University of
South-Eastern Norway

MARINE OPERATIONAL CHALLENGES WHEN INSTALLING FLOATING OFFSHORE WIND TURBINES

A NORWEGIAN PERSPECTIVE FEATURING WINDWORKS JELSA

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MASTER THESIS

May of 2022

ABSTRACT

BACKGROUND

Norway is a modern and technologically advanced energy nation with comprehensive experience from the offshore petroleum industry, close proximity to marine environments and deep-water fjords and waterways. The national authorities and actors from various industries acknowledge the importance of a green transition. Recent floating wind projects with positive results have shown great opportunities, but the floating wind industry is still in a beginning phase, lacking relevant experience and guidelines. LCOE for floating wind is often higher compared to land-based and fixed turbines. Optimizing marine activities can reduce costs.

PURPOSE

To identify marine operational challenges when installing floating offshore wind turbines using spar and semi-submersible foundations.

METHODOLOGY

A qualitative method was applied for this thesis. As research design, a systematic literature review was conducted. This was used to collect and analyze data from existing documents and literature to extract important correlations and relevant information regarding the conditions in the installation phase for the floating wind industry.

CHALLENGES

Challenges are related to port capabilities, assembling components, towing and lifting components, offshore installation processes, weather, experience, costs, vessels and component behaviors when floating.

CONCLUSION

Challenges related to port suitability, towing, and lifting operations related to mounting turbines on floating foundations were identified as key topics when installing floating offshore wind turbines using spar and semi-submersible foundations. Metocean uncertainty, risk of unexpected incidents and lack of experience were factors related to the challenges.

Keywords: Floating offshore wind, marine operations, spar, semi-submersible, WindWorks Jelsa, Hywind, WindFloat

Acknowledgement

I would like to express special thanks to my supervisor for providing guidance and support throughout this project. I would also like to thank my family for the amazing support they have given me. Special gratitude goes out to my employer for the support and for offering flexible hours, enabling me to conduct this research and write my master thesis!

By conducting this research on floating offshore wind, I was able to explore a topic that was quite new for me. I found it very interesting to learn about how this industry works today and how it may need to develop and adapt in order to be competitive in the future. While I had some previous experience related to port logistics, the technical aspects of towing and lifting operations were new but exciting topics to explore.

Terms and abbreviations

Athwartship – Being across the ship from side to side

Ballast – Any heavy material carried temporarily or permanently in a vessel/structure to achieve desired draft and stability

Beaufort scale – Scale and tool to measure and express wind force

Buoyancy – The ability of something to float in water or other fluid

Draft – Distance between the waterline and the deepest point of the vessel/structure

Displacement – The weight of the water that a vessel/structure pushes aside when it is floating

Dry-dock – A basin that can be flooded and also drained to a allow a vessel/structure to be floated and then also made to rest on a dry platform

FOWT – Floating Offshore Wind Turbine

Heave – A measure of extent to which a nautical vessel/structure goes up and down in a short period of time

KPI – Key Performance Indicators

LCOE – Levelized Cost of Energy

Marine operations – *Non-routine operation of a limited defined duration related to handling of object(s) and/or vessel(s) in the marine environment during temporary phases. In this context the marine environment is defined as construction sites, quay areas, inshore/offshore waters or sub-sea*

Mating (in this context) – The turbine is mounted on top of the foundation

Metocean – Sea state conditions including winds, waves and currents

Pitch – The measure of extent to which a nautical vessel/structure rotates on its athwartships axis, causing bow and stern to go up and down (see description for "Athwartship")

Roll – The tilting motion of a vessel/structure from side to side

Slip-forming – A construction method where concrete is poured into a continuously moving form

Spar – Type of floating foundation

Wave period – The measure of time it takes for the wave cycle to complete. One wave cycle equals one completion of a wave's repeating up-and-down pattern

Wave Spectrum (Spectra) – The distribution of wave energy with frequency and direction concerning ocean surface waves

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1. Introduction

In order to reach the emission reduction goals by 2050, a major upscale in renewable energies is needed, including green hydrogen and renewable electricity. Almost 80% of the planet's offshore wind resources are in waters with depths of more than 60 m. Here are the bottom-fixed wind turbines no longer feasible, which has created a significant opportunity for floating offshore wind technology (Ibrahim et al., 2022, p. 1-3). Floating wind could represent a third of all offshore wind capacity by 2050, as long as national governments deliver on their ambitions and plans (WindEurope, 2021b). However, floating turbines still tend to have higher LCOE compared to land-based and fixed offshore turbines, partially due to floating foundation characteristics (Hill, 2020, p. 239-241). In order to compete, upscaling floating turbines can lead to significant reduction in LCOE (Kikuchi & Ishihara, 2019, p. 2 & 11). Optimizing marine activities related to installing floating offshore wind farms can also offer cost reductions (Desmond et al., 2022). WindEurope highlights the need for significant investments in relevant ports in order to upgrade and expand their abilities to handle turbines which are constantly getting bigger (Cecchinato et al., 2021, p. 7-8).

While fixed offshore turbines require installation on the seabed in shallow waters, floating turbines are much more flexible related to water depths, which can offer better wind conditions and less impact on coastline and population. It is also possible to finalize floating turbines in port and tow them directly to the site offshore for anchor hook-up. This avoids complex installation activities offshore, and most marine operations can be executed using conventional vessels. However, projects can be restricted to limited weather windows, limited experience in the field and limited amount of suitable ports. This research has the purpose of identifying some of the marine operational challenges when installing floating offshore wind turbines. This is to gain insight to what the industry needs to focus on for optimizing marine operations in order to ensure a safe, efficient and competitive industry. The research is written from a Norwegian perspective and uses a development-project called WindWorks Jelsa as setting to implement findings in order to clarify and identify even more relevant challenges.

1.1 Background for choice of topic

Norway is a modern, industrial and technologically advanced energy nation with comprehensive experience from the offshore oil- and gas industry, close proximity to marine environments and access to deep-water fjords and waterways. The national authorities as well as actors from various industries acknowledge the importance of a green and climate friendly transition. Positive results from recent floating wind projects have shown great potential in developing more floating wind farms which can produce large amounts of sustainable energy. That is why projects are now in motion towards developing floating wind farms in the Norwegian part of the North Sea. This can be the start of a new industrial venture in Norway. But in order to make this happen, the offshore industry and developers must acknowledge and adapt to relevant challenges when installing and handling floating offshore wind turbines. Proper strategies regarding choice of design, choice of ports and facilities, choice of vessels and choice of marine operations must be in place based on corresponding risk assessments for the various alternatives. These topics and operational questions gave me motivation and desire to conduct a research with the purpose of creating an understanding of challenges for relevant designs within the various stages of marine operations needed to build and install floating offshore wind turbines.

1.2 Research question

What are the marine operational challenges related to installing floating offshore wind turbines using spar and semi-submersible foundations?

2. Research methodology

A qualitative method was applied for this thesis. While a quantitative method applies numbers and statistical procedures to collect and analyze data, the qualitative methodology has higher focus on text and less formal procedures regarding collecting and analyzing the data (Johannessen et al., 2016, p. 237). This methodology concept has the strength of generalizing the theory by disclosing phenomena, establishing or finding casual links, as well as investigating if certain features must be addressed or included for something to occur. This can be achieved by selecting a limited number of units based on a specific intention. The selected units should be of particular interest and able to add valuable information (Jacobsen, 2018, p. 237). The qualitative method I used was the guideline for this thesis.

