetration (Kai-Tung et al., 2019).

Figure 37 – Suction anchor installation (Global Maritime, 2019).

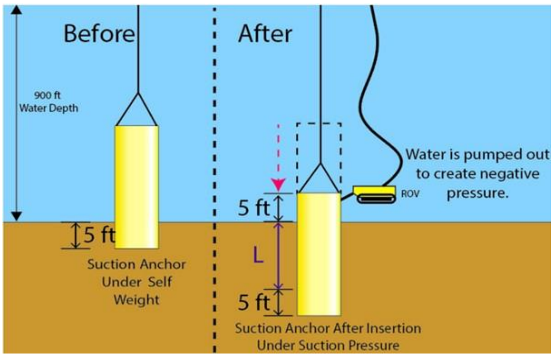


Figure 38 – Suction anchor installation (DrillingFormulas, 2016).

Vertical resistance of the suction anchor is caused by the weight of the anchor, the friction of the anchor against the soil and the shear strength of the soil. The weight of the anchor is often between 300 and 400 tonnes, depending on the size (Equinor, n.d-b). Vertical resistance is also caused by the shear strength against the outside wall of the skirt. The inverse bearing capacity of the clay at the skirt tip level is also a contributing factor to vertical resistance (Arany and Bhattacharya, 2018). Horizontal resistance is caused by the shear strength of the clay surrounding the anchor (DNV, 2017).

When loading a suction anchor to its failure limit, the variation of resistance in the soil will cause the anchor to tilt. Therefore, the rotation point of the anchor needs to be stated individually for each location. The pad eye needs to be installed at the optimum height to prevent tilt when the anchor is at failure load (Sørlie, 2013). The optimum attachment point for the pad eye is typically located around 2/3 from the top, if the soil is normally consolidated clay (Kai-Tung et al., 2019).

Multi-Line Anchors

When using suction anchors, one can utilise its ability to withstand force from multiple directions. For example, Equinor has installed suction anchors on Hywind Scotland, where some of the anchors have multiple turbines connected. Equinor will continue this practice when installing Hywind Tampen, by connecting three turbines to one suction anchor (Equinor, 2019a). This practice can reduce the cost of installing moorings for FOWFs with suction anchors.

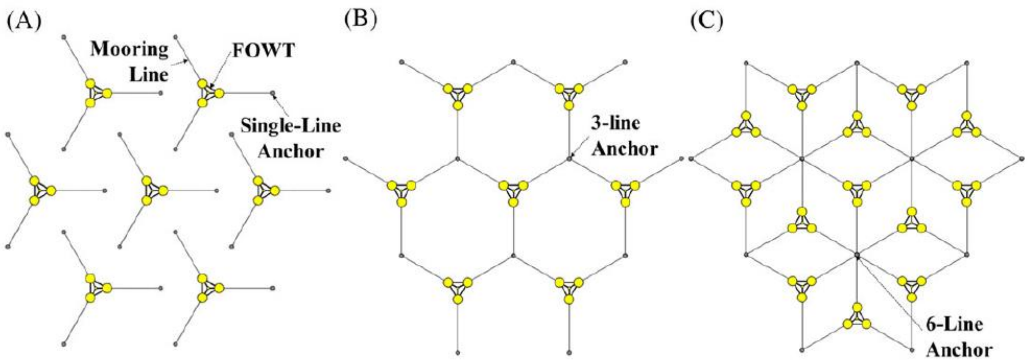


Figure 39 – (A): Single line, (B): 3-line, (C): 6-line (Fontana et al., 2018).

Fontana et al. (2018) conducted simulations on the OC4 semi-submersible turbine, where it was investigated how the forces acted on one suction anchor with multiple mooring lines connected. The study showed that sharing one suction anchor with three turbines connected could reduce the resultant tension on the anchor. The resultant tension was reduced because of the contribution from upwind turbines could counteract the force from the downwind turbine.

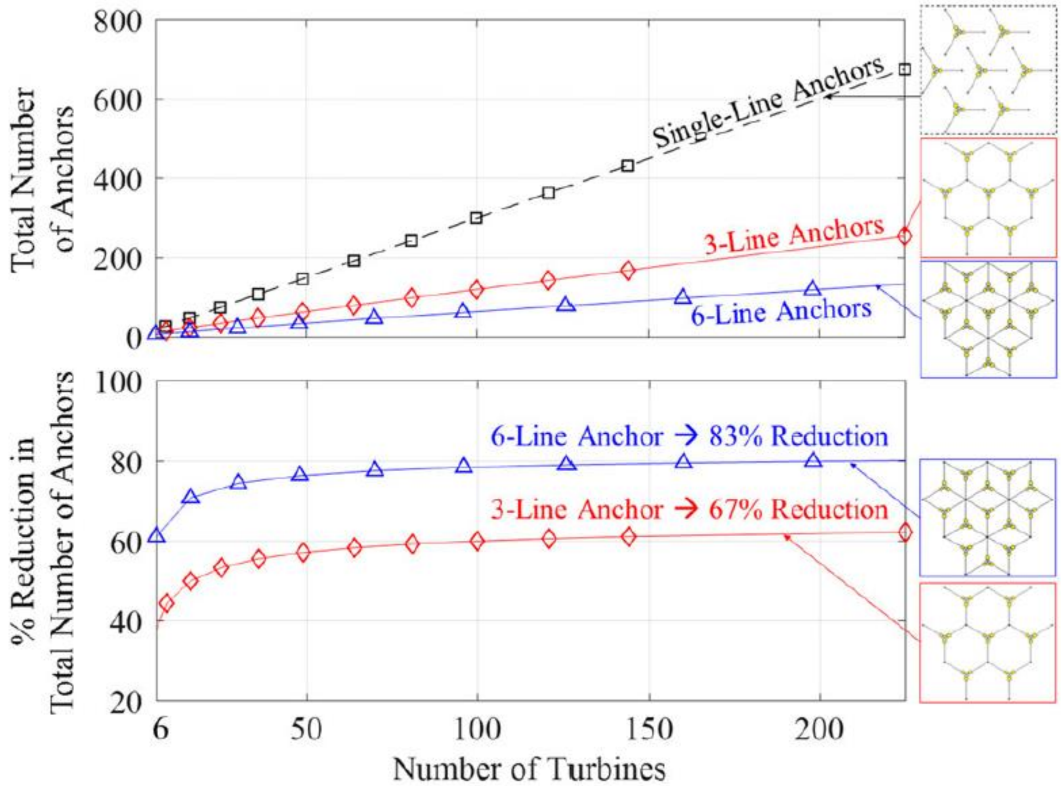


Figure 40 – Comparison on number of anchors with single, 3, and 6- line configuration (Fontana et al., 2018).

The pattern of FOWTs and anchors were set to keep an equal angle between the mooring lines. As seen in Figure 39, the pattern for single line (A), 3-line (B) and 6-line (C) anchors. For all configurations, the mooring line had a catenary shape consisting of: 835 metres of 76 mm chain with a fairlead to anchor radius of 797 metres. In the 3-line anchor configuration, the spacing between each mooring line on the anchor was 120º. In the 6-line anchor configuration, the spacing was 60º (Fontana et al., 2018).

The simulation included three load cases, including normal operation, extreme operating and extreme no operating. In single line and 3-line configuration, WWC was simulated from 0º, 30º and 60º. For the 6-line configuration WWC from 0º, and 30º were simulated, resulting in coverage of all mooring line tensions due to the respectively 120º and 60º rotational symmetry.

4.6.2 Drag Embedment Anchor

The DEA is the anchor most used for the mooring of MODUs in the North Sea. For the Windfloat Atlantic project, DEAs were used for the mooring of the semi-submersible FOWTs (Vryhof, 2020). DEAs for mooring of FOWTs represent a significant cost reduction compared to suction anchors due to easier installation and cheaper vessel requirements. Also, the operation is less weather dependent. The DEAs are commonly used in the O&G industry. Therefore, the hardware cost is lower, and the anchors are easily available (Principle Power, n.d).

Figure 41 – DEA (Author's photo).

The design of a DEA varies, depending on the desired characteristics. For example, an 18 tonnes Stevpris Mk6 anchor is 6.4 metres long and 7.1 metres wide (Vryhof, 2018). Generally, the DEA consists of four main parts; the shank, the fluke, the shackle, and the forerunner, as illustrated in Figure 42. The shank is the supporting structure that connects the shackle and forerunner to the fluke with a given angle. The fluke is the part of the anchor that causes penetration and resistance in the soil. The fluke has a given angle to the shank, called the fluke angle (Vryhof, 2018). The fluke angle is often adjustable and should be adjusted according to the density of the soil. The shackle is mounted on the tip of the shank and connects the anchor to the forerunner. The forerunner is the part of the anchor line, which is supposed to penetrate the soil and can be made of either wire or chain (DNV, 2019a). Some DEAs have a bridle mounted on the aft part of the shank. The bridle is supposed to control the direction of the anchor when landing on the seabed. The bridle is also used to connect piggy-back anchor if needed.

DEAs are mainly used in catenary mooring configurations since the DEA is primarily designed to resist horizontal loads. Vertical resistance can be achieved by certain designs of DEAs (Vryhof, 2018). The total resistance is caused by the anchor and the lower part of the mooring line. In general, the main resistance is generated by the soil in front of the anchor, where the fluke area is the main factor to determine the resistance (DNV, 2019a).

The fluke angle is adjustable and is often fixed between 30º to 50º. The fluke angle is adjusted according to the density of the soil. The fluke angle is set to a high angle, around 50°, to achieve the best resistance and penetration in soft clays (Vryhof, 2018). The fluke angle is illustrated in Figure 42. For hard clay, the lower angle is used for best penetration. If the angle used is too high, the anchor can experience difficulties penetrating the soil, such as bumping (DNV, 2019a).

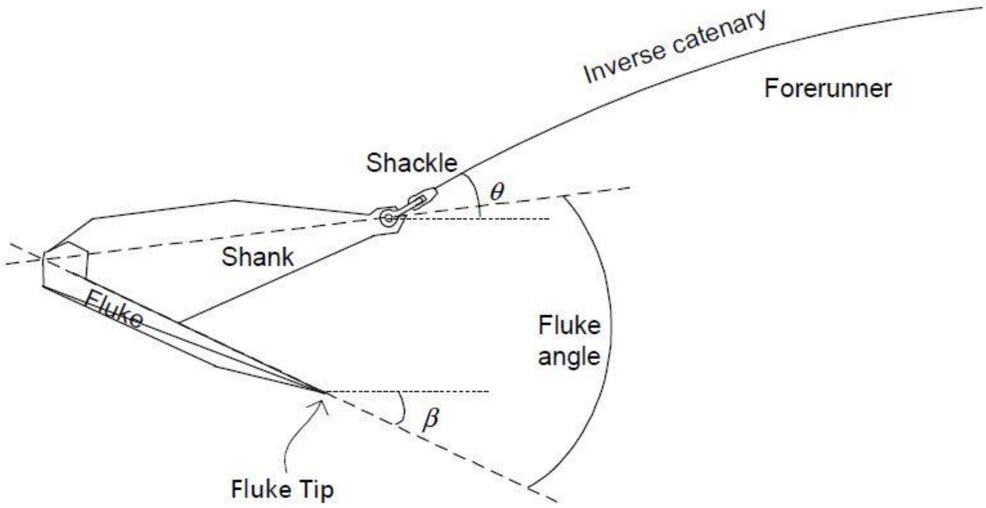


Figure 42 – DEA nomenclature (DNV, 2019a).

Soft clay has a low shear strength and is less resistant. Therefore, the anchor will need to penetrate deeper to achieve the ultimate holding capacity (Vryhof, 2018). The resistance will increase when the penetration depth increases. Normally, the installation depth of the anchor is set to an intermediate depth to be able to predict the drag of the anchor if the tension exceeds the proof tension (DNV, 2019a).

The embedded part of the forerunner will cause additional resistance. Normally, the material of the forerunner is wire or chain, and the material gives its resistance. Using a wire forerunner, the forerunner will have a slighter curvature than a chain forerunner, as shown in Figure 43. The cutting resistance of the chain causes the difference in the curvature compared to the wire, caused by the larger surface area of the chain. The cutting resistance of the chain causes a steeper slope of the forerunner, causing less penetration than an anchor with a wire forerunner. When tensioning the anchor with a chain forerunner, the steeper slope of the forerunner will cause an upward force component in the y-axis, as illustrated in Figure 43 (DNV, 2019a).

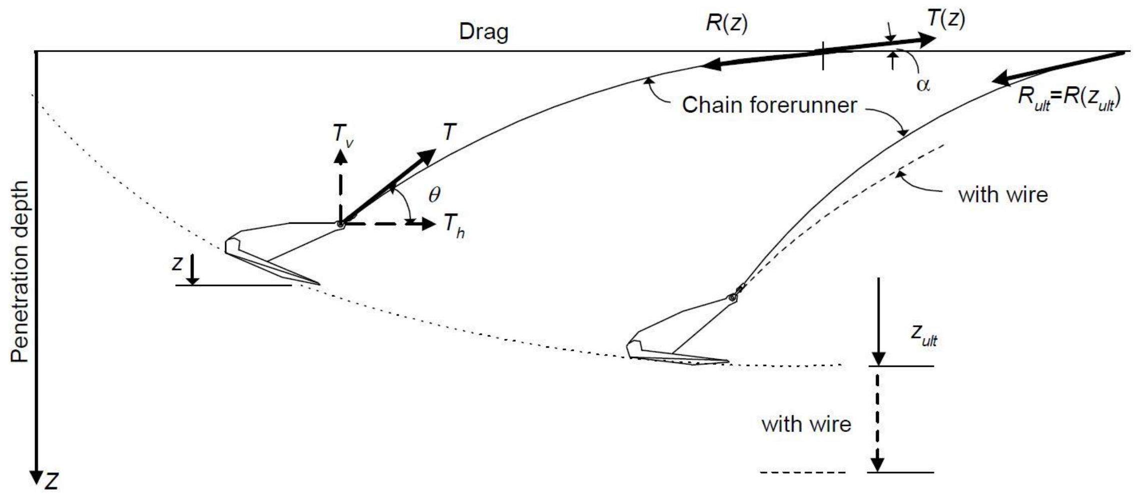


Figure 43 – Illustration of DEA with chain and wire forerunner (DNV, 2019a).