2.1 Problem analysis

When conducting a research on a specific topic, I figured I would gain an increasing comprehension of the topic as the process evolved. Terms and topics could change which is why a problem analysis was recommended (Johannessen et al., 2016, p. 67). In starting phases I quickly discovered the wide range of directions my topic could take me in. The below problem analysis shows how I narrowed down my view of inclusion for this thesis.

First, I needed to determine main terms. The term “marine operations” is often used in this research and is described in the glossary list. The generic term covers activities in the marine environment such as load-out/load-in, transportation/towage, lift/lowering, tow-out/tow-in, float-over/float-off and construction afloat (DNV GL, 2015, p. 8).

Scoping searches showed that the FOWT components are often constructed in separate places. The towers may have been built in Holland, the blades in Germany, the nacelle in Denmark and the foundation in Spain. All components are then shipped to a suitable port for assembly before the complete FOWT is towed offshore. At the offshore site, huge anchors are ready to be linked to the FOWT. After commissioned, the operation and maintenance phase begin, which also requires vessel assistance.

2.1.1 Limiting the research

I quickly discovered challenges related to most of the marine operations applicable when installing a FOWT, including the logistics and handling of heavy nacelles, long and fragile blades, and large tower sections. However, what seemed to be unique with a FOWT compared to fixed turbines were topics related to the installation and handling of the floating foundations. The research was therefore limited to mainly focus on the marine operations related to handling the foundations. This includes tow-in/-out and mating of turbine and foundation. The actual transport at sea, operations related to ballasting and offshore anchoring operations were excluded. While several FOWT concepts have been introduced to the industry over the recent years, scoping searches indicated that the spar and semi-submersible types were favorites. The research was therefore limited to these two types in order to mitigate the complexity.

2.2 Research design

To use a method means to follow a specific path towards a goal. To avoid drawing quick conclusions of contexts and with lack of evidence, it was important to follow a suitable methodology and define clear evidential requirements. Systematics, thoroughness and transparency were important characteristics for this research. This could help evaluating the probability of whether assumptions were true or not (Johannessen et al., 2016, p. 25-26). Based on the topic and the limited number of relevant completed projects, it was decided to do a systematic literature review. This qualitative method focuses on collecting and analyzing data from existing documents and literature to extract important correlations and relevant information regarding the specific conditions in the industry which I wished to study (Jacobsen, 2018, p. 97, here from Grønmo, 2004).

The guidebook by Boland et al. (2017) with how to do a systematic review includes a 10-step approach which was used as contributing guidelines. Step 3 concerns literature searching and recommends an adequately balanced main search. In terms of specificity, identifying relevant evidence was important. In terms of sensitivity, avoiding the use of too many pieces of evidence and irrelevant sources was also recommended (Boland et al., 2017, p. 65). I wanted to be thorough and openminded in my searches, but at the same time avoid the excessive use of many small pieces from less relevant sources. I also had to identify and assess the type of evidence available. I decided to mainly use ‘published literature’ as evidence, but I also used ‘grey literature’ in an active but critical way to help gain insight and direction, as well as to retrieve published literature from the reference lists.

The time dimension for the research was also addressed. With Hywind Scotland and WindFloat Atlantic as pioneering projects with first power in 2017 and 2019, I decided to limit allowable data based on their year of start-up. This to ensure more accurate and updated content. For more general topics concerning marine operational challenges also applicable in the floating offshore wind industry, including towing and lifting, I decided to use a 10-year historical search limit. In order to search for evidence, bibliographic databases were identified. With guidance from my supervisor and the USN library, the interdisciplinary reference database ‘Web of Science’ by Clarivate was elected as the main database for retrieving scientific studies. The USN inter-library loans system enabled me to obtain full text papers for most of the potentially eligible references. In order to find supporting facts, publications and reports, ‘*Google*’ was used as main tool. It was decided to limit searches to the English language when searching for scientific studies in order to enable a wider audience to validate the findings.

A systematic screening and selection process were conducted for each search in order to only include data related to the research question. Before reviewing the search results, it was recommended to determine inclusion and exclusion criteria to be applied in the process (Boland et al., 2017, p. 81).

Table 1

Inclusion (One or more criteria had to be met)	Exclusion (One or more criteria had to be met)
Content related to the building, handling, transporting and/or installing of floating platforms for the offshore wind industry.	Content only related to operation and maintenance of floating wind turbines.
Content related to challenges when towing floating structures.	Content only related to decommissioning of floating wind turbines.
Content related to lifting floating structures at sea.	Content only related to other platform designs than spar and semi-submersible types.
Content related to port challenges and requirements within the floating offshore wind industry.	Content only related to the design and performance of floating offshore wind turbines.
Content related to economic challenges during the installation of floating offshore wind farms.	Content only related to the construction and/or material usage when building floating wind turbines.

2.2.1 WindWorks Jelsa

In order to clarify topics and challenges, as well as have the ability to discover even more relevant marine operational challenges, I decided to use a Norwegian development project called WindWorks Jelsa. This project had not gotten its approvals yet, but preliminary plans include some information regarding the preferred port and facility at Norsk Stein Jelsa, some investment plans, spar and semi-submersible concepts as choice of foundations, and some relevant challenges. In order to retrieve updated information of the project and Norsk Stein Jelsa, I established a dialogue with a senior advisor in NorSea (developer), and the lead ship agent at Norsk Stein. In discussion part 2, general topics and challenges was implemented in the setting of WindWorks Jelsa in order to clarify and extract an even better comprehension of the relevant challenges when installing floating offshore wind turbines.

2.3 Reliability and validity of the research

A fundamental principle in any research is to assess the data's reliability as synonymous and with accuracy. It is also important to assess the data's validity (Johannessen et al., 2016, p. 40). These were determining factors when selecting and extracting data during the research review. Many scientific studies as well as official websites were excluded due to lack of relevance, lack of reference info and lack of adequate formal structures.

2.4 Ethical considerations

It was important to conduct ethical consideration throughout this research in order to protect sources and give credit to the owner of the data. All the data I extracted from sources and used in my research got proper reference according to guidelines. Information received from Norsk Stein and NorSea was given reference based on their own desires. It was also important that I stayed neutral when presenting the literature and other external information. This to ensure that the content was not twisted.

3. Reviewed literature

Table 2

Author (Year)	Research context	Title	Challenges
Rinaldi et al. (2021)	UK	Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms	Uncertainty when operating in harsh conditions, uncertainty in how offshore wind turbines adapt to a more dynamic environment, and uncertainty in availability of suitable port facilities. These uncertainties together with limited experience in the field leads to an overall uncertainty in KPIs which makes it challenging to evaluate the success rate in advance.