When installing a fluke anchor as permanent mooring, the size, tension, and installation depth are considered to the expected load during service time. When considering the installation depth, a survey to inspect the soil condition must be carried out. The fluke anchor is partly self-installing, which means that the anchor will penetrate the soil when exposed to external forces in the right direction, which will mobilize additional resistance. The self-installing feature depends on the soil, if the soil is stiff to soft clay, the drag is predictable and can be accepted. The drag and penetration path cannot be predicted in difficult soils such as layered or hard clay or sands. Therefore, the installation depth and tension must be considered. The installation tension should be set higher than the expected load to reduce the risk of drag (DNV, 2019a). For permanent mooring of FOWTs, the long service time, cyclic loading, and reduced number of mooring lines per unit results in the requirement for higher proof tension.

Ballast is filled inside the fluke to increase the weight of standard anchors. The ballast is usually lead balls. The weight can be adjusted multiple times during the service time by adding or removing the lead balls.

Stevtensioner

The Stevtensioner, developed by Vryhof Engineering, is a tool to eliminate the need for Bollard Pull (BP) when proof tensioning DEA's. The tool allows the AHTS to pull the DEA to desired proof tension using its winch. The Stevtensioner utilizes a reaction anchor to change the vertical tension from the AHTS winch to horizontal tension, causing embedment and tensioning of the anchor. The technology is based on the principle that a vertical load applied on a horizontal string causes high horizontal tension. Usually, the required vertical load is 40% of the needed horizontal tension (Vryhof, 2018).

Using the Stevtensioner, the anchors are tensioned using the vessels winch differing from traditional tensioning, using the vessels BP (Vryhof, 2018). For example, Normand Drott (N. Drott) could tension a DEA using its Special Handling Winch (SHW) with a pulling capacity of 500 tonnes, compared to its BP of 339 tonnes. Using the Stevtensioner, the proof tension of the anchor could then be 1,250 tonnes (Solstad Offshore, n.d-b).

As shown in Figure 44, the reaction anchor should be laid in the opposite direction of the main anchor. When both anchors are laid, the tensioning can start by lowering the Stevtensioner to the seabed and start hauling in the active chain connected to the main anchor. The active chain will pass through the Stevtensioner, the reaction anchor retains. The Stevtensioner is then lowered to the seabed using the recovery line. After that, the procedure is repeated in a yo-yo movement to achieve the desired tension (Vryhof Engineering, 2019).

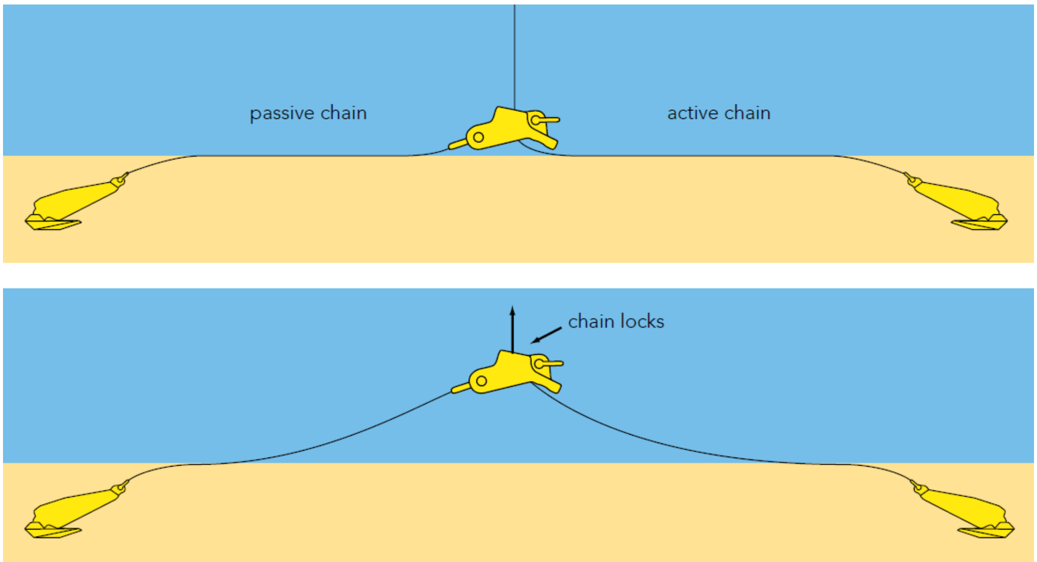


Figure 44 – Stevtensioning procedure (Vryhof, 2018)

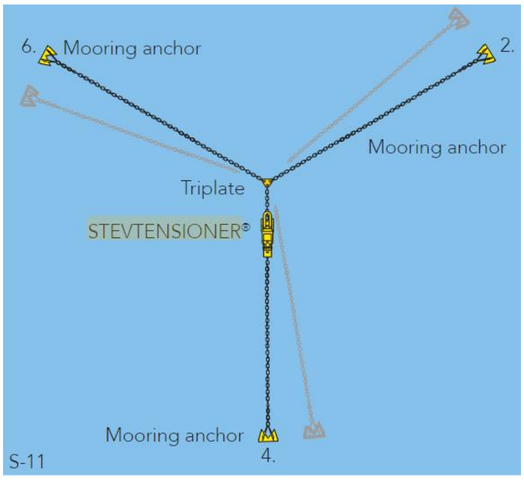


Figure 45 – Multiple anchor stevtensioning (Vryhof, 2018).

If the anchors are spread with equal spacing, the Stevtensioner can be used for equal tensioning of multiple anchors, as shown in Figure 45. This method is not yet tested, but Vryhof claims it should be possible (Vryhof, 2018, Solstad Offshore, 2021).

Reaction Anchor Connected to the Bow

Another method to tension the anchor without using the vessels BP is by using a reaction anchor connected to the AHTS vessels bow. Far Sapphire installed anchors for a FOWF using this method. The tensioning was done by connecting the reaction anchor to the vessels Smit-bracket in the forecastle. After that, the main anchor was connected to the vessels SHW. The reaction anchor allowed the vessel to tension the main anchor only using the vessels winch capacity (Bourbon Offshore, 2017).

This method could be an alternative if the vessels BP is not sufficient, but the operation is challenging due to the lack of equipment fitted for catching and connecting the bow reaction line. If this method is to be used, the vessel should be modified for safe working with chain and wire on the forecastle, which is mainly outfitted for mooring of the vessel (Solstad Offshore, 2021).

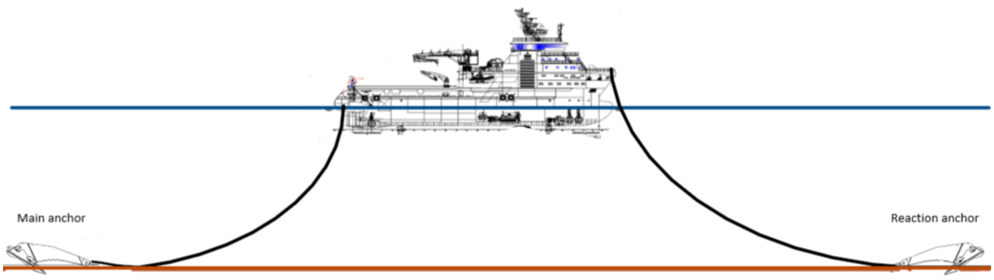


Figure 46 – Illustration of bow reaction anchor (Author's illustration).

4.7 Vessel Terminology

CSVs and AHTS vessels are used to install the anchors and the mooring configuration, depending on the anchor type. Typically, an AHTS is needed to install and connect the mooring line for all anchor types. An AHTS is equipped with equipment specifically relevant for the mooring of FOWTs and is subject to modifications. In this chapter, the CSV and AHTS characteristics will be introduced. Then, the specific AHTS equipment is described. The properties of the relevant AHTS vessels, subject to utilization in FOWT mooring installation, are also presented.

4.7.1 Construction Support Vessel

A CSV is a versatile vessel, primarily designed for use in the O&G industry, working on subsea installations. As such, a CSV often features great station keeping capabilities with a Dynamic Positioning (DP) class 2 or DP 3 class. For lowering heavy units to the seabed, an AHC crane is installed on the aft deck. The crane can neutralize the heave motions from waves and keep the load with a zero relative speed compared to the seabed (Babicz, 2015). The lifting capacity can range up to 800 tonnes with the ability to work at depths of up to 4,000 metres (NOV, 2018, MacGregor, 2018). The CSV is equipped with a ROV to monitor lifting, work, and survey on subsea installations. CSVs offer a large aft deck for storing units and equipment to be used in operation.

4.7.2 Anchor Handling Tug Supply Vessel

An AHTS vessel is a vessel designed for the offshore O&G industry. Typical tasks for an AHTS vessel is to set and retrieve anchors of offshore units and for towing these units (Dokkum, 2020). To perform these tasks, an AHTS features a DP system and a powerful propulsion system giving the vessel the necessary BP for anchoring offshore units, often exceeding 300 tonnes for bigger vessels (DOF Group et al., 2021). BP is a measurement of a ships' thrust in tonnes at zero ahead speed (Babicz, 2015).

The stern of an AHTS features a shark jaw and towing pins to secure the chain under operation. Cargo rail cranes and tugger winches are used for handling and manipulating the anchors and chains whilst on deck. An AHTS is equipped with a set of winches featuring SHW, secondary winches and Anchor Handling (AH)/towing winches. The chain lockers located aft of the winch arrangement are used for storing the chain used in a mooring operation. For lifting heavier units, an AHTS can also feature an A-frame or an offshore crane. Some AHTS has ROV installed to monitor the anchors' setting and survey after installation.

4.7.3 Anchor Handling Tug Supply Vessel Equipment Terminology

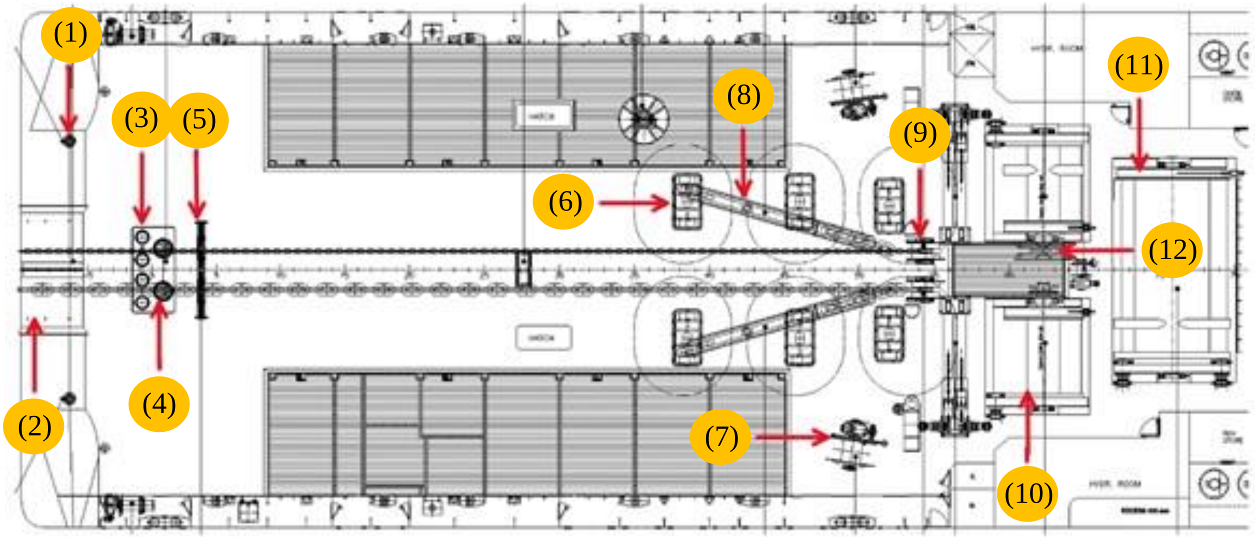


Figure 47 – Normand Prosper deck layout; (1) Pop-up pin, (2) Stern roller, (3) Towing pins, (4) Shark jaw, (5) Centering device, (6) Chain locker, (7) Tugger winch, (8) Chain chute, (9) Chain guide, (10) AH/Towing winch, (11) Special handling winch, (12) Chain gypsy (Solstad Offshore, n.d-c).

Towing Pins

The towing pins ((3) in Figure 47) are located aft of the ship. The towing pins main task is to keep the chain in place. With the help of the towing pins, the chain cannot move uncontrolled athwartships on deck and will be guided into the shark jaw. Locking arms are stored inside the towing pins. The locking arms will either be in the deployed position or stored inside the towing pin. The locking arms shall prevent the mooring line from slipping out of the towing pins. The locking arms can also be used to pull the chain into the shark jaw. One pop-up pin is located on each side of the stern roller **(**(1) in Figure 47). These do not contain locking arms, and the primary purpose of the pop-up pins is to prevent the mooring line from extreme athwartships movement (Kongsberg Maritime, n.d-c).

Shark Jaw

The shark jaw ((4) in Figure 47 & Figure 49) is located in front of the towing pins. The main purpose of the shark jaw is to secure the chain. When the chain is secured in the shark jaw, as seen in Figure 48, the deck crew can safely disconnect or insert parts of the mooring line. The insert ((1) in Figure 48) of the shark jaw can be changed to fit different chain dimensions. Some vessels have a hydraulic regulated insert. To prevent the chain from slipping out of the shark jaw, the towing pins with deployed locking arms can be lowered. When holding the socket of a wire, a bolt can be inserted on top of the shark jaw to prevent the socket from slipping out. The safest is to avoid putting the socket in the shark jaw (Kongsberg Maritime, n.d-c). One mitigation is to connect the chain piece to the socket and secure the chain in the shark jaw instead.

Figure 48 – Shark jaw and (1) shark jaw insert (Author's photo).

Centering Device

The centering device ((5) in Figure 47 & Figure 49) is located in front of the shark jaw. There is one set consisting of two manipulators for each towing pin, and when used, it swings up towards the centre, as illustrated in Figure 49. The centering device is either in the open position or flushes with the deck. The main purpose of the centering device is to push the mooring line into the shark jaw (Kongsberg Maritime, n.d-a).

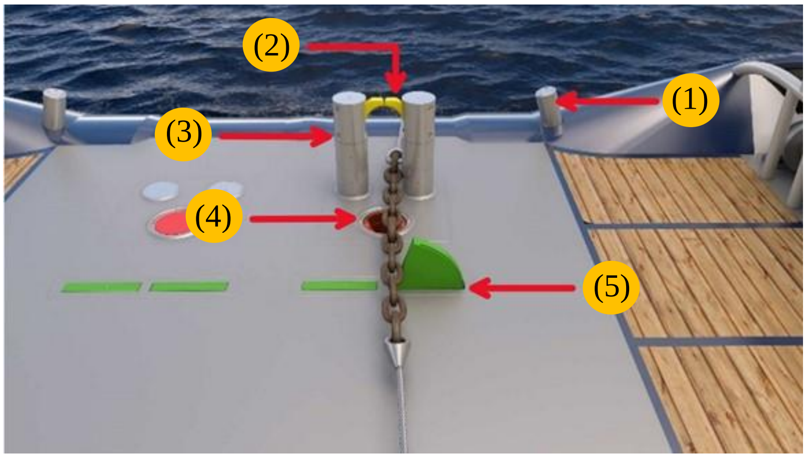


Figure 49 – AHTS aft deck equipment; (1) Pop-up pin, (2) Locking arms, (3) Towing pins, (4) Shark jaw, (5) Centering device (Kongsberg Maritime, n.d-a).

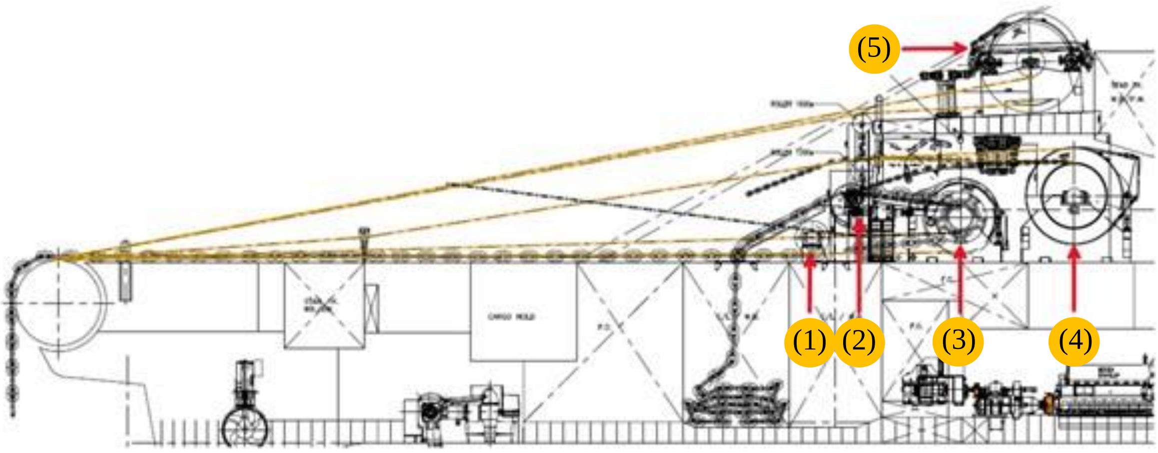


Figure 50 – Far Sapphire deck layout; (1) Chain guide, (2) Chain hauler, (3) Chain gypsy & AH/towing winch, (4) Special handling winch, (5) Secondary winch (Solstad Offshore, n.d-a).

Chain Guide

The chain guide (Figure 51 & (1) in Figure 50) is located aft of the chain gypsy, and the primary purpose of the chain guide is to guide the chain at the right angle to the gypsy to get ideal contact between the chain and gypsy. The chain guide must be adjusted for the particular chain size (Kongsberg Maritime, n.d-b).

Figure 51 – Chain guide (Vik, 2021)

Figure 52 – Chain gypsy (Vik, 2021)

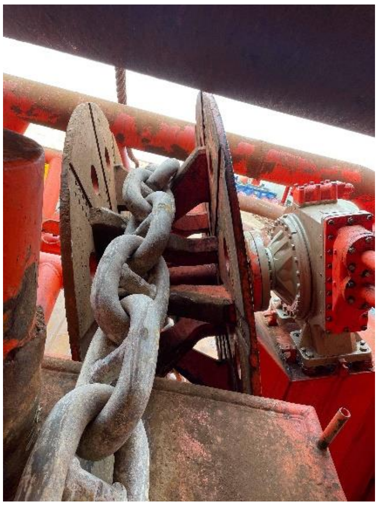


Figure 53 – Chain hauler (Vik, 2021)

Chain Gypsy

The chain gypsy (Figure 52 & (3) in Figure 50) is mounted on the winch, and its purpose is to run the chain. The chain gypsy is made for particular chain sizes and must be changed for the respective chain size. The same shaft drives the chain gypsy as the respective AH/towing winch. Therefore, when using the chain gypsy, the respective AH/towing winch must be tied up.

Chain Hauler

The purpose of the chain hauler (Figure 53 & (2) in Figure 50) is to pull the chain from the gypsy to the chain lockers. The chain hauler is adjustable and must be adjusted for the particular chain size (Kongsberg Maritime, n.d-b).

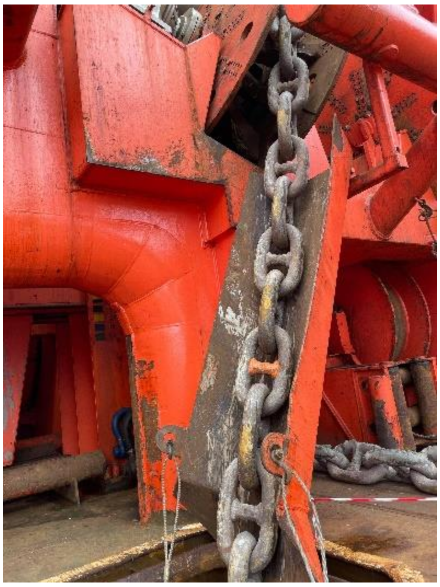


Figure 54 – Chain chute for chain locker nr. 1 PS (Vik, 2021)

Chain Chute

The chain chute (Figure 54 & (8) in Figure 47) guide the chain into the correct chain locker. To get the chain to slip easier from the chain hauler to the chain locker, rollers can be installed in the chute.

Chain Locker

The chain locker ((6) in Figure 47) is the main storage for the chain onboard an AHTS. Normally, the number of chain lockers ranges from 4 to 6 with varying sizes. The chain can also be stored on the vessel's winches.

Secondary Winch

Secondary winches ((5) in Figure 50) is used for storing mooring lines. These winches are less powerful than the SHW and AH/towing winches. On some vessels, there are storage winches beneath deck.

Special Handling Winch

The SHW ((4) in Figure 50) is the most powerful winch onboard. It is also useful for maintaining pull force as the core diameter is big (Kongsberg Maritime, n.d-d). The SHW is often used to store mooring line. The storage capacity is depending on the size of the mooring line.

Anchor Handling/Towing Winch

AH/towing winches ((3 in Figure 50) are versatile and can be used for towing, anchor handling, storage of mooring line or small amounts of chain. When using the chain gypsy, the AH/towing winches must be tied up since the gypsy and winch is driven by the same shaft.

A-frame

A-frames can be installed on the vessel and is used to lift loads overboard. The A-frame can be mobilized and demobilized depending on whether its needed or not. As seen in Figure 55, the A-frame for anchor handling can be installed aft of the ship and fitted with a sheave, making it possible to turn the working wire through the sheave. Using this method, large weights can be lifted using the winch. The A-frame can be tilted forward and aft using hydraulic cylinders. The lifting capacity is dependent on the size and can range between 10 to more than 800 tonnes (AXTech, n.d). The largest A-frame installed on an AHTS vessel to date is 350 tonnes, onboard Normand Installer (Solstad Offshore, 2021). The A-frame can be utilized for anchor handling, plough towing, subsea machine handling, AUV/ROV, well intervention, and high-pressure water jets (AXTech, n.d).

Figure 55 – Far Sapphire with A-frame (Solstad Offshore, n.d-a)

5 Discussion

5.1 Licencing Authorities

For a developer to be able to construct a FOWF, there is an extensive process from before the application can be sent, until the FOWF is fully commissioned. The application process is comprehensive and can result in public inquiries. The responsibilities within the application process are distributed between various authorities.

In the application process, the responsibilities are divided between MPE and NVE. The MPE is responsible for handling the application procedure for the memorandum, including the PSR and the PSCR. On the other hand, the role of NVE in the application process is to assist MPE with professional advice, and assist the authorities to approve the PSDP (NVE, 2019). The process and distribution of responsibilities will be explained further in the coming guide for offshore wind in Norway, which will be published on the 11th of June 2021 (Olje- og energidepartementet, 2021). The guide is expected to clarify the application process and make clear the required information in the application as well as the PSR, PSCR and PSDP.

The Norwegian O&G industry has long-standing experience and well-developed regulations regarding the harvesting of energy resources offshore. The Norwegian MPE is responsible for regulating the Norwegian offshore wind industry (Ministry of Petroleum and Energy, 2021). The MPE has delegated the responsibility for inspecting the construction and operation of offshore wind farms to the PSA (Petroleum Safety Authority Norway, 2020). As a result of this, the MPE is responsible for opening areas for application for a licence, and awarding licence to the qualified constructors. On the other hand, the PSA is responsible for regulating the development and operation of the wind farms.

PSA has the responsibility for supervision with the O&G industry, and there are parallels to the offshore wind industry regarding installing structures offshore. On the other hand, the FOW industry does not have the same consequences of failure as the O&G industry because there is no extraction of hydrocarbons under high pressure in the FOW industry. Also, an O&G platform is permanently manned. A FOWT is normally unmanned. An O&G structure is therefore applicable to the stricter consequence class 2. In contrast, a FOWT can be in conjunction with consequence class 1 due to the smaller consequences of a failure, as described in section 4.2.5 (Ikhennicheu et al., 2021). One may consider the regulations for the offshore wind industry to be less rigorous. However, there are still potential for fatal accidents and significant economic losses in the offshore wind industry, which will demand strict regulations of the FOW industry.

Regarding FOWTs, one may consider registering the units in the ship registry, which also presents a demand for regulations from the Norwegian Maritime Authority. However, one may draw parallels to the O&G industry, where the fixed installations are not registered in the ship registry, which could also be the case for FOWTs (Lie, 2021).

However, the insurance companies will demand that the FOWTs are certified by a classification society. Also, there is an industry-standard that the FOWTs are certified by a classification society (DNV, 2021). The classification society plays an important role in the development of a wind farm. Classification societies like DNV have an advisory role from the start and during the operation of an offshore wind farm. DNV offers standards for constructing FOWTs and mooring systems, which will serve as minimum requirements when constructing an offshore wind farm. DNV has executed research for the offshore wind industry (DNV, 2021).

5.1.1 Dimensioning Requirements

The mooring system of a FOWT is designed to withstand the expected weather at the location of the FOWF. The design is based on three main limit states; ULS, FLS, and ALS. These limit states are the three main requirements for the mooring system.

ULS is the maximum expected load on the mooring system, and the mooring system is designed to withstand these forces, including a given safety factor. The environmental forces to be used when designing against the ULS is a 50-year return period for a FOWT mooring design. On the other hand, an O&G structure applies a 100-year return period (DNV, 2020). This could coincide with the fact that the possible consequences of a failure in the mooring design of a FOWT are lower.

Differing from the ULS, which is a weather state, FLS is considering the fatigue lifetime of a mooring system over a given period. The mooring system is designed to endure the expected fatigue loads during its lifetime. For example, the mooring system shall withstand a given number of cycles of a given force as displayed in the S-N curve. On the other hand, ALS is a limit state that the mooring system shall endure in a damaged condition, and the rest of the mooring lines shall then keep the unit within a given position offset.

The limit state requirements are based on the expected consequences of a drift off. In terms of redundancy and consequences, a FOWT differs from installations in the O&G industry due to them normally being unmanned. The lack of hydrocarbons involved in FOWTs reduces the consequences in case of a failure. A semi-submersible MODU is permanently manned and connected to a live drilling well with a riser. A failure of the mooring system could potentially lead to a big environmental impact and loss of life. The only connection to a FOWT is the electrical export cable. A failure of the mooring system, causing a large drift off, will not necessarily cause any harm to the environment.

According to DNVGL-ST-0119 Floating wind turbine structures (DNV, 2018a), a FOWT shall be designed in conjunction with consequence class 1 if the mooring system is deemed redundant. For example, a FOWT using a catenary mooring system with three lines can be classified as redundant. A failure of one mooring line will probably cause a large drift off and subsequent disconnection of the power cable, but the remaining two anchors will then share the load and prevent the FOWT from drifting off completely (Lie, 2021). On the other hand, a FOWT utilizing a TLP mooring system will not be considered redundant due to its inherent lack of stability if disconnected from its tendons. Therefore, such a configuration needs to be designed in conjunction with consequence class 2 and therefore hold a higher safety factor than that of a redundant mooring system.

A FOWT with a 3-line catenary system can also be deemed non-redundant and therefore qualify for consequence class 2. The mooring configuration is in conjunction with consequence class 2 if a mooring line failure and subsequent drift off can cause a collision with adjacent structures. For example, Hywind Tampen is located between the Gullfaks and Snorre platforms, meaning a turbine drift off could lead to a collision with the producing platforms at the oil fields. In comparison, the Utsira Nord field features greater distances to the nearest manned oil-producing structures, giving smaller consequences of a potential mooring system failure and drift off. This coincides with DNVs consequence class 1, stating that a complete loss of structure can qualify for consequence class 1 if it does not cause harm to other structures (DNV, 2018a).