Ren et al. (2021)	Norway	Active heave compensation of floating wind turbine installation using a catamaran construction vessel	The foreseen increase of floating offshore wind turbines will lead to higher installation and maintenance costs. The study acknowledges the challenge of dynamic environments when installing FOWT which can increase costs.
Cordal-Iglesias et al. (2020)	Spain	Framework for development of an economic analysis tool for floating concrete offshore wind platforms	A potential challenge is to make calculations of main economic aspects of offshore wind platforms built in concrete considering different locations of the European Atlantic Arc.
Barter et al. (2020)	USA	A systems engineering vision for floating offshore wind cost optimization.	The floating offshore wind industry is still small and lack own methods for manufacturing, installing, operating and maintaining the turbines/farms. Investments in developing maintenance strategies and new vessels for the industry is unlikely to occur until the industry is more established.
Zhao et al. (2019)	Norway	Numerical study on the feasibility of offshore single blade installation by floating crane-vessels	The motions from waves create an operational challenge for floating vessels. Using a mono-hull vessel to execute a blade installation at sea can be a more challenging operation compared to using a semi-submersible vessel. Jack-up vessels can offer a stable elevated working platform but are limited by water depth. Shortage of crane

			vessels is therefore a critical issue for the offshore wind industry.
Ren et al. (2021)	Holland + Norway	Model-free anti-swing control of complex-shaped payload with offshore floating cranes and a large number of lift wires.	Lifting operations become more challenging when structures/payloads grow in size and weight. Larger cranes/vessels are required.
Sanchez et al. (2019)	Spain	Foundations in offshore wind farms: Evolution, characteristics and range of use. Analysis of main dimensional parameters in monopile foundations	Within the period of 2009-2018, we have seen growth in turbine power, turbine length and diameter, and in depth and distance to coast (Sanchez et al., 2019, table 6.). If this trend continue, so can marine operational challenges.
Zhang et al. (2019)	China	Numerical analysis of offshore integrated meteorological mast for wind farms during wet towing transportation	When towing, shorter towrope length can increase pitch and heave motion responses, as well as the risk of towed object crashing into tugboat. Longer towrope can increase roll motion.
Le et al. (2021)	China	Towing performance of the submerged floating offshore wind turbine under different wave conditions	When the wave period decreases during towing, the heave, pitch and roll motions can increase. Higher wave height can also have impact on towing performance.
Li et al. (2021)	Norway & Russia	Assessment of operational limits: Effects of uncertainties in sea state description	Motion responses of a semi-submersible vessel can be much lower compared to a mono-hull vessel, causing this type to have higher operability with higher allowable sea states. However,

			semi-submersible vessels are much more costly to use.
Verma et al. (2019)	Norway	A comprehensive numerical investigation of the impact behavior of an offshore wind turbine blade due to impact loads during installation	Lifting operations using floating crane vessels is critical and can cause damage to structures for instance when installing an offshore wind turbine blade due to motions of the sea.
Judge et al. (2019)	Ireland & Norway	A lifecycle financial analysis model for offshore wind farms	For crews to access a wind turbine at sea, the limited significant wave height is a relevant factor for availability. Increased dry CAPEX and number of turbines have the most effect on the total installation cost.
Lee et al. (2021)	South Korea	An optimization model of tugboat operation for conveying a large surface vessel	A floating crane can collide with quayside if not positioned with a safe distance during operation. Waves reflected by the quay as well as waves disturbed by tugboats can cause irregular conditions. For the floating crane mentioned in this study, it is recommended to have a weather limit of Beaufort scale 5 or less for safe operation. When external forces are large, including for instance irregular winds, waves and/or currents, more

			thrust force from tugboats is required to follow the designated path for a tow.
Guachamin-Acero & Li. (2018)	Norway	Methodology for assessment of operational limits including uncertainties in wave spectral energy distribution for safe execution of marine operations	Failing to understand operational and allowable limits, including wave height, peak period etc., can cause operational risk. Uncertain operational limits, including variability in the wave spectral energy distribution, can also be a challenge.
Aliyar et al. (2021)	India	Experimental investigation of offshore crane load during installation of a wind turbine jacket substructure in regular waves	During lifting operations of a wind turbine jacket substructure, heave, roll and pitch can occur and vary for instance based on the wave period. The energy of the sea can lead to a peak crane load of up to 2-3 times the actual weight of the structure.
Ramachandran et al. (2021)	Ireland	Floating offshore wind turbines: Installation, operation, maintenance and decommissioning challenges and opportunities	Spar-type has high draft, potentially unstable motion during mating and tighter weather constraints than other types. Semi-submersible type is more sensitive to wave height during towing. Optimizing the marine operations required throughout the life cycle of a wind farm. Installation locations can offer challenges in terms of bad weather conditions.

			There is also lack of standards related to installation approaches, costs and time for each operational task.
Cecchinato et al. (2021).	Belgium	A 2030 Vision for European Offshore Wind Ports – Trends and opportunities	Lack of suitable ports for handling and installing FOWTs. The floating wind industry is growing, and the upcoming volumes, size and weight of offshore wind components require suitable ports and vessels. Lack of suitable crane vessels could be the case in the future.
Crowle & Thies (2022)	UK	Floating offshore wind turbines port requirements for construction	Steel- and concrete-type spar both have deep draft. Minimum waterway requirements can offer challenges. Float-out of a semi-sub from dry-dock needs precision in order to prevent trim/heel.
Crowle & Thies (2021)	UK	Installation innovation for floating offshore wind	High number of vessels required for installing FOWTs. Uncertainties can extend schedules and increase CAPEX.
Mathern et al. (2021)	Switzerland	Concrete support structures for offshore wind turbines: Current status, challenges and future trends	Concrete support structures require adequate area for assembly, formwork, casting etc. Concrete endurance must be evaluated.

3.1 Spar and Semi-submersible foundations

Spar-type has high draft, potentially unstable motion during mating and tighter weather constraints than other types. Semi-submersible type is more sensitive to wave height during towing (Ramachandran et al., 2021, p. 10-11).

3.1.1 Spar and Hywind

The spar-type floater, also known as the Hywind concept, was developed by Equinor ASA, and used in their pilot and demonstration-scale floating wind farm called Hywind – Scotland (Ramachandran et al., 2021, p. 3). The spar, also referred to as a spar-buoy, is constructed using either steel or concrete as main construction materials. Both steel and concrete-based spar-foundations have very deep drafts and achieve their intact stability from adding solid ballast to their base (see fig.1). Depending on the size, a steel-type spar weighs between 2500 and 5000 tons before ballasted (Crowle & Thies, 2022, p. 2 & 4).

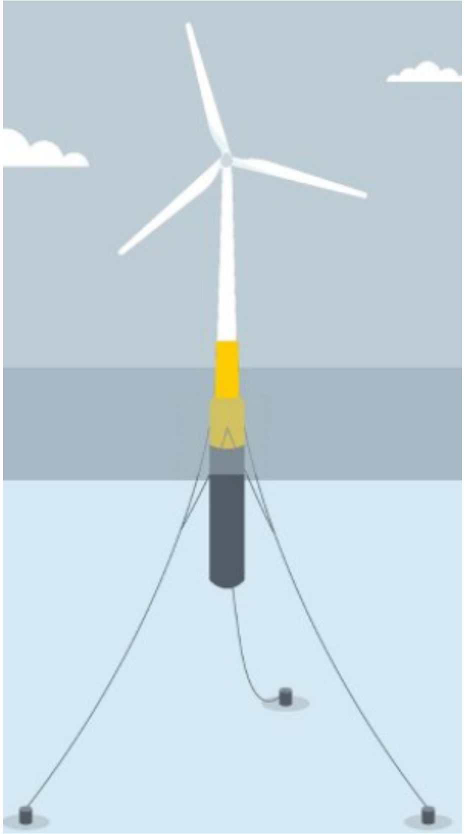

Figure 1. Spar concept example. (Equinor, 2021)

The advantage of concrete-type structures is the increased robustness when exposed to the environment and less need for maintenance compared to structures made of steel. That being said, the use of concrete structures for floating wind has been limited to a few nearshore wind farms. Building offshore concrete structures require assembly and lay-down areas for placing and reinforcing steel, doing formwork, as well as casting and curing the concrete. Concrete endurance and crack limitations must be addressed based on load and temperature effects (Mathern et al., 2021, p. 9-11).