5.2 Mooring Designs

5.2.1 Mooring Configuration

The design of the mooring configuration is subject to a compromise between line tension and platform offset. The mooring line material and configuration decide the line tension, where a heavy mooring line, such as a chain, would increase the line tension and reduce the offset. Also, high tension and reduced offset could be achieved using a taut mooring configuration of synthetic fibre rope. On the other hand, lower tension and larger offset can be achieved by using a catenary mooring configuration, combining chain with lighter materials such as steel wire rope or synthetic fibre rope. For an FOWF, the offset should be large enough to reduce the extreme line tension, but small enough to avoid colliding with adjacent structures, nor stretching the electrical export cable. However, the tension should be low enough to reduce the requirements for larger mooring lines (Nilsen, 2021).

FOWTs differ from floating units in the O&G industry, both temporary and permanent units. FOWTs are planned to be deployed in greater quantities, requiring a higher total number of mooring lines for a FOWF. A permanent moored semi-submersible unit is often moored with a mooring configuration consisting of 16 mooring lines. Compared to a temporary moored semi-submersible unit where it is moored with a total of 8-12 mooring lines depending on the unit (Lie, 2021). To reduce the number of total mooring lines and thus costs for a FOWF, simplification of the mooring configuration is needed. A FOWF is scheduled to be in service for 20-30 years, creating a need for larger and stronger dimensions of the mooring design.

There are normally three mooring lines per FOWT (Principle Power, n.d, Equinor, 2019a, Equinor, n.d-b). This presents a challenge with redundancy, which means that each of the mooring lines for FOWTs should be stronger to compensate for the lack of redundancy. The exposed wind area for a FOWT is large due to the large rotor diameter, which means that the mooring system shall be designed to withstand both large wind forces and wave forces while the WTG are in production. Compared with an O&G unit, the greatest force acting on the unit is usually the wave force. The wave forces will also expose the FOWT, but the wind forces will be greater when the WTG is in production. However, when the WTG is parked, the wave forces will be the strongest (Nilsen, 2021).

5.2.2 Catenary & Taut Properties

For mooring of a FOWT, the mooring configuration needs to be decided upon the same factors used in the O&G industry. The depth, WWC conditions and cost are such factors (Lie, 2021). The most common configurations are taut mooring and catenary mooring, which both have advantages and disadvantages. The depth on the Norwegian continental shelf ranges from shallower waters in the southern North Sea to deeper waters in the Norwegian Sea, creating conditions that are beneficial for both catenary and taut mooring configurations. The Utsira Nord field in Norway, with an average depth of 267 metres, could be suitable for both catenary and taut mooring designs (NVE, 2010).

A taut mooring configuration requires an anchor that can withstand both horizontal and vertical forces and an elastic mooring line. On the other hand, a catenary mooring configuration only requires an anchor that can withstand horizontal forces. Such a configuration utilizes geometric stiffness for resistance and control of the position offset of the FOWT, therefore requiring longer and heavier mooring lines. This creates a larger seabed footprint which could conflict with O&G subsea structures, and the larger position offset could conflict with adjacent floating or fixed structures. On the other hand, a taut mooring configuration has a smaller position offset and seabed footprint, as the normal mooring line length is 1.5 times the depth (Lie, 2021).

A catenary configuration could have advantages over a taut configuration at smaller depths where the weight of the mooring line creates a soft resistance and less snapping loads than those found in a taut configuration. At smaller depths, the catenary configuration could also create vertical forces at the anchor, requiring anchors that can withstand such forces. Another mitigation for small depth catenary mooring is to use subsea buoys or clump weights to get the desired catenary shape of the mooring lines. Xu et al. (2021) simulated a configuration using a combination of buoys and clump weights for a FOWT in shallow water. The simulation showed promising results with reduced tension in the mooring lines and reducing the horizontal offset of the FOWT.

Taut configurations are normally only used at greater depths, such as those found in Brazil or the Norwegian Sea (Lie, 2021). Wave heights in the area could also be a limitation for taut mooring lines because the mooring lines are under constant tension. In contrast, a catenary configuration has higher tolerances in harsh conditions (Lie, 2021). Also, experience with using taut moorings at shallower depths is not as extensive as catenary moorings (Subrata, 2005).

This factor could increase the safety factors used for the anchors and mooring lines in a taut configuration, thus increasing costs over a catenary configuration.

5.2.3 Mooring Line Materials

The materials used for offshore mooring of floating units are typical chain, steel wire rope, and synthetic fibre ropes. The properties of the different materials vary. The properties of synthetic fibre ropes are more complex and advanced than traditional chain or steel wire rope (DNV, 2020). The materials used for mooring chain and wire is steel. Even though price and breaking load can be compared, the choice of mooring line material also depends on the properties of the material. The desired properties could be high or low weight, specific elasticity, MBL or price. For example, a high weight in the bottom chain could be desired in a catenary mooring design. A 180 mm chain could be utilized in the bottom chain due to its high weight, even though the needed MBL in the mooring configuration is lower than the actual MBL of the 180 mm chain.

Klingan (2016) estimated prices for different mooring line materials based on data from Equinor. The estimate does not indicate which quality or type of the mooring line material and is only valid for a rough estimate. The estimate was based on an equation as follows:

$$Cost = \frac{\pi}{4} \cdot Length \cdot Weight_{in\ air} \cdot Price\ coefficient$$

Length in metres, weight in air given in N/m and the price was given as coefficients given in Table 2 as NOK/N:

	Chain	Steel Wire Rope	Polyester Rope
Price coefficient (NOK/N)	2.5	5.0	7.0

Table 2 – Price coefficients (Klingan, 2016).

DNV (2020) estimated the elasticity of different mooring line materials. The estimate for wire rope does not indicate which type of steel wire and is only valid for a rough estimate. The equation was used to calculate the elasticity of the R5 stud-less chain and Bridon Bekaert`s Spiral Strand SPR2+ 1860 grade in Table 3. The estimate was based on the equation as follows:

$$Wire\ rope\ =\ 1.13\ \cdot 10^{11}\frac{N}{m^2}$$

$$Chain\ =\ (6.00 - 0.0033\ \cdot diameter) \cdot 10^{10}\frac{N}{m^2}$$

Material	Diameter (mm)	Weight per metre in air (kg/m)	MBL (kN)	Price per metre (NOK)	Elasticity (GPa)
R5 stud-less chain	116	269	14,950	5,180	56
Bridon Spiral Strand SPR2+ 1860 grade	120	78.1	15,480	3,009	113
OTS Polyester Multicore	211	33	14,710	1,850	4.5-6.8
OTS Dextron (HMPE)	166	14	14,710	8,040	48

Table 3 – Comparison of different mooring line materials (InterMoor, n.d-b, Bridon Bekaert, 2018, OTS, 2021, DNV, 2020, Klingan, 2016)

Polyester fibre ropes have a fatigue life that is 50 times greater than steel wire (Weller et al., 2015). Chain and steel wire do both suffer from corrosive problems during their service time. Corrosion is not a problem for synthetic fibre ropes. To protect the steel wire rope from corrosion, the wire can be protected by a plastic sheathing, which will increase its fatigue life.

Gnawing and sharp objects can be a problem for synthetic fibre ropes. On the other hand, chain and steel wire rope are not vulnerable to sharp objects. However, all materials are vulnerable to gnawing. For a sheathed steel wire rope, gnawing can puncture the protective sheathing causing corrosion and damaging the strands. Chain is also susceptible to gnawing as, over time, the gnawing would cause abrasion to the steel. Periodic inspections are needed for all materials to detect such damages.

Steel can handle higher temperatures than synthetic fibre ropes. Overheating is more likely to occur with greater dimensions and certain lay types of synthetic fibre ropes (Weller et al., 2015).

As shown in Table 3 synthetic fibre ropes are lighter and more elastic than chain and wire. Compared to steel, synthetic fibre ropes have a high strength to weight ratio, and some types have neutral buoyancy in seawater (Weller et al., 2015). The strength of a polyester rope is about half that of a steel wire rope of equal diameter (Subrata, 2005). For example, a synthetic fibre rope with a MBL of 14,710 kN has a diameter of 211 mm, while a steel wire with a MBL of 15,480 kN has a diameter of 120 mm.

The elastic stiffness of the synthetic fibre ropes is not constant but varies with the load range and the mean load. Also, the stiffness varies with age (Subrata, 2005). Synthetic fibre ropes can be extended 1.2 to 20 times as much as steel, which will dampen the wave motions (Subrata, 2005). The elasticity in the materials differ. The spiral strand steel wire is less elastic than steel chain, HMPE and polyester.

The wire rope and synthetic fibre rope is not fitted to be in the touchdown point because these materials cannot withstand long time abrasion with the seabed (Lie, 2021). The synthetic fibre ropes should not be in contact with the seabed. In addition to the sand filter, a special sheathing is used for polyester ropes intended for touching the seabed. The chain is better fitted to be used in the touchdown point due to its higher abrasion resistance. Steel wire ropes are vulnerable to cyclic bending and should be avoided at the touchdown point (Lie, 2021).

A large chain can be used to get the desired weight and properties in a mooring configuration. For synthetic fibre ropes and steel wire ropes with a smaller weight per metre than the chain, additional clump weights can be added to get the desired properties for the mooring line. Subsea buoys can be used to increase the total buoyancy of the mooring line.

5.2.4 Connecting Components

Components used in temporary and permanent mooring lines in the O&G industry are different. The most common permanent mooring configuration on the Norwegian continental shelf usually consists of chains, steel wire ropes, coupling plates and LTM D-shackles to connect the different components in the mooring line. Steel wire rope is more common than fibre rope for permanent moorings on the Norwegian continental shelf (Lie, 2021). In contrast, temporary mooring line configuration usually consists of a bottom chain, synthetic fibre rope, chaser stopper, and rig chain. Swivels and Kenter shackles are used to connect components in temporary mooring lines. Wire rope is normally not used in temporary moorings on the Norwegian continental shelf.

The main difference between permanent and temporary is the fatigue requirements. As a result of this, swivels and Kenter shackles are not used in permanent moorings. Swivels and Kenter shackles can be used in temporary mooring configurations as the service time and intervals between inspections are shorter (DNV, 2020). Components used in a mooring configuration that cannot be inspected shall have a fatigue life safety factor 7-10 times greater than design fatigue life. Theoretically calculated fatigue life for a component to be anchored for 20 years shall have 20 x 10 = 200 years fatigue life (Lie, 2021).

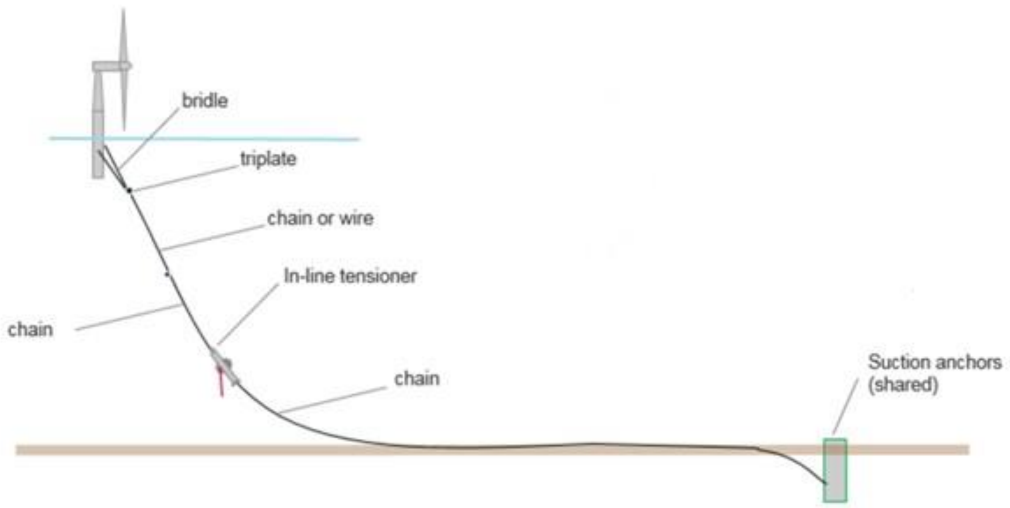


Figure 56 – Hywind Tampen mooring configuration draft, depth 260 – 300 metre (Equinor, 2019a).

The in-line tensioner is usually not needed in O&G unit moorings because the O&G unit normally has mooring winches installed to adjust the tension and length of the mooring line. For FOWTs, there is normally not installed winches on board the floater, which means that adjustment of the mooring lines must be performed by a vessel using the in-line tensioner.

5.2.5 Anchor Types

The anchor types suitable for the mooring of FOWTs in Norway could be suction anchors or DEAs because the soil on the Norwegian continental shelf is mainly soft to medium clay (Lie, 2021). The choice of anchor depends on the properties of the mooring configuration, as mentioned in section 5.2.2. The anchor types differ in characteristics, cost, and installation, but both anchors fit the same soil types. For the mooring of FOWTs, the total cost of the anchor is an important factor.

The properties of the anchors differ, and DEAs require special mooring configurations to be suitable. The DEA can not be used in a taut configuration because the anchor is unable to resist vertical loads. A long ground chain is used in a catenary configuration to ensure that the DEA is not exposed to vertical forces. On the other hand, suction anchors can resist loads in all directions, making them suitable for all mooring configurations. The DEA must be proof tensioned with a high load because of the long service time. The proof tension should be higher than the expected load during the service time, as there are fewer anchors per unit, each anchor must resist higher loads, in contrast to a DEA in a mooring for a MODU. However, the total number of mooring lines per unit also increases the required size of the suction anchor. On the other hand, the size of the suction anchor could be reduced in a shared anchor configuration since the resultant force is reduced (Fontana et al., 2018).

However, the cost of the suction anchor is higher than for the DEA. The suction anchor requires a CSV with an AHC crane and ROV for installation (Solstad Offshore, 2021). Also, the suction anchor is more expensive in hardware cost due to its specific design and larger size. On the other hand, the DEA is a cheaper alternative both in hardware and installation cost. The fluke angle of the DEA can be adjusted to fit for multiple soil types, which makes the DEA adaptable. Also, the DEA is used in large quantities in the O&G industry, contributing to reduce the overall cost (Lie, 2021). However, the cost of installing a DEA for FOWTs could be higher, as the requirements for the vessel's BP and equipment could be higher than for the mooring of MODUs. As a result, the number of AHTS vessels capable of meeting the requirements is lower, increasing the cost (Solstad Offshore, 2021).

One mitigation to reduce the cost of a suction anchor is to use shared anchors for multiple turbines. Fontana et al. (2018) concluded that the total number of anchors could be reduced by 67% when using a shared anchor configuration. In contrast, the DEA can not be used as a shared anchor because the anchor can only resist loads in one direction. However, the installation time and cost of the DEA can be reduced by installing multiple anchors in one operation. Using the Stevtensioner, three anchors can be installed in one operation. The Stevtensioner or a reaction anchor connected to the vessels bow could also reduce the required BP of the AHTS. The required BP of the AHTS is reduced since the Stevtensioner or reaction anchor is used to proof tension the anchors using the onboard winch. By using the Stevtensioner, installation time, fuel consumption, and overall cost could be reduced. However, using the reaction anchor connected to the bow could increase installation time due to a more complicated hook-up procedure. On the other hand, installing a suction anchor requires an AHTS in addition to a CSV to install and connect the mooring lines to the FOWT, resulting in demand for multiple vessels.

5.3 Vessel Modifications

Solstad AHTS Vessels Relevant for Mooring of Floating Offshore Wind Turbines

	Normand Prosper	**Normand Drott**	**Far Sapphire**
LOA (m)	95	95	92.7
Beam (m)	24	24	22
Deck size(m^2)	750	760	800
Main engine power (kW)	2 x 7,680 main 4 x 2,188 auxiliary	2 x 7,680 main 4 x 2,100 auxiliary	4 x 4,000 main 2 x 2,100 auxiliary
BP (t)	337	339	272
ROV	1 x work class	1 x work class	1 x work class
Deck crane	2 x 5 t at 10 m/3 t at 14.3 m	2 x 5 t at 10 m/3 t at 14.3 m	2 x 5 t at 10 m/3 t at 14.3 m
Offshore crane	None	None	1 x 20 t at 20 m, 600 m wire and AHC
SHW power	1 x 500 t (1st layer), 0-70 m/min	1 x 500 t (1st layer), 0-70 m/min	1 x 500 t (1st layer), 0-70 m/min
SHW chain capacity	700 m of 120 mm chain	700 m of 120 mm chain	800 m of 120 mm chain
SHW drum size	D_{inner}:3.5 m D_{outer}:5.4 m L: 6.5 m+1.1 m	D_{inner}:3.5 m D_{outer}:5.4 m L: 6.5 m+1.1 m	D_{inner}:3.5 m D_{outer}:5.05 m L: 6,5 m+1.1 m
AH/towing winch	Starboard (STB): 1x 450 t (1st layer), 0-40 m/min Port Side (PS): 1x 450 t (1st layer), 0-40 m/min	STB: 1x 450 t (1st layer), 0-25,6 m/min PS: 1x 450 t (1st layer), 0-25.6 m/min	STB: 1x 350 t (1st layer), 0-50.6 m/min with AHC PS: 1x 450 t (1st layer), 0-39.5 m/min
AH/towing winch drum size	STB: D_{inner}=1.5 m D_{outer}=3.75 m L=3.5m PS: D_{inner}=1.5 m D_{outer}=3.75 m L=2.15 m+0.9 m	STB: D_{inner}=1.5m D_{outer}=3.75 m L=3.5 m PS: D_{inner}=1.5 m D_{outer}=3.75 m L=2.15 m+0.9 m	STB: D_{inner}=1.5 m D_{outer}=3.75 m L=3 m PS: D_{inner}=1.5 m D_{outer}=3.75 m L=3 m
2nd winch	2 x 170 t (1st layer), 0-37 m/min	2 x 170 t (1st layer), 0-24 m/min	2 x 170 t (1st layer), 0-37 m/min

Max chain size	All equipment built for max 166 mm chain	All equipment built for max 166 mm chain	All equipment built for max 165 mm chain
Chain locker	6 pcs, total of 1,005.4 m^3 5,100 m of 120 mm chain	6 pcs, total of 1,005.6 m^3 5,100 m of 120 mm chain	5 pcs, total of 953 m^3 4,900 m of 120 mm chain
A-frame	Optional, 250 t, 15 m outreach aft, 8 m outreach forward	Optional, 250 t, 15 m outreach aft, 8 m outreach forward	Optional, 250 t, 16.4 m outreach aft, 10.2 m outreach forward

Table 4 – Comparison of SOFF AHTS vessels (Solstad Offshore, n.d-c, Solstad Offshore, n.d-b, Solstad Offshore, n.d-a)

From SOFF's point of view, Normand Prosper (N. Prosper), N. Drott and Far Sapphire are best fitted for projects like mooring of FOWTs. Compared to the other vessels in the SOFF AHTS fleet, these vessels have higher capacities in all segments. Also, these vessels are available in the spot market for this kind of projects. N. Prosper and N. Drott are equal vessels, with just some minor variance in BP and deck size. Regarding chain locker capacity, N. Prosper and N. Drott have more capacity than Far Sapphire, which has one chain locker less than N. Prosper and N. Drott (Solstad Offshore, n.d-c, Solstad Offshore, n.d-b, Solstad Offshore, n.d-a).

As shown in Figure 57, Far Sapphire can load the chain via the SHW, by first spooling the chain on the winch, then loading the chain to the chain lockers from the SHW. The chain can be loaded faster by loading chain with this method than loading the chain via the gypsy (Solstad Offshore, n.d-a). This method is to be banned by the O&G companies after several breaks in chain moorings, as the companies suspect that this method could be a strain on the chain (Solstad Offshore, 2021)

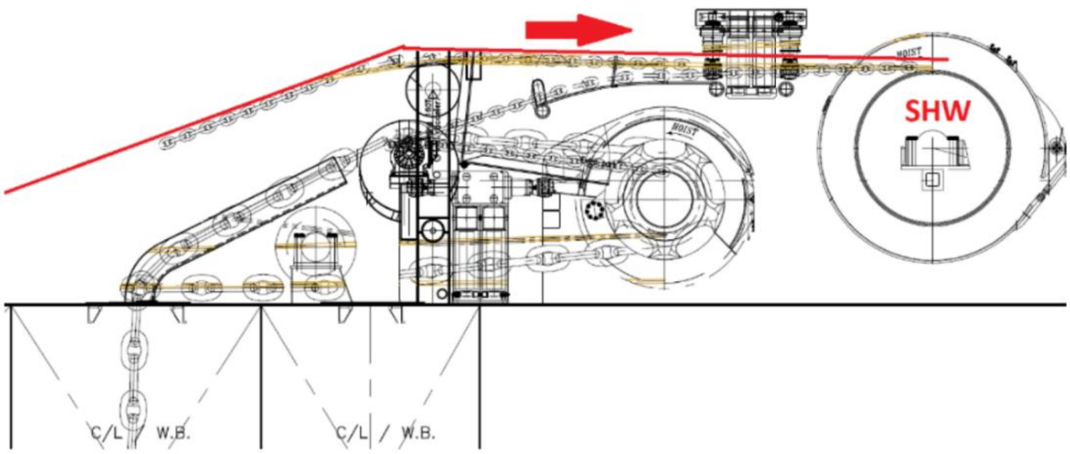


Figure 57 – Far Sapphire SHW chain spooling (Solstad Offshore, n.d-a)

All vessels are equipped with winches and equipment from the same producer, Kongsberg Maritime, which means that the modifications available for these vessels are similar. As seen in Table 4, the specifications for the equipment are almost the same for all three vessels. Far Sapphire has retrofitted one of the towing winches for AHC mode, which means that the winch is heave compensated. The winch features three different operating modes: AHC mode, constant tension mode, and auto-landing mode. The auto-landing mode will automatically change from AHC to constant tension when the load is landed on the seabed. Far Sapphire is equipped with an offshore crane with 20 tonnes lifting capacity. The crane features AHC mode and 600 metres of wire.

As a standard, most AHTS vessels are equipped for maximum 166 mm chain size in shark jaws, chain gypsies, chain haulers, and all other equipment handling chain on board. Therefore, the vessels must be modified to fit the chain size which is planned to use in the mooring of FOWTs.

The chain chute configuration differs slightly between the vessels. N. Prosper has permanently installed chain chutes. The chain chutes onboard N. Drott are movable. On Far Sapphire, the chain chutes have rollers fitted to ease the sliding of the chain. For all vessels, the chain chutes must be modified to bear the high weight as well as the size of a 180 mm chain. For modifications, N. Drott is most suitable because of the movable chain chutes, as seen in Figure 58. In contrast, the chain chutes on N. Prosper is a large fixed structure, as seen in Figure 59 (Solstad Offshore, 2021).

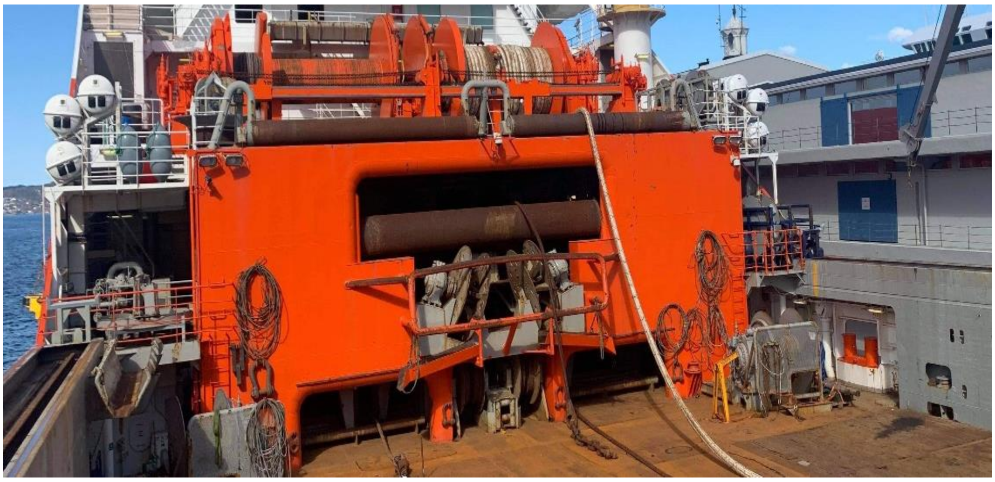


Figure 58 – N. Drott movable chain chutes (Skaaden, 2021).

Figure 59 – N. Prosper fixed chain chutes (Author's photo).

5.3.1 Vessel Equipment Modifications

As an estimate, SOFF is calculating that the dimensions of the mooring systems will be up to 180 mm chain. The weight of the DEAs is estimated to be up to 50 tonnes, and the proof tension of DEAs will exceed 400 tonnes. Using this estimate as a basis, one can suggest changes to the existing AHTS vessels. The main challenge is that the vessels are built and designed to handle a maximum of 166 mm chain (Solstad Offshore, 2021). This means that all chain handling equipment will be too small to handle a 180 mm chain. To discover the challenges and solutions, the vessels that SOFF desire to utilize for FOWT installations was investigated. The desired vessels are N. Drott, N. Prosper, and Far Sapphire, the specs of the vessels are given in Table 4. The challenges found in the investigation are presented in this section.

The clearance between the towing pins is 543 mm, and the width of a 180 mm chain is 603 mm (InterMoor, n.d-b, Rolls-Royce Marine, 2009). The width of the chain does not fit in between the towing pins. To circumvent the problem of clearance, one pin in each towing pin pair can be deployed to control the chain's athwartships movement. Then, the locking arms cannot hold the chain in place inside the shark jaw. However, SOFF evaluated that the risk of chain slipping out of the shark jaw is small. The weight of the chain hanging off the vessel will be high enough to prevent the chain from slipping. Therefore, the application of locking arms could be circumvented.

The shark jaw can hold a maximum 165 mm chain, which means that a 180mm chain cannot fit inside the shark jaw. One mitigation could be to mill the shark jaw to make the clearance larger, but the Working Load Limit (WLL) of the shark jaw could be reduced. The producer of the shark jaw has confirmed that the shark jaw can be modified up to a 190 mm chain without reducing the WLL (Solstad Offshore, 2021). Both the towing pins and the shark jaws are fitted in one module delivered by Kongsberg Maritime. Another solution to make the equipment fit, the vessels can be refitted with a new module containing towing pins and shark jaws with larger clearance to fit bigger chain diameters.

The centring device is not powerful enough to move chain larger than approximately 90 mm. One may circumvent this by using tugger winches for the same application to move the chain to the centre of the shark jaw. Also, when pre-laying anchor systems, the vessel can be manoeuvred to move the chain's position on deck (Solstad Offshore, 2021).

Regarding chain handling equipment on the winch, all components are made for a maximum of 166 mm chain. The challenge with the main components is described in the following paragraphs.

The clearance between the deck and the guide rollers could be too small. Also, the clearance between the sidewalls of the chain guide could be too small. According to Solstad Offshore (2021), the guide rollers can be adjusted to fit up to a 190 mm chain, the clearance between the deck and roller is also adequate.