According to Equinor's official website, the spar-type design which they used in the Scotland project is just over 90 meters in overall length. When not in ballast, it can be transported/towed vertically through the water to a designated location where it is filled with seawater to make it upright. The seawater is then partially replaced by solid ballast and the draft is adjusted. This spar will then have a draft of 85-90 meters when upright and a total weight (displacement) of about 12.000 tons. Its diameter above the surface is 9-10 meters while the submerged part is 14-15 meters in diameter (Equinor, n.d.a). For a port to be fit for the handling of a spar-buoy, the recommended minimum channel width is 90 meters (Crowle & Thies, 2022, p. 6).

Based on the 2021 discussion paper by the European academy of wind energy, the spar-type foundation requires deep water ports and sheltered areas during installation. The port must be suitable for heavy-lift vessels to enter and operate in a safe matter, and the waterway must be suitable for challenging towing operations (Ramachandran et al., 2021, p. 10). Due to its high draft, the discussion-paper suggest that the spar-type structure require offshore assembly, but at the same time, sheltered coastal areas are required for some installation operations (Ramachandran et al., 2021, p. 3). Assembly of the steel-based spar structure is performed onshore by building the hull horizontally. The structure can then be loaded onto a heavy transport vessel and taken to a sheltered location for float-off. If choosing a concrete-based spar instead of steel, the construction process is different. The structure is then slip formed vertically inside a dry dock, before being moved to a deep-water location for further slip forming. In final stages, solid ballast is poured into the base (Crowle & Thies, 2022, p. 3-4).

Figure 2. Hywind turbine mating operation with the Saipem 7000. Credit: Equinor (Seglem, 2017)

The choice and composition of ports depends on infrastructure characteristics and space available related to type of floating platform for each project. For the Hywind Scotland project, the developers used a collaborative approach between ports in order to conduct the different project activities. The spar-foundations were built in a shipyard in Spain before being sent to a Norwegian port for further assembly and mating of the turbines (Ramirez et al., 2020, p. 19). Due to the shape and size of the spar-foundation, weighing about 2.500 tons unballasted, the foundation requires complex logistics related to transportation (Ramirez, 2020, p. 12).

The spar structures were built in Fene, Spain, and are 91 meters long (Equinor, n.d.d). After being construction, the structures were loaded onto a semi-submersible vessel called Albatross. This was done by using trailers to move the structures onto the vessel followed by assembling full grillage to secure them safely. The vessel then transported the spar structures to the site in Stord, Norway. After arrival on site, removable parts of the grillage were dismounted. This enabled the vessel to use its submersible capabilities which further enabled the spar structures to come afloat (Semar, n.d.). In Stord, the spar-foundation was towed from a quay to a sheltered but deep-water location in the fjord outside Stord (see fig.2), where it was ballasted and made upright (Equinor, n.d.b). The ballast consisting of magnetite was inserted using a rock installation vessel (Ramachandran et al., 2021, p. 3). The semi-submersible crane vessel *Saipem 7000* lifted the fully assembled turbine from the quay in Stord and out and onto to the ballasted spar-buoy positioned in the fjord (Equinor, n.d.b).

Metocean assessments were conducted before the Hywind Scotland project was started. This was done to identify suitable weather windows to perform marine operations. Wind and wave conditions throughout a full year were relevant data when assessing allowable conditions and durations for marine operations involved in this project. Different limits for significant wave heights and winds speeds were used to calculate predicted weather windows. For instance, significant wave of 2 meters and wind speed of 10 m/s for 48 hours were used as limiting factors. Assessment results suggested that the months from April to September were likely to have the widest operational time windows (Ramachandran et al., 2021, p. 4).

For the on-going offshore wind project called Hywind Tampen, concrete-type spar foundations were slip-formed in one location and then towed to another for further slip-forming (Haugaland Vekst, 2021). This second step of slip-forming was conducted in close proximity to shore using floating barges. After the concrete spar foundations were completed, they were further towed to Sløvåg for next step (E24, 2022). Equinor uses the Wergeland base in Sløvåg (Norway) as location for the installation and mating of the offshore wind turbines onto the floating structures (Kommunal- og moderniseringsdepartementet, 2021, p. 12). According to sources, Equinor uses a fixed onshore crane instead of a floating crane vessel to conduct the heavy lifting operations. The crane is a PTC-200 delivered by Mammoet (Wergeland Group, 2022). Its lifting capacity is 3.200 tons at 50 meters extraction (Mammoet, n.d.).

3.1.2 Semi-submersible

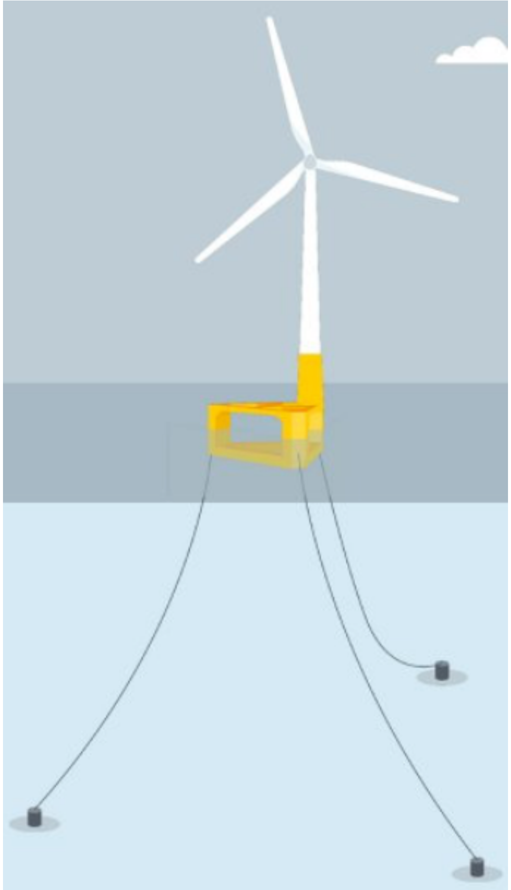

Figure 3. Semi-submersible concept example. (Equinor, 2021)

A full-scale semi-submersible wind turbine can be completely constructed and assembled onshore and then towed to the wind farm location offshore (Ramachandran et al., 2021, p. 7). According to WindEurope in March 2021, the only large-scale semi-submersible commercial floating wind farm currently completed, was the WindFloat Atlantic (WindEurope, 2021a). WindFloat Atlantic is located off the coast of Portugal and uses semi-submersible platforms developed and built by Principle Power. This design consists of three steel-based columns connected to each other in a triangular formation using bracings (see fig.3 & 4). The weight of the complete foundation for a single turbine is about 2.500 tons and has a draft of about 10 meters during transport (Ramirez et al., 2020, p. 11). According to sources, most recent semi-sub designs have the turbine either mounted in one corner or on one side in order to maximize the use of onshore crane capacity. Other concepts have several turbines in a single platform (Crowle & Thies, 2022, p. 3).

Based on data from one of the WindFloat Atlantic partners, Repsol, the assembling of the semi-submersible platform was conducted in dry-docks which enhanced accessibility and cost-effectiveness. When floated, the height of the platform is 30 meters and the distance between each column is 50 meters (Repsol, 2019). If conducting a float-out from a dry-dock, the semi-submersible platform might require buoyancy in order to minimize draft and to have zero trim and heel during the operation (Crowle & Thies, 2022, p. 3).