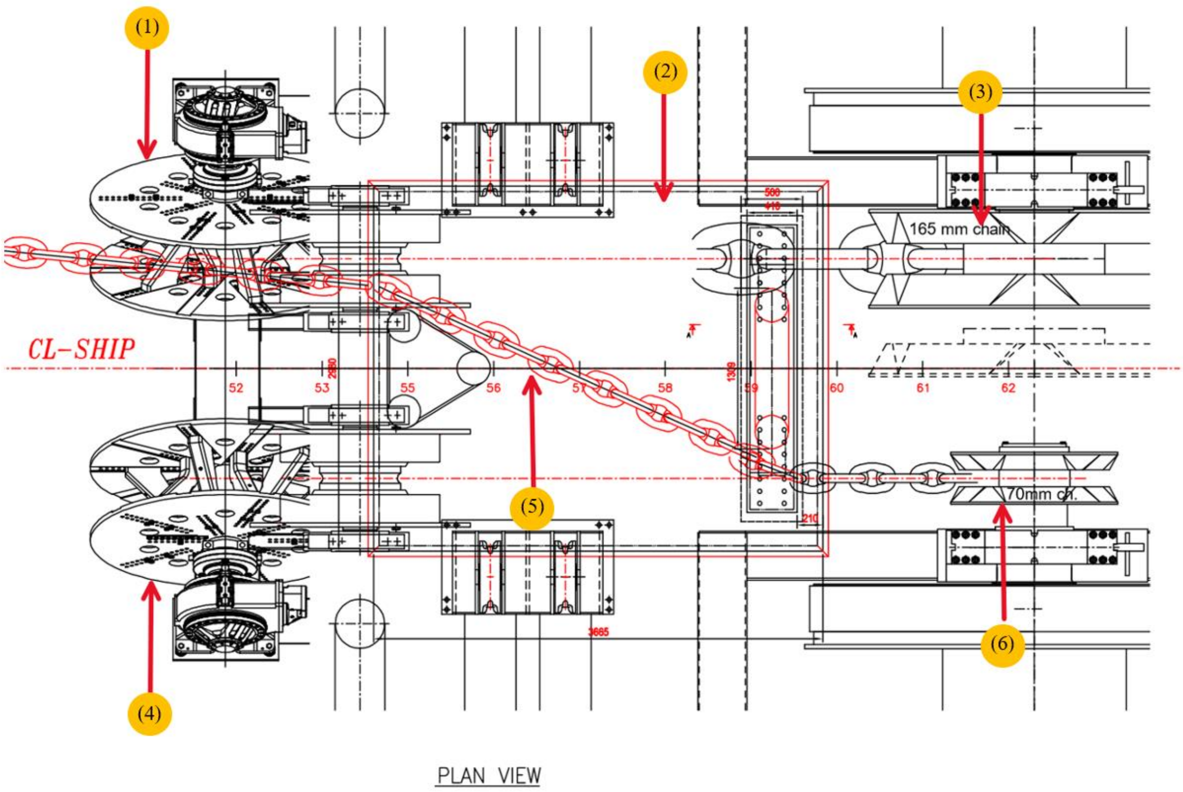


Figure 60 – Cross-loading chain; (1) Chain hauler PS, (2) Chain-crossing table, (3) Chain gypsy PS, (4) Chain hauler STB, (5) Crossing chain, (6) Chain gypsy STB (STX Norway Offshore Brattvaag, 2010).

The largest chain gypsies for the vessel are made for a maximum of 166 mm chain, which mean that the 180 mm chain cannot fit inside the chain gypsy. There are larger chain gypsies available by the manufacturer, which can be ordered and fitted on the winch. However, the traditional cross-loading, using SB winch to load both SB and PS chain lockers, cannot be used due to the weight of the chain would tear the cross-loading equipment, such as the table and guides. When installing the mooring chain at Hywind Scotland, N. Prosper cross-loaded 147 mm chain. The chain-crossing table (2) in Figure 60 cracked due to the high loads. Therefore, there is a need for suitable gypsies on both winches to avoid cross-loading (Solstad Offshore, 2021).

The chain haulers are adjustable, but these are also initially made for a maximum of 166 mm chain. The chain haulers can be adjusted to the maximum size and fit for larger chain sizes. Running the chain haulers without perfect adjustment to the chain can be done because the chain is heavy, and the slip will be tolerable even if the chain hauler does not fit perfectly. When loading a chain of 180 mm, the loading speed must be slow, and therefore the risk of using smaller chain haulers is low (Solstad Offshore, 2021).

The chain chutes for N. Prosper, N. Drott and Far Sapphire are different. The chain chutes on N. Drott are shown in Figure 61 and are easiest to modify because the chain chutes are movable, differing from the fixed chain chutes onboard N. Prosper. Therefore, it is most likely to make changes to N. Drott. The challenge with all existing chain chutes on the mentioned vessels is that they are too small and cannot handle a 180 mm chain size and weight. As seen in Figure 62, the internal width of the chain chute is 810 mm on top and 328 mm on the bottom. The width of a 180 mm chain is 603 mm (InterMoor, n.d-b, STX Norway Offshore Brattvaag, 2009). According to Figure 62, the clearance should be sufficient, but the problem could be that the contacting surface is larger than for the 165 mm chain. The larger contacting surface could result in increased friction, and therefore the sliding speed of the chain would be slow. Slower sliding speed can result in poor stacking of the chain in the chain locker. Therefore, new chain chutes must be manufactured and mounted on board.

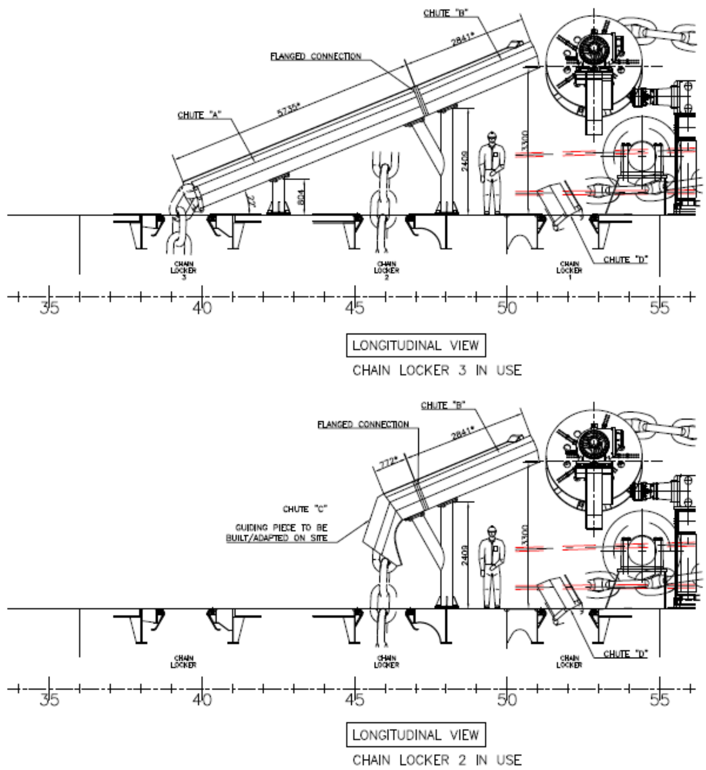


Figure 61 – N. Drott Chain chutes (STX Norway Offshore Brattvaag, 2009).

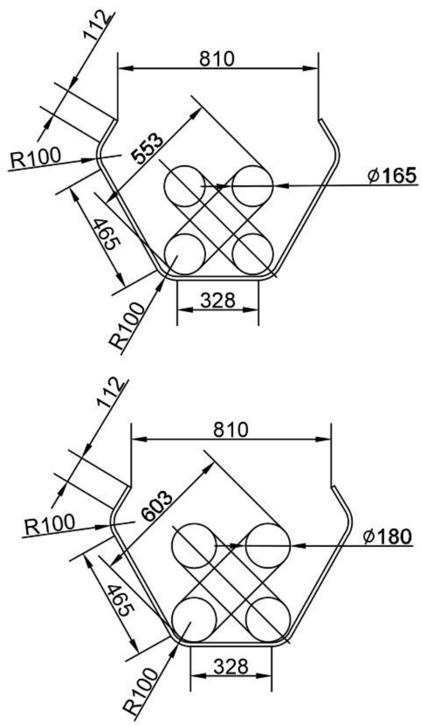


Figure 62 – 165 mm and 180 mm chain in chain chute (STX Norway Offshore Brattvaag, 2009)

There are also alternative methods for loading the chain to the respective chain locker. For example, some vessels have movable chain haulers, such as Island Victory, as shown in Figure 63. The chain haulers are skidded aft or forward to the individual chain locker. By using movable chain haulers, the need for chain chutes is eliminated. Movable chain haulers could improve stowing in the chain lockers, which could increase the capacity. SOFF could also fit portable chain haulers in any variant onboard their vessels.

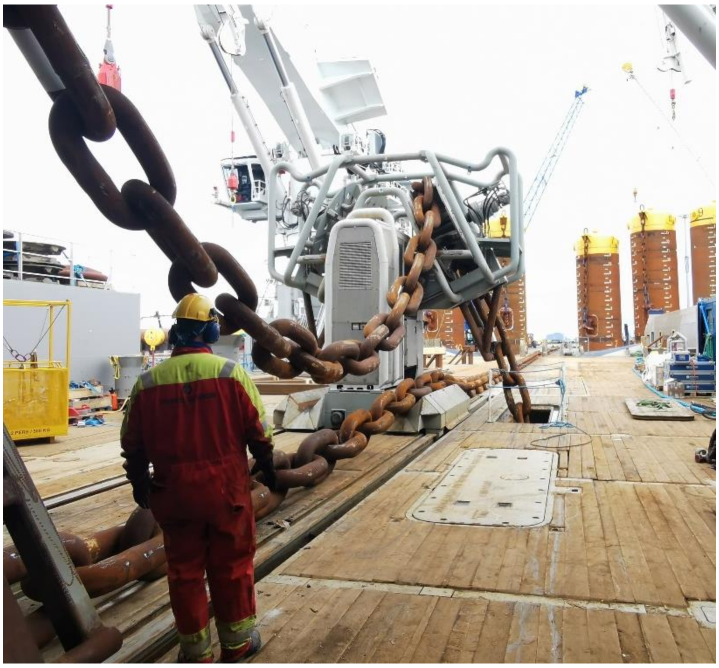


Figure 63 – Island Victory chain hauler (Island Offshore, 2020).

Far Sapphire has one chain locker less than N. Drott and N. Prosper, which has identical chain lockers. For all vessels, the chain lockers can handle any chain size, but the capacity is limited by maximum length, and its capacity will be reduced when using a chain with a large diameter. Usually, the chain is loaded in a pile inside the locker, and the pile of chain will slide as the angle of repose gets steeper. The actual chain locker capacity differs between loadings as the capacity relies on the chain to slide and stow in the best manner. Experience has shown that the angle of repose for larger chains are higher. Therefore, it could be a problem to stow the larger FOWT mooring chain properly inside the chain lockers. Generally, lower loading speeds makes the angle of repose higher, resulting in reduced capacity in the chain lockers.

Therefore, it may be necessary to install rollers in the chain chutes or similar solutions as the chain hauler onboard Island Victory to make the chain slip easier, increasing the chain loading speed. On the other hand, the chains used for FOWFs will probably be relatively new and less corroded than older chains. Smoother chains could result in the chain slides easier. Water and lubricants can also be used to make the chain smoother. The angle of the chain chute is steeper in the forward chain lockers than in the aft chain lockers. Experience has shown that the angle of repose is lower in the forward lockers than in the aft lockers because of the different angle of the chain chutes. As a result of this, the chain capacity in the forward lockers is normally higher than in the aft chain lockers.

Regarding Utsira Nord installation, the site is close to possible load-out bases, such as Stord (NVE, 2010). The short transit time to load-out bases could reduce the consequence of lacking chain locker capacity. Other mitigations for lacking chain size capacity is to implement other mooring designs for the FOWF. Designs utilizing smaller chains, other mooring line types, or clump weights to achieve the desired stiffness of the mooring lines.

Usually, the anchors are launched past the stern roller, resting on the back to avoid damaging the fluke, as shown in Figure 64. The anchor cannot be deployed on its back when using the DEA in permanent moorings. The restriction is because the mooring line will be twisted when turning the anchor using the propellers. Therefore, the anchor must be lifted past the stern roller to prevent damaging the anchor and to ensure that the anchor has the correct orientation. A crane or an A-frame can lift the anchor past the stern roller (Solstad Offshore, 2021).

Figure 64 – DEA resting on back for launching (Author's photo)

The vessels BP could be insufficient to proof tension the anchors, which should be proof tensioned with more than 400 tonnes, according to the estimate of Solstad Offshore (2021). The vessel with the highest proven BP is Island Victory, which features a BP of 477 tonnes (Island Offshore, n.d). However, a normal AHTS in the Norwegian AHTS fleet has a BP of approximately 250-400 tonnes (DOF Group et al., 2021). The BP of N. Prosper, N. Drott, and Far Sapphire is given in Table 4, and is insufficient to meet the required proof tension. Besides building more extensive and powerful vessels, one can meet the proof tension requirements using a reaction anchor. A reaction anchor can be utilized either by using the Stevtensioner, or by connecting a reaction anchor in the bow of the vessel. Both methods will give the vessel possibility to tension the anchors by using winch power instead of propulsion power.

The proof tension could be increased using a reaction anchor connected to the bow, compared to traditional proof tensioning, using the vessels BP. The challenge of using a reaction anchor in the bow is that the vessel is not built for such operations in the forecastle. The forecastle is made for mooring operations when berthing the vessel. There is also a safety issue that the buoy needs to be caught and connected to the pulling winch at forecastle by using a smaller vessel, such as the fast rescue craft. If the hook-up operation and arrangement on the forecastle are improved, the method could be an alternative to traditional proof tensioning. Such improvements could be a dedicated tugger winch, towing hook, and a shark jaw to secure the anchor line once on deck. Safer and less weather-dependent procedures need to be composed to recover the buoy safely. However, the challenge is the lack of space in the forecastle.

To achieve the highest proof tension, the Stevtensioner must be used, because the achieved tension when using a reaction anchor in the bow is limited to the winch power. The winch pulling force could be 40% of the desired horizontal proof tension when using the Stevtensioner (Vryhof, 2018, Vryhof Engineering, 2019).

One challenge with tensioning multiple anchors in one operation is that the soil conditions could be different between the anchors, which can cause unequal penetration of the anchors. A solution to circumvent the penetration problem could be by pre-tensioning each anchor with a given tension to ensure proper penetration before connecting the Stevtensioner to all anchors. The choice of method needs to be evaluated for each site to find the safest and cheapest installation. In difficult soil conditions, there could be favourable to proof-tension each anchor individually to ensure proper penetration.

6 Conclusion

The FOW industry in Norway is still under development, awaiting the white paper from the MPE. To be awarded a licence for constructing a FOWF in Norway, the company shall go through an application process. The content of the application is described in Havenergilova and Havenergilovforskrifta. Additional guidance will be described in the guide for offshore wind in Norway, which will be released on the 11th of June 2021 by the MPE (Olje- og energidepartementet, 2021). The constructors of FOWFs in Norway must be in accordance with regulations from MPE, NVE, PSA, and regulations from classification authorities.

The mooring designs available for FOWTs to date are mainly based on designs from the O&G industry. For medium depths, such as Utsira Nord, catenary mooring systems are well suited. The mooring line configuration in catenary mooring systems provides geometric stiffness as the restoring forces. The offset could be large, but the line tension is lower. The mooring line material is subject to costs, as well as the properties of the mooring design. Chain could increase the weight of the mooring line, and improve the catenary effect of the mooring system, resulting in increased restoring and resisting forces. Other catenary configurations, using a combination of chain and wire or synthetic fibre in combination with clump weights could reduce the need for large chain as well as reducing the total weight of the mooring line.

Taut mooring systems could be a cost-effective solution, using polyester or HMPE ropes. The restoring and resisting forces in taut mooring systems are provided by the elastic stiffness of the mooring lines. The offset in a taut mooring configuration is smaller than for catenary mooring configurations, and the line tension is high. HMPE or polyester ropes could reduce the total cost of the mooring system, and it reduces the requirements for the installation vessels. HMPE and Polyester is also cheaper and has better fatigue performance than chain.

The anchor type will also determine the design of the mooring system as the DEA cannot resist vertical loads. The suction anchor can resist loads in all directions, making it suitable for all mooring designs. The suction anchor is however more expensive in installation and hardware cost. To summarize, design of mooring systems is a compromise between line tension and floater offset.

Regarding SOFF's AHTS vessels, the modifications is mainly required by the large chain. The chain handling equipment, such as chain gypsy, chain hauler, chain guide and chain chutes could be modified to fit chain diameters up to 190 mm. The towing pins and locking arms cannot be used to secure the chain in the shark jaw. The shark jaw could be milled to fit up to 190 mm chain, without reducing the WLL. The centering devices cannot be used to move larger chains, but tugger winches as well as manoeuvring the vessel could give the same result. An A-frame are needed to launch the anchor, to ensure that the mooring line is not twisted.

To achieve the desired proof tension of DEAs, high BP, a Stevtensioner or a reaction anchor in the bow are needed. The method which could result in the highest tension is the Stevtensioner, applying a vertical load on a horizontal string.

To commercialize the installation of FOWTs, the industry needs simplification, as well as experience in installing anchor systems in a large quantity. Large FOWFs are planned in the next ten years, which will contribute to additional cost reductions. New technologies and methods specialized for FOWTs are expected to contribute to additional cost reductions.

7 References

4C OFFSHORE. 2021. *Kincardine - phase 2 Floating Wind Farm* [Online]. www.4coffshore.com: 4C Offshore. Available: https://www.4coffshore.com/windfarms/united-kingdom/kincardine---phase-2-united-kingdom-uk4n.html [Accessed 31.05. 2021].

ANDERSEN, M. T., WENDT, F., ROBERTSON, A., JONKMAN, J. & HALL, M. 2016. Verification and Validation of Multisegmented Mooring Capabilities in FAST v8. *International Ocean and Polar Engineering Conferance.* Rhodes, Greece: National Renewable Energy Laboratory.

ARANY, L. & BHATTACHARYA, S. 2018. Simplified load estimation and sizing of suction anchors for spar buoy type floating offshore wind turbines. *Ocean Engineering,* 159**,** 348-357.

AUTHOR'S ILLUSTRATION 2021.

AXTECH. n.d. *A-frames* [Online]. axtech.no: AXTech. Available: https://www.axtech.no/works/a-frames [Accessed 08.03 2021].

BABICZ, J. 2015. WÄRTSILÄ ENCYCLOPEDIA OF SHIP TECHNOLOGY.

BORLET, R. M., LARSEN, K., YTTERVIK, R. & NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET, F. F. I. I. F. M. T. 2016. Design and Optimization of Mooring Systems for Floating Wind Turbines. NTNU.

BOURBON OFFSHORE 2017. Mooring lines installation Procedure. *In:* BOURBON OFFSHORE (ed.).

BRIDON BEKAERT 2018. Advanced rope soulutions for the offshore oil & gas exploration, construction and production industries. https://www.bridon-bekaert.com/: Bridon Bekaert.

BUREAU VERITAS 2019. Classification and Certification of Floating Offshore Wind Turbines. https://marine-offshore.bureauveritas.com/ni572-classification-and-certification-floating-offshore-wind-turbines: Bureau Veritas.

BW IDEOL. n.d.-a. *A floating barge for offshore wind turbines* [Online]. BW Ideol. Available: https://www.bw-ideol.com/en/technology [Accessed 10.05 2021].

BW IDEOL. n.d.-b. *Our projects* [Online]. Available: https://www.bw-ideol.com/en/our-projects [Accessed 10.05 2021].

CAMPANILE, A., PISCOPO, V. & SCAMARDELLA, A. 2018. Mooring design and selection for floating offshore wind turbines on intermediate and deep water depths. *Ocean engineering,* 148**,** 349-360.

CASTRO-SANTOS, L. & DIAZ-CASAS, V. 2016. Floating Offshore Wind Farms. 1st ed. 2016. ed. Cham: Springer International Publishing : Imprint: Springer.

CHAPLIN, C. R. 2001. Torsional failure of a wire rope mooring line during installation in deep water. *In:* JONES, D. R. H. (ed.) *Failure Analysis Case Studies II.* Oxford: Pergamon.

DNV 2015. Offshore mooring steel wire ropes. www.rules.dnv.com: DNV.

DNV 2017. Geotechnical design and installation of suction anchors in clay. DNV.

DNV 2018a. Floating wind turbine structures. www.dnvgl.com: DNV.

DNV 2018b. Offshore Fibre Ropes. rules.dnvgl.com: DNV.

DNV 2018c. Offshore mooring chain. dnvgl.com: DNV.

DNV 2019a. Design and Installation of Fluke Anchors. dnv.com: DNV.

DNV 2019b. Design, testing and analysis of offshore fibre ropes. rules.dnvgl.com: DNV.

DNV 2020. Position mooring. DNV.

DOF GROUP, HAVILA SHIPPING, ISLAND OFFSHORE, KLINE OFFSHORE, OLYMPIC SUBSEA, SIEM OFFSHORE, SOLSTAD OFFSHORE & VIKING SUPPLY SHIPS 2021. North Sea AHTS Capacities. Tobias Bjørshol Roksvaag.

DOKKUM, K. V. 2020. *Ship Knowledge,* Vlissingen, The Netherlands, DOKMAR Maritime Publishers BV.

DRILLINGFORMULAS 2016. Suction Anchor Calculation. https://www.drillingformulas.com/suction-anchor-calculation/: DrillingFormulas.

EQUINOR 2017. Hywind Scotland 5 turbines at Buchan Deep August 2017. equinor.com: Equinor.

EQUINOR 2019a. Hywind Tampen PUD del II - Konsekvensutredning.

EQUINOR 2019b. Offshore vind - Konstrukjsonsutfordringer med flytende vind - Hywind. *In:* HASLUM, H. (ed.) *Konstruksjonsdagene 2019.* Petroleumstilsynet: Equinor.

EQUINOR 2021. Hywind Scotland remains the UK's best performing offhore wind farm. Equinor.com: Equinor.

EQUINOR. n.d-a. *Heidrun* [Online]. equinor.com: Equinor. Available: https://www.equinor.com/en/what-we-do/norwegian-continental-shelf-platforms/heidrun.html [Accessed 26.04 2021].

EQUINOR n.d-b. Hywind Scotland Fact Sheet. equinor.com: Equinor.

EQUINOR. n.d-c. *Hywind Tampen: the world's first renewable power for offshore oil and gas* [Online]. equinor.com. Available: https://www.equinor.com/en/what-we-do/hywind-tampen.html [Accessed 03.02 2021].

EUROPEAN WIND ENERGY ASSOCIATION 2013. Deep Water The next step for offshore wind energy. *In:* SARAH AZAU, STÉPHANE BOURGEOIS, ZOË CASEY, JACOPO MOCCIA, VILMA RADVILAITE, JULIAN SCOLA & WILKES, J. (eds.). windeurope.com: European Wind Energy Association.

FMCG n.d. FMCG Clump weights. FMCG.

FONTANA, C. M., HALLOWELL, S. T., ARWADE, S. R., DEGROOT, D. J., LANDON, M. E., AUBENY, C. P., DIAZ, B., MYERS, A. T. & OZMUTLU, S. 2018. Multiline anchor force dynamics in floating offshore wind turbines. *Wind energy (Chichester, England),* 21**,** 1177-1190.

GICON & GLOSTEN n.d. Glosten and Gicon partnership. glosten.com: Glosten.

GLOBAL MARITIME. 2019. *Successful suction anchor installation* [Online]. https://www.globalmaritime.com/news/successful-suction-anchor-installation: Global Maritime. [Accessed 05.04 2021].

GWEC 2010. Annual market update 2010. gwec.net: Global Wind Energy Council.

GWEC 2020. Global Offshore Wind Report 2020. gwec.net: Global Wind Energy Council.

HAVENERGILOVA. 2010. *Lov om fornybar energiproduksjon til havs* [Online]. Olje- og energidepartementet. Available: https://lovdata.no/pro/NL/lov/2010-06-04-21 [Accessed 02.03 2021].

HAVENERGILOVFORSKRIFTA. 2020. *Forskrift til havenergilova* [Online]. Norway: Olje- og energidepartementet. Available: https://lovdata.no/pro/SF/forskrift/2020-06-12-1192 [Accessed 02.03 2021].

HOLE, K. B. & LARSEN, K. 2018. Design of Mooring Systems for Large Floating Wind Turbines in Shallow Water. NTNU.

IACS 2016. Offshore Mooring Chain. iacs.org.uk: IACS.

IKHENNICHEU, M., LYNCH, M., DOOLE, S., BORISADE, F., MATHA, D., DOMINGUEZ, J. L., VICENTE, R. D., HABEKOST, T., RAMIREZ, L., POTESTIO, S., MOLINS, C. & TRUBAT, P. 2021. Review of the state of the art of mooring and anchoring designs, technical challenges and identification of relevant DLCs. www.corewind.eu: Corewind.

INTERMOOR n.d-a. Common Link Dimensions 16 to 210mm. *In:* 210MM, C. L. D. T. (ed.). Intermoor.com: InterMoor.
INTERMOOR n.d-b. Common Studless Link. *In:* DIMENSIONS, C. S. L. (ed.). Intermoor.com: InterMoor.
ISLAND OFFSHORE 2020. Island Victory chain hauler, "Helga".
ISLAND OFFSHORE. n.d. *Island Victory* [Online]. islandoffshore.com: Island Offshore. Available: https://www.islandoffshore.com/vessel/mv-island-victory [Accessed 04.03 2021].
JENSEN-ERIKSEN, N. 2015. Building trust: the history of DNV 1864–2014. *Scandinavian Economic History Review,* 63**,** 205-207.
KAI-TUNG, M., YONG, L., CHI-TAT THOMAS, K. & YONGYAN, W. 2019. *Mooring System Engineering for Offshore Structures,* Cambridge, MA, Gulf Professional Publishing.
KLINGAN, K. E. 2016. *Automated Optimization and Design of Mooring Systems for Deep Water.* NTNU.
KONGSBERG MARITIME. n.d-a. *Centering device for anchor handlig vessel* [Online]. Kongsberg.com: Kongsberg. Available: https://www.kongsberg.com/maritime/products/deck-machinery-and-cranes/deck-machinery/anchor-handling-vessels/centering-device-ahts/ [Accessed 23.02 2021].
KONGSBERG MARITIME. n.d-b. *Chain guides for anchorhandling vessel* [Online]. Kongsberg.com: Kongsberg Maritime. Available: https://www.kongsberg.com/maritime/products/deck-machinery-and-cranes/deck-machinery/anchor-handling-vessels/chain-guides-ahts/ [Accessed 23.02 2021].
KONGSBERG MARITIME. n.d-c. *Shark jaws for anchor handlig vessels* [Online]. Kongsberg.com: Kongsberg Maritime. Available: https://www.kongsberg.com/maritime/products/deck-machinery-and-cranes/deck-machinery/anchor-handling-vessels/shark-jaws-ahts/ [Accessed 23.02 2021].
KONGSBERG MARITIME. n.d-d. *Special handling winches for anchor handling vessel* [Online]. konsberg.com: Kongsberg Maritime. Available: https://www.kongsberg.com/maritime/products/deck-machinery-and-cranes/deck-machinery/anchor-handling-vessels/special-handling-winches-ahts/ [Accessed 04.03 2021].
LLOYDS REGISTER. 2021. *Offshore Wind* [Online]. Lloyds Register. Available: https://www.lr.org/en/clean-energy/offshore-wind/ [Accessed 02.05.2021 2021].
MACGREGOR. 2018. *Offshore Support Vessels* [Online]. www.macgregor.com: MacGregor Norway AS. Available: https://www.macgregor.com/globalassets/picturepark/imported-assets/79954.pdf [Accessed].
MINISTRY OF PETROLEUM AND ENERGY. 2013. *The Ministry* [Online]. government.no. Available: https://www.regjeringen.no/en/dep/oed/the-ministey/id755/ [Accessed 08.02 2021].
MINISTRY OF PETROLEUM AND ENERGY 2020. Opning av områda Utsira Nord og Sørlige Nordsjø II for konsesjonshandsaming av
søknader om fornybar energiproduksjon etter havenergilova. *In:* ENERGIDEPARTEMENTET, O.-O. (ed.). regjeringen.no.
MINISTRY OF PETROLEUM AND ENERGY 2021. Veileder for havvind kommer samtidig med stortingsmeldingen. regjeringen.no: regjeringen.no.
NICCOLO, B., GIULIO, F., ENZO, M. & CLAUDIO, B. 2020. Influence of Clumps-Weighted Moorings on a Spar Buoy Offshore Wind Turbine. *Energies (Basel),* 13**,** 6407.