The WindFloat Atlantic project consists of three semi-submersible units, but they were not all built in the same location. One foundation was built in a shipyard in Fene (Spain) and then sent to the nearby port of Ferrol for mating the wind turbine. The complete unit was transported to Viana do Castelo in Portugal before final tow-out. The two other platforms were built by ASM Industries in Setúbal and Aveiro, Portugal (Ramirez et al., 2020, p. 19).

Figure 4. WindFloat semi-submersible assembly in port. Credit: DOCK90 (Power-technology, 2020)

The semi-submersible foundation is more sensitive to wave height limits during towing, compared to the spar-type, which makes it a challenge to find right weather windows for marine operations. Towing of floating offshore wind turbines is a continues operation and it is challenging to halt the operation in the middle of the towing process. It is therefore recommended to identify safe havens along the designated towing route in order to avoid difficulties in case of rough weather. For the WindFloat and Kincardine projects, some of the semi-submersible foundations were constructed in one place and assembled and mated with the turbines in another. This involves extra towing or the use of specialized heavy-transport vessels. If choosing ports with shipyards where both construction, assembly and mating of foundation and turbine can take place, unnecessary transport can be avoided. Due to a much shallower draft compared to the spar solution, assembly and mating of the turbine can usually be conducted alongside the quay (Ramachandran et al., 2021, p. 7 & 10).

3.2 General weather conditions

Uncertainty when operating in harsh conditions and uncertainty in how offshore wind turbines adapt to a more dynamic environment are potential operational challenges when installing floating wind turbines. These uncertainties together with limited experience in the field leads to an overall uncertainty in KPIs which makes it challenging to evaluate the success rate in advance (Rinaldi et al., 2021, p. 2).

Failing to understand operational and allowable limits, including wave height, peak period and so on, can cause operational risk. Uncertain operational limits, including variability in the wave spectral energy distribution, can also be a challenge (Guachamin-Acero & Li, 2018, p.

192-193). Installation locations can offer challenges in terms of bad weather conditions (Ramachandran et al., 2021, p. 10-11). The motions from waves can create an operational challenge for floating vessels (Zhao et al., 2019, p. 442). For crews to access a wind turbine at sea, the limited significant wave height is a relevant factor for availability (Judge et al., 2019, p. 376).

Having a general understanding of the metocean conditions within the specific geographical area of a project is very important when planning the installation of floating offshore wind turbines. Predicting suitable weather windows and associated costs based on current, wind and waves is required in order to calculate design loads, site selection and so on. A challenge is the high complexity of the ocean environment, including several variables which makes it difficult to predict the operating conditions (Ramachandran et al., 2021, p. 12).

3.3 Tug and tow

The general purpose of tugboats is to assist surface vessels that does not have self-propulsion, and in general if movement in port is limited due to the size of the vessel. To convey a large surface vessel in a harbor area, several tugboats are used to assist. The overall control performance of the operation depends on how the tugboats cooperate. The conveying is conducted manually, and performance depends on the experience of the tugboat operators. It is recommended to have good strategy and coordination in place. This includes guiding the thrust forces of each tugboat in order to convey the vessel along the preferred path. According to the South-Korean research from 2021 regarding environmental disturbances during conveying operations, it is suggested that winds and currents are factors with more impact than the impact of wave conditions (Lee et al., 2021, p. 655 & 673).

The number of tugboats required depends on the circumstances and conditions of each operation and situation. It is economically favorable to have a smaller number of tugboats during normal conditions, but the research confirms the need for several tugboats during rough environmental conditions to ensure a safe operation. It is also recommended to avoid minimizing the duration of a conveying operation due to safety reasons (Lee et al., 2021, p. 673-674).

When towing, shorter towrope length can increase pitch and heave motion responses, as well as the risk of towed object crashing into tugboat. Longer towrope can increase roll motion (Zhang et al., 2019, p. 8-9). When the wave period decreases during towing, the heave, pitch and roll motions can increase. Higher wave height can also have impact on towing performance (Le et al, 2021). When external forces are large, including for instance irregular winds, waves and/or currents, more thrust force from tugboats is required to follow the designated path for a tow (Lee et al., 2021, p. 673).

3.4 Crane operations

Lifting operations using floating crane vessels is critical and can cause damage to structures for instance when installing an offshore wind turbine blade due to motions of the sea. An impact can cause complex damage to the blade which can affect its structural integrity. A major challenge is the sensitivity of the vessel and crane tip when affected by waves (Verma et al, 2019, p. 127 & 143-144). A floating crane can collide with quayside if not positioned with a safe distance during operation. Waves reflected by the quay as well as waves disturbed by tugboats can cause irregular conditions. For the floating crane mentioned in the study by Lee *et al.* (2021), it is recommended to have a weather limit of Beaufort scale 5 or less to ensure a safe operation (Lee et al., 2021, p. 659, 662, 671).

During lifting operations of a wind turbine jacket substructure, heave, roll and pitch can occur and vary for instance based on the wave period. The energy of the sea can lead to a peak crane load of up to 2-3 times the actual weight of the structure (Aliyar et al., 2021, p. 12). Lifting operations become more challenging when structures/payloads grow in size and weight. Using larger cranes/vessels is one solution, but one can also use a combination of low-capability cranes to achieve the same performance, causing less tension on each wire. However, this can lower the installation height (Ren et al., 2021, p. 1-2). Using a mono-hull vessel to execute a blade installation at sea can be a more challenging operation compared to using a semi-submersible vessel. Jack-up vessels can offer a stable elevated working platform but are limited by water depth. Shortage of crane vessels is therefore a critical issue for the offshore wind industry (Zhao et al., 2019, p. 442). Motion responses of a semi-submersible vessel can be much lower compared to a mono-hull vessel, causing this type to have higher operability with higher allowable sea states. However, semi-submersible vessels are much more costly to use (Li et al., 2021, p. 19).

According to Guachamin-Acero & Li, the landing, lift-off and mating of a turbine and foundation using heavy lift vessels are often critical operations which depends on winch speed and how the vessel for instance respond to wave actions. The impact velocity must correspond with the allowable limit of an impact force. If conducting heavy lift operations in offshore sites, including the North Sea, unexpected vessel responses can occur due to wind and swell. This can cause delays and extra costs. To prevent large uncertainties in the dynamic responses, a proper representation of the actual wave spectra must include safety margins to the operational limits. To ensure reliable marine operation analysis, safety margins should include parameters such as wind, current and human decisions. The paper also suggests the fact that analytical wave spectra may not always represent the actual forecasted or measured spectra in open seas. This can cause lower safety levels than expected when floating vessels are executing marine operations (Guachamin-Acero & Li, 2018, p. 185-186 & 192-193).

When installing offshore wind turbines, the so-called jack-up crane vessels has been the typical choice for executing lifting operations. According to Zhao *et al.*, floating crane vessels are more flexible in regard to water depth and relocating efficiency. It is also assumed that modern floating crane vessels are or can be equipped with good dynamic positioning systems in order to mitigate any variance in horizontal motions (Zhao et al., 2019, p. 443 & 461).