NORDVIK, S. B. & LARSEN, K. 2019. Installation of Anchors for Mooring System of Floating Wind Turbines. NTNU.

NOV. 2018. *Lifting & Handling product portfolio* [Online]. www.nov.com: National Oilwell Varco. Available: https://www.nov.com/products/offshore-cranes [Accessed].

NS ENERGY. 2021. *Kincardine Floating Offshore Wind Farm, Scotland* [Online]. www.nsenergybusiness.com: NS Energy. Available: https://www.nsenergybusiness.com/projects/kincardine-floating-offshore-wind-farm-scotland/ [Accessed 31.05 2021].

NVE 2009. Vindkart for Norge. nve.no: Norges vassdrags- og energidirektorat.

NVE 2010. Havvind Forslag til utredningsområder. *In:* ENERGIDIREKTORAT, N. V.-O. (ed.). nve.no: NVE.

NVE. 2019. *Vindkraft til havs* [Online]. Norwegian Water Resources and Energy Directorate. Available: https://www.nve.no/energiforsyning/kraftproduksjon/vindkraft/vindkraft-til-havs/ [Accessed 02.06 2021].

OLJE- OG ENERGIDEPARTEMENTET. 2021. *Stortingsmeldingen om langsiktig verdiskaping fra norske energiressurser legges frem 11. juni* [Online]. Regjeringen.no: Olje- og energidepartementet. Available: https://www.regjeringen.no/no/aktuelt/fcfcv/id2847975/ [Accessed 02.06 2021].

PELASTAR n.d. Pelastar. pelastar.com.

PETROLEUM SAFETY AUTHORITY NORWAY 2020. Wind powers in place. *In:* NORWAY, P.-P. S. A. (ed.). Petroleum Safety Authority Norway.

PIVOTBUOY. n.d. *Pivotbuoy technology* [Online]. Available: https://pivotbuoy.eu/technology/ [Accessed 10.05 2021].

PRINCIPLE POWER 2020. Windfloat Atlantic. facebook.com: Principle Power.

PRINCIPLE POWER. n.d. *Windfloat* [Online]. principlepowerinc.com. Available: https://www.principlepowerinc.com/en/windfloat [Accessed 26.01 2021].

ROLLS-ROYCE MARINE 2009. Shark Jaw/Towpin. *In:* JAW/TOWPIN, S. (ed.).

RYSTAD ENERGY 2021. Offshore Wind Market Update February 2021. *In:* FLØTRE, A. D. (ed.).

SKAADEN, E. B. 2021. Normand Drott chain chutes.

SOLSTAD OFFSHORE n.d-a. Far Sapphire Detailed Vessel Spec. Solstad Offshore.

SOLSTAD OFFSHORE n.d-b. Normand Drott Detailed Vessel Spec. *In:* SPEC, N. D. D. V. (ed.). Solstad Offshore.

SOLSTAD OFFSHORE n.d-c. Normand Prosper Detailed Vessel Spec. Solstad Offshore.

STX NORWAY OFFSHORE BRATTVAAG 2009. Arrangement rig chain chutes. *In:* 725-437-018 (ed.) *AutoCAD.*

STX NORWAY OFFSHORE BRATTVAAG 2010. Arrangement of chain crossing table. *In:* TABLE, A. O. C. C. (ed.) *Autocad.*

SUBRATA, C. 2005. *Handbook of Offshore Engineering (2-volume Set),* Amsterdam, Elsevier Science.

SØRLIE, E. 2013. *Bearing capacity failure envelope of suction caissons subjected to combined loading.* Master, Norwegian University of Science and Technology.

TEUFELBERGER. *Full-locked coil rope* [Online]. www.teufelberger.com. Available: https://www.teufelberger.com/en/vollverschlossenes-forderseil-vvs.html [Accessed 26.05 2021].

TEUFELBERGER. *Half-locked coil guide rope* [Online]. www.teufelberger.com. Available: https://www.teufelberger.com/en/half-locked-coil-guide-rope.html [Accessed 26.05 2021].

USTUTT 2016. Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m.

VESTAS. 2021. *V164-9.5 MW at a glance* [Online]. www.vestas.com: Vestas. Available: https://www.vestas.com/en/products/offshore%20platforms/v164_9_5_mw#! [Accessed 31.05 2021].
VIK, E. 2021. Normand Prosper chain handling equipment.
VRYHOF Stevadjuster. vryhof.com.
VRYHOF 2018. Vryhof Manual. 8 ed. www.vryhof.com: Vryhof.
VRYHOF. 2020. *Windfloat Atlantic Represents Important Landmark for the Floating Wind Industry* [Online]. vryhof.com: Vryhof Anchors. Available: https://vryhof.com/cases/windfloat-atlantic-represents-important-landmark-for-the-floating-wind-industry/ [Accessed 26.01 2020].
VRYHOF ENGINEERING 2019. Generic Stevtensioning Procedure Using Reaction Anchor and AHV. *In:* ENGINEERING, V. (ed.).
WELLER, S. D., JOHANNING, L., DAVIES, P. & BANFIELD, S. J. 2015. Synthetic mooring ropes for marine renewable energy applications. *Renewable energy,* 83**,** 1268-1278.
WINDEUROPE. 2021. *Innovations in floating wind technologies key to further cost reductions* [Online]. WindEUROPE. Available: https://windeurope.org/newsroom/news/innovations-in-floating-wind-technologies-key-to-futher-cost-reductions/ [Accessed 05.04.21 2021].
XU, K., LARSEN, K., SHAO, Y., ZHANG, M., GAO, Z. & MOAN, T. 2021. Design and comparative analysis of alternative mooring systems for floating wind turbines in shallow water with emphasis on ultimate limit state design. *Ocean Engineering,* 219**,** 108377.
XU, K., MOAN, T., GAO, Z. & SHAO, Y. 2020. Design and Analysis of Mooring System for Semi-submersible Floating Wind Turbine in Shallow Water. NTNU.

8 Appendix 1

Summary of North Sea AHTS-fleet

Vessel name	Company name	LOA/Beam	BP	Deck Area	Source
Normand Prosper	Solstad Offshore	95 m/24 m	337 t	750 m^2	(Solstad Offshore, n.d-e)
Normand Drott	Solstad Offshore	95 m/24 m	339 t	760 m^2	(Solstad Offshore, n.d-c)
Normand Ranger	Solstad Offshore	91 m/22 m	280 t	760 m^2	(Solstad Offshore, n.d-f)
Normand Ferking	Solstad Offshore	89.35 m/22 m	239 t	760 m^2	(Solstad Offshore, n.d-d)
Far Sapphire	Solstad Offshore	92.7 m/22 m	272 t	798 m^2	(Solstad Offshore, n.d-a)
Far Sigma	Solstad Offshore	87.4 m/21 m	272 t	754 m^2	(Solstad Offshore, n.d-b)
Siem Pearl	Siem Offshore	91 m/22 m	285 t	800 m^2	(Siem Offshore, n.d-b)
Siem Diamond	Siem Offshore	91 m/22 m	284 t	800 m^2	(Siem Offshore, n.d-a)
Kl Saltfjord	K-line Offshore	95.2 m/24 m	397 t	750 m^2	(Kline Offshore, n.d-a)
Kl Sandefjord	K-line Offshore	95.2 m/24 m	390 t	750 m^2	(Kline Offshore, n.d-b)
Havila Venus	Havila Offshore	92 m/22 m	292 t	750 m^2	(Havila Shipping, n.d-b)
Havila Jupiter	Havila Offshore	92 m/22 m	294 t	750 m^2	(Havila Shipping, n.d-a)
Skandi Hera	DOF	93.8 m/23 m	277 t	800 m^2	(DOF Group, n.d-a)
Skandi Vega	DOF	109.5 m/24 m	350 t	1,070 m^2	(DOF Group, n.d-d)

Skandi Skansen	DOF	107.2 m/24 m	349 t	1,070 m^2	(DOF Group, n.d-c)
Skandi Iceman	DOF	93.5 m/24 m	319 t	800 m^2	(DOF Group, n.d-b)
Island Vanguard	Island Offshore	86.3 m/22 m	227 t	740 m^2	(Island Offshore, n.d-b)
Island Victory	Island Offshore	123.4 m/25 m	477 t	1,200 m^2	(Island Offshore, n.d-c)
Island Valiant	Island Offshore	93.4 m/22 m	230 t	860 m^2	(Island Offshore, n.d-a)
Olympic Zeus	Olympic	93.79 m/23 m	285 t	800 m^2	(Olympic Subsea, n.d)
Njord Viking	Viking Supply	85.2 m/22 m	247 t	750 m^2	(Viking Supply Ships, n.d-b)
Magne Viking	Viking Supply	85.2 m/22 m	251 t	750 m^2	(Viking Supply Ships, n.d-a)

DOF GROUP. n.d-a. *Skandi Hera* [Online]. dof.no: DOF Group. Available: http://www.dof.no/en-GB/DOF-Fleet/AHTS/Skandi-Hera [Accessed 04.03 2021].
DOF GROUP. n.d-b. *Skandi Iceman* [Online]. dof.no: DOF Group. Available: http://www.dof.no/en-GB/DOF-Fleet/AHTS/Skandi-Iceman [Accessed 04.03 2021].
DOF GROUP. n.d-c. *Skandi Skansen* [Online]. dof.no: DOF Group. Available: http://www.dof.no/en-GB/DOF-Fleet/CSV/Skandi-Skansen [Accessed 04.03 2021].
DOF GROUP. n.d-d. *Skandi Vega* [Online]. dof.no: DOF Group. Available: http://www.dof.no/en-GB/DOF-Fleet/AHTS/Skandi-Vega [Accessed 04.03 2021].
HAVILA SHIPPING. n.d-a. *Havila Jupiter* [Online]. havilashipping.no: Havila Shipping. Available: https://www.havilashipping.no/fleet/ahts/havila-jupiter [Accessed 04.03 2021].
HAVILA SHIPPING. n.d-b. *Havila Venus* [Online]. Havilashipping.no: Havila Shipping. Available: https://www.havilashipping.no/fleet/ahts/havila-venus [Accessed 04.03 2021].
ISLAND OFFSHORE. n.d-a. *Island Valiant* [Online]. islandoffshore.com: Island Offshore. Available: https://www.islandoffshore.com/vessel/mv-island-valiant [Accessed 04.03 2021].
ISLAND OFFSHORE. n.d-b. *Island Vanguard* [Online]. islandoffshore.com: Island Offshore. Available: https://www.islandoffshore.com/vessel/mv-island-vanguard [Accessed 04.03 2021].
ISLAND OFFSHORE. n.d-c. *Island Victory* [Online]. islandoffshore.com: Island Offshore. Available: https://www.islandoffshore.com/vessel/mv-island-victory [Accessed 04.03 2021].
KLINE OFFSHORE. n.d-a. *KL Saltfjord* [Online]. klineoffshore.com: Kline Offshore. Available: https://www.klineoffshore.no/kl-saltfjord/category847.html [Accessed 04.03 2021].

KLINE OFFSHORE. n.d-b. *KL Sandefjord* [Online]. klineoffshore.com: Kline Offshore. Available: https://www.klineoffshore.no/kl-sandefjord/category845.html [Accessed 04.03 2021].
OLYMPIC SUBSEA. n.d. *Olympic Zeus* [Online]. olympic.no: Olympic Subsea. Available: https://www.olympic.no/fleet--chartering/subsea--renewable/olympic-zeus / [Accessed 04.03 2021].
SIEM OFFSHORE. n.d-a. *Siem Diamond* [Online]. Siemoffshore.com: Siem Offshore. Available: https://www.siemoffshore.com/vessels/siem-diamond [Accessed 04.03 2021].
SIEM OFFSHORE. n.d-b. *Siem Pearl* [Online]. siemoffshore.com: Siem Offshore. Available: https://www.siemoffshore.com/vessels/siem-pearl [Accessed 04.03 2021].
SOLSTAD OFFSHORE. n.d-a. *Far Sapphire* [Online]. Solstad.com: Solstad Offshore. Available: https://www.solstad.com/vessel/far-sapphire/ [Accessed 04.03 2021].
SOLSTAD OFFSHORE. n.d-b. *Far Sigma* [Online]. Solstad.com: Solstad Offshore. Available: https://www.solstad.com/vessel/far-sigma/ [Accessed 04.03 2021].
SOLSTAD OFFSHORE n.d-c. Normand Drott Detailed Vessel Spec. *In:* SPEC, N. D. D. V. (ed.). Solstad Offshore.
SOLSTAD OFFSHORE. n.d-d. *Normand Ferking* [Online]. Solstad.com: Solstad Offshore. Available: https://www.solstad.com/vessel/normand-ferking/ [Accessed 04.03 2021].
SOLSTAD OFFSHORE n.d-e. Normand Prosper Detailed Vessel Spec. Solstad Offshore.
SOLSTAD OFFSHORE. n.d-f. *Normand Ranger* [Online]. Solstad.com: Solstad Offshore. Available: https://www.solstad.com/vessel/normand-ranger/ [Accessed 04.03 2021].
VIKING SUPPLY SHIPS. n.d-a. *Magne Viking* [Online]. vikingsupply.com: Viking Supply Ships. Available: https://vikingsupply.com/vessel/magne-viking/8 [Accessed 04.03 2021].
VIKING SUPPLY SHIPS. n.d-b. *Njord Viking* [Online]. vikingsupply.com: Viking Supply Ships. Available: https://vikingsupply.com/vessel/njord-viking/9 [Accessed 04.03 2021].

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