The *Saipem 7000* is a self-propelled, dynamically positioned and semi-submersible crane vessel. It has an overall length of 197,95 meters, a breadth of 87 meters and an operating draft of 27,5 meters. The draft during transit is 10,5 meters and the transit speed is about 9,5 knots. The vessel is equipped with two twin, fully revolving bow mounted Armhoist cranes. If conducting a main crane tandem lift, it can lift a total weight of 14.000 tons (Saipem, n.d). On April 12, 2022, the *Saipem 7000* was positioned in the Åmøyfjord, Norway, for testing. The vessel was performing a scheduled load test of the main cranes with the presence of the classification society. During the testing operation, an incident occurred onboard. Based on a preliminary assessment, the main block wire broke when lifting the testing load, which consisted of two cargo barges (Saipem, 2022).

3.5 Ports

Lack of suitable ports for handling and installing floating offshore wind turbines is one of the key challenges addressed in the 2030 vision report by WindEurope. Floating offshore wind is difficult without ports (Cecchinato et al., 2021, 8). Ports play a key role in the development of offshore wind. They facilitate the local supply chain, the necessary logistics, and the supporting infrastructure such as handling and storage of components. Ports are where components for offshore wind farms are either constructed or transported to after construction. It is also where the assembly operations take place, unless turbines are assembled at sea, in which case, components are transported from port to the offshore wind farm by specialized vessels. WindEurope highlights the need for significant investments in relevant ports in order to upgrade and expand their abilities to handle turbines which are constantly getting bigger. They especially recommend reinforcing quays, improving or facilitating deep-sea berths, and diversifying their services (Cecchinato et al., 2021, p. 7-8). Uncertainty in availability of suitable port facilities makes it challenging to evaluate success rate in advance of a project (Rinaldi et al., 2021, p. 2).

When planning to develop a port for the offshore wind industry, it is important to plan infrastructure and logistics based on the quantity of turbines and types of foundations to be installed in the particular port. That is why the port and the wind farm developers must work together. The port must know what type of foundations to prepare for as well as the quantity expected, while the developers must know the current port capabilities, and any future investment plans for the port (Cecchinato et al., 2021, p. 15-18). Assembling turbine-structures for floating wind is usually conducted onshore or along the quay in port, which means the need for vessels is different compared to assembling at sea using bottom-fixed foundations (Cecchinato et al., 2021, p. 20).

3.6 Trends and economics

Within the period of 2009-2018, we have seen growth in turbine power, turbine length and diameter, and in depth and distance to coast (Sanchez et al., 2019, table 6.). The floating wind industry is growing, and the upcoming volumes, size and weight of offshore wind components require suitable ports and vessels (Cecchinato et al., 2021, 8, 15 & 18). A potential challenge is to make calculations of main economic aspects of offshore wind platforms built in concrete considering different locations of the European Atlantic Arc

(Cordal-Iglesias et al., 2020, 2.1). Increased dry CAPEX and number of turbines have the most effect on the total installation cost (Judge et al., 2019, p. 376).

The floating offshore wind industry is still small and lack own methods for manufacturing, installing, operating and maintaining the turbines/farms. Investments in developing maintenance strategies and new vessels for the industry is unlikely to occur until the industry is more established (Barter et al., 2020, p. 7). Optimizing the marine operations required throughout the life cycle of a wind farm is important, but there is lack of standards related to installation approaches, costs and time for each operational task (Ramachandran et al., 2021, p. 10-11). According to research by Crowle & Thies, floating wind installation generally requires a higher number of conventional vessels compared to fixed offshore installations. Marine operations play a crucial role in all stages of a floating wind farm's life cycle, but the different stages include various uncertainties which can extend construction schedules and increase the capital expenditure (Crowle & Thies, 2021). Based on the WindEurope report, the North Sea is and will continue to be the main hub for offshore wind activity, due to its favorable wind resource and shallow waters (Cecchinato et al., 2021, p. 14).

Based on planned projects and projects in motion, the annual installation rate of turbines offshore in Europe is expected to almost double within 2025, from about 400 units to about 800 units. The choice of foundations still indicate that bottom-fixed solutions is the main trend, but different designs within floating wind are being evaluated, with spar-buoy and semi-submersible platforms as the most popular options (Cecchinato et al., 2021, p. 15-18).

3.7 Norway and WindWorks Jelsa

According to the Norwegian Ministry of Petroleum and Energy, it is now opened to apply concession for offshore wind projects in Norwegian waters. The two areas (Utsira Nord and Sørlige Nordsjø 2) now open for applications to develop offshore wind farms, facilitates an overall development capacity of 4500 MW of wind power. According to the article posted under the sitting government of 2020, the development opportunities for offshore wind in these areas are big (Mess. Go. 038 (2020)).

The company WindWorks Jelsa was established in the fall of 2020 by NorSea, Suldal municipality and Ryfylke IKS. Its purpose is to conduct a comprehensive suitability study for establishing a large-scale industrial facility and port at Jelsa with the aim of producing foundations and assembling wind turbines for the floating offshore wind industry. The exact location of the planned facility is at the quarry of Norsk Stein AS located in the area of Jelsa in Suldal municipality. The intention with the WindWorks Jelsa project is to establish a full-scale, efficient and low-emissions production facility for floating offshore wind. The developers acknowledge the increasing demand for organizing large-scale facilities to support the development of the floating wind industry. In order to ensure a competitive development, one must achieve cost reduction similar to what has been seen for bottom-fixed installations. A facility in Jelsa can contribute in this matter by enabling the construction of floating foundations and the assembling and mating of complete turbines, which are towed directly to the final destination offshore (NorSea, 2021).

Norsk Stein Jelsa as choice of location is due to its massive quarry with relevant products, and its large crater which is situated right next to the fjord with clear passage to the North Sea. According to NorSea, producing floating turbines is challenging and requires big and heavy facilities in order to make production viable. That is why they claim the quarry at Jelsa to be highly suitable. The crater has a depth of 40 meters below sea level and a potentially usable area of over 200 acres when Norsk Stein has completed their current material extraction in the designated area. The goal is to use the crater to develop one or several dry-dock facilities. In and around these dry-docks, foundations can be constructed, and turbines can be assembled and mated with the corresponding foundations. After completion, the dry-docks can be filled with seawater which will make the FOWTs floating. Access from the dry-docks to the fjord will enable the floating turbines to be towed out and to the installation site offshore (NorSea, n.d.).

The Norsk Stein quarry is located in the southern part of the Sandsfjord, just before the narrow strait with the name Straumbergsundet, which leads to the continuing Sandsfjord. This fjord overlaps with the Saudafjord and eventually ends in Sauda (Kystinfo, 2022). According to the official Norwegian statistical database, there was a steady flow of bulk and general cargo ships calling at Sauda in all quarters of 2021 (Statistics Norway, n.d.). Norsk Stein at Jelsa claims to be Europe’s biggest quarry, exporting millions of tons of split aggregates each year to the European market (Norsk Stein, n.d.).

Figure 5. Norsk Stein Jelsa. Credit: Screenshot from www.kystinfo.no (Kystinfo, 2022)

The Norwegian Coastal Administration sets guidelines and regulations to ensure safe and efficient maritime traffic and operations in Norwegian coastal areas. According to their local guidelines for pilotage, all vessels with more than 6.000 gross tonnage shall have minimum of one tugboat to assist on arrival and departure. All vessels above 20.000 gross tonnage shall have two tugboats at arrival. This applies for all ports and harbors which are not specified with separate guidelines. What type and number of tugboats required to assist at any given time must be evaluated based on the assisted vessel’s size and maneuvering equipment. Weather and wind conditions are significant factors when evaluating needs. Thrusters with satisfying power can substitute the need for tugboat (Kystverket, 2020, 4.2).

4. Challenges

This chapter presents identified challenges retrieved from the literature obtained during the systematic literature review. The challenges concern marine operations related to installing floating offshore wind turbines. Challenges are divided into main topics. These topics of challenges are further discussed, compared and linked in the following the discussion chapter.

4.1 Port challenges

The 2030 vision-report by WindEurope shares a strong and comprehensive message regarding ports and their key role in developing and supporting the floating offshore wind industry in the coming years. Ports facilitate the local supply chain, the necessary logistics, and the supporting infrastructure, including handling and storage of components. The literature indicates that floating offshore wind turbines have the advantage of being fully assembled in port. This means high demand for ports and high requirements to port capabilities. There is high need for significant investments in relevant ports in order to upgrade and expand their abilities to handle turbines which are constantly getting bigger. It is especially recommended to reinforce quays, improving or facilitating deep-sea berths, and diversifying their services.

The below figure shows an overview of various factors that can have an impact on the suitability and performance level of a port related to installing floating offshore wind turbines:

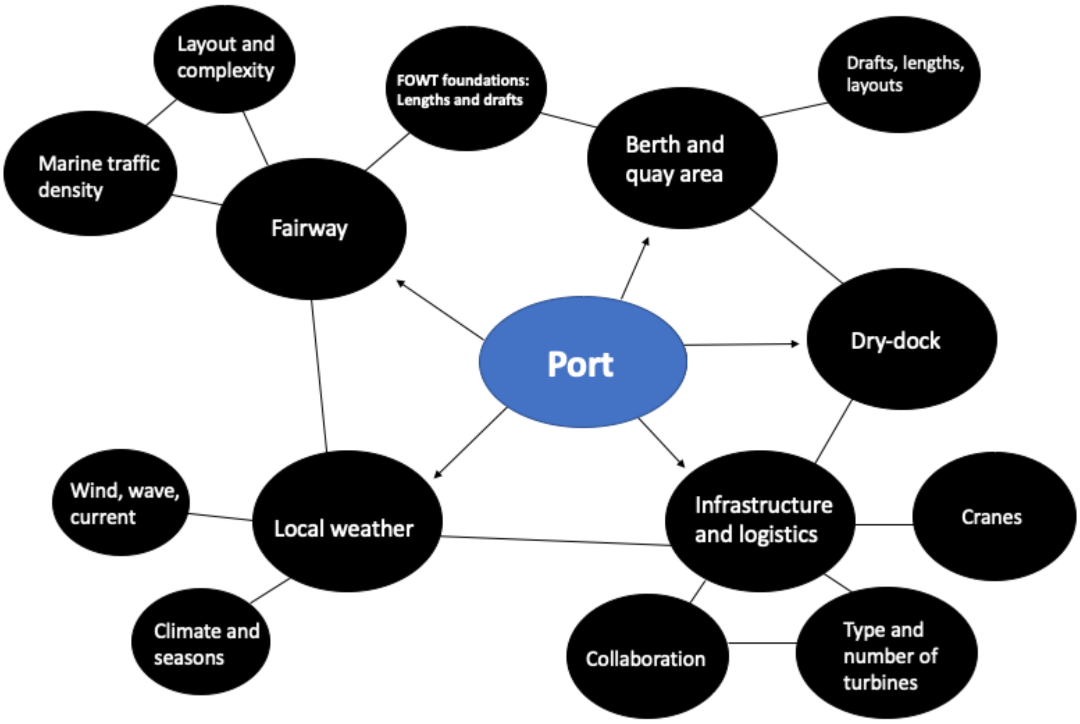

Figure 6. Identified factors and challenges with impact on port suitability

4.1.1 Local weather

To calculate design loads, site selection and operational approach, it is required to predict/evaluate suitable weather windows. A challenge is predicting how floating vessels and floating structures perform and respond in a dynamic environment. Failing to understand operational and allowable limits, including wave height, wave period, peak period, wind and current, operational risks can occur. Uncertain operational limits, including variability in the wave spectral energy distribution, can be a challenge to marine activities operating in port. Vessels, cranes and/or the floating turbines can respond in a critical way, causing damage to structure, crew and/or infrastructure. Identified challenges are related to the following factors:

- Uncertainty related to waves and currents in a specific area at a given time.
- Uncertainty related to wind and temperatures in a specific area at a given time.

These challenges are still current for marine operations due to the high complexity of the ocean environment, including various variables making it difficult to predict the metocean conditions when planning a specific operation in a given area. There is also limited experience in the field related to floating offshore wind installation. This gives uncertainty to the key performance indicators which makes it challenging to evaluate the success rate in advance of an operation.

4.1.2 Quay, berth and fairway

Length, breadth, draft and layout of a quay, berth and/or fairway can set physical limitations to the handling and installation of FOWT components. The foundations which supports the turbines can be massive structures, both related to length, breadth, draft and weight. Literature suggest that an unballasted steel-type spar can weigh up to 5.000 metric tons, have an overall length of more than 90 meters and a diameter of 14-15 meters. Some spar-type foundations are constructed in one port and further assembled in another. If using a vessel to carry the structures from port to port, loading could be executed at quayside using trailers. If necessary, relevant quays must be reinforced in order to handle these structures.

Once the spar-structure is removed from the quay, from the dry-dock or from the vessel's cargo deck and is floating by itself, the next step is to add ballast in order to make the structure in upright position. Due to its deep draft when ballasted, the spar-foundation must be positioned in a place where it can still have adequate underwater clearance when in ballast. The steel-type is in one complete piece when in floating position, and therefore require adequate water depth before ballasting can begin. The concrete-type can be partially slip formed in one place and further slip formed and completed in another. It is recommended to have a minimum canal width of 90 meters during a spar-tow, but it is not identified if this applies for the ballasted or unballasted state.

After the spar is ballasted in a deep-water berth or in a fjord of some kind, the next step is to lift the fully assembled turbine to and onto the floating spar. The literature suggest that this must be conducted in a sheltered area with favorable metocean conditions. The literature indicates that some ports can be exposed to ice during winter seasons. If using a semi-submersible heavy-lift vessel to carry the turbine from place of assembly and to and onto the floating spar, the crane vessel may have an operating draft of 27,5 meters. The crane vessel could have adequate dynamic positioning systems and be able to operate without tugs. If the ballasted spar is positioned in the fjord, it requires several tugboats to keep it in place. Based on the literature, it is possible to do mating of turbine and foundations at quayside if water depth is adequate. A combination of barges can be used as an alternative quay facility.

The literature suggest that the semi-submersible foundation is easier to handle during installation compared to the spar-type. It can be fully constructed onshore and the mounting of the turbine can be carried out at quayside due to low draft. The semi-submersible foundations mentioned in the literature consists of three steel-based columns connected by bracings. It has a big footprint and could weigh about 2.500 tons. Each column could have a 10-meter diameter and the distance between each column could be 50 meters. The semi-submersible foundation can be constructed in a dry-dock and made afloat by buoyancy when water is entered into the dry-dock. It can also be constructed onshore and loaded from quay and onto a semi-submersible vessel for further transport. If constructing onshore instead of using a dry-dock, costs could increase, and accessibility could be lower.

4.2 Challenges related to towing and lifting

4.2.1 Tug and tow

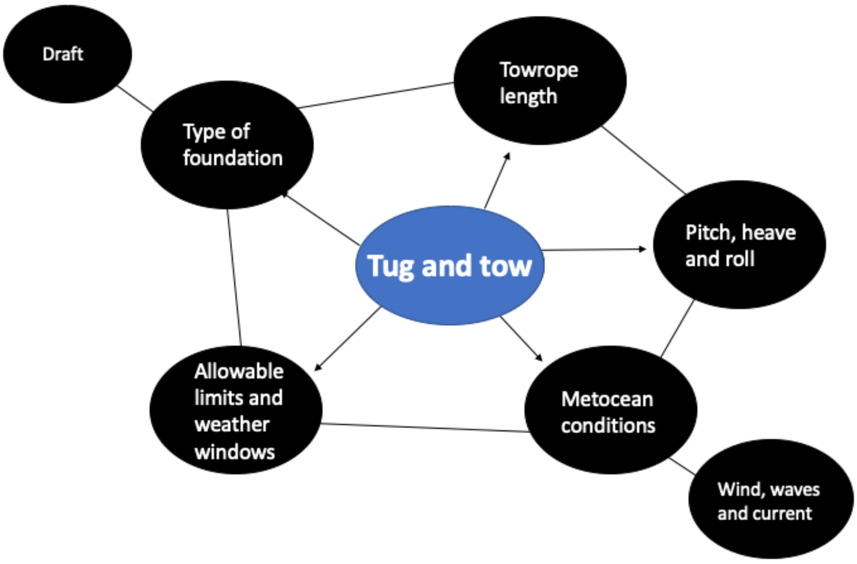

Figure 7. Factors with impact on tug and tow operations

To ensure a safe and efficient operation using multiple tugboats, it is required to have good strategy, coordination, and experienced tugboat operators. The coordination must include guiding the thrust forces of each tugboat in order to convey the towed object along the preferred path. The literature indicates that metocean conditions, including waves, winds and currents, can have impact on the safety and efficiency of a tugboat operation. It is suggested that wind and current are factors with higher impact compared to the wave factor. Using fewer tugboats is economically favorable, but if the metocean conditions are rough, safety and efficiency can decrease if not having adequate force available. External forces can include irregular winds, waves and currents which can make it challenging to stay on path if not having adequate amount of thrust force from tugboats.

Each operation must be evaluated separately based on metocean conditions and other circumstances. The literature suggest that increased wave height and/or decreased wave period can have impact on the performance of a tugboat operation. Decreased wave period means that a cycle of waves takes shorter time to complete. A decreased wave period can cause more heave, pitch and roll motions. Increased pitch and heave can also be caused by short towrope. This can also lead the towed object to smash into something. Longer towrope can help but roll motion can increase. Assessing allowable conditions is important in order to avoid incidents. For the Hywind Scotland project it was determined that the months from April to September had the widest operational time windows for marine operations.

The steel-type spar is in a horizontal state when unballasted and in a vertical state when ballasted. When floating in a unballasted state, the foundation has low draft and is more convenient to tow. When positioned in a deep-water area, tugboats must continue to keep the spar in position while seawater is filled into the foundation. The seawater is then partially replaced by solid material as ballast. When the spar is ballasted, towing is more difficult due to the high draft of the structure. The concrete-type spar is different because it is constructed in a vertical state. This can be slip-formed in one place and then towed to a deep-water area for further slip-forming. After slip-forming is complete, solid ballast is poured into the structure.

The literature suggest that a towing operation becomes more challenging when the towed object has higher draft. The spar-type foundation can have a draft of more than 80 meters when adjusted by ballast. However, the literature also informs of the spar being less sensitive to wave height during towing. The semi-submersible type foundation has a draft of about 10 meters during transport. A challenge identified in the literature is the fact that semi-submersible foundations can be more sensitive to wave heights during towing. This means identifying safe weather windows to execute towing operations can be challenging. The literature mentions that the towing of a floating offshore wind turbine is a continues operation and it can be challenging to halt the tow in the middle of the operation. It is therefore recommended to have safe havens along the route in case of rough weather.

4.2.2 Lifting operations

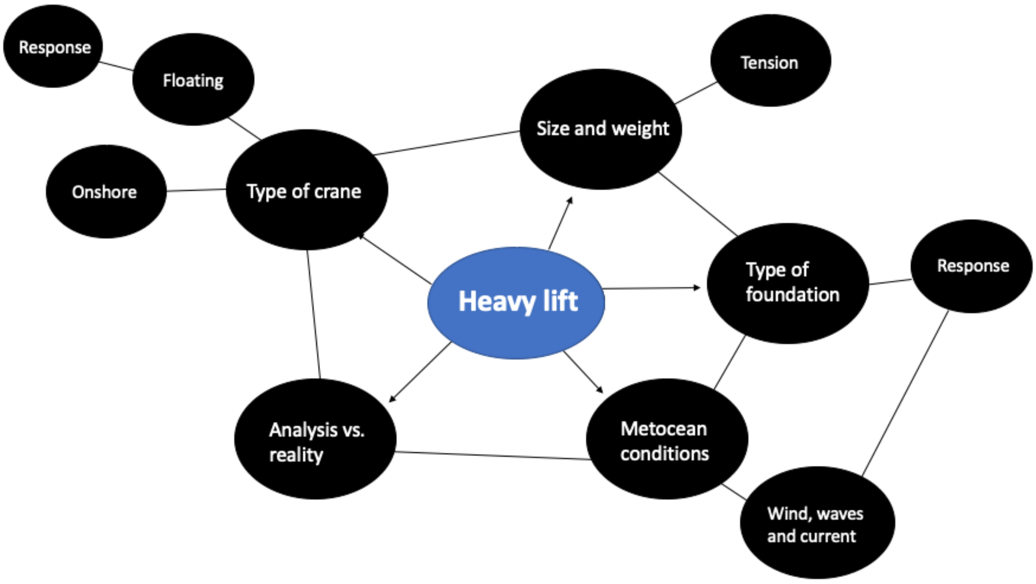

Figure 8. Factors with impact on lifting operations

The literature mentions heavy lift operations both related to fixed onshore cranes and floating crane vessels. Identified challenges relates to when evaluating operational windows and limits of payload size and weight, related to metocean conditions such as winds and waves. For instance, the energy of the sea can lead to a peak crane load of 2-3 times the actual weight of the payload. If the weight exceeds the crane weight capabilities, the wires can break. Uncertainties to how the crane and the payload respond to external forces is a challenge to predict. To ensure a reliable marine operation analysis, parameters such as wind, current and human decisions should be included in the defined safety margins.

If using a floating crane vessel, the literature mentions the mono-hull type vessel, the semi-submersible type vessel and the jack-up type vessel. During an installation process at sea, it is suggested that semi-submersible and jack-up type crane vessels offer more stability compared to the mono-hull type. A jack-up crane vessel has the ability of offering a stable and elevated working platform, but it can only be used in shallow waters. This has led to shortage of capable crane vessels in the offshore wind industry. The literature recommends floating crane vessels as the solution due to their favorable relocating ability, good dynamic positioning systems and no water-depth limitations. A mono-hull vessel is one option with no water-depth limitations, but it can have a high level of motion responses, for instance during a blade lift operation. A semi-submersible crane vessel eliminates several of limitational challenges due to its favorable features.

The semi-submersible vessel has no water-depth limitations and has higher operability at sea. When submerged at sea, this type of vessel can have much lower motion responses compared to a mono-hull type vessel. This allows these vessels to operate in higher sea states. A challenge is their must higher operational cost compared to other types. According to Guachamin-Acero & Li, operating offshore in areas like the North Sea, a challenge can be the unexpected vessel responses which can arise due to wind and swell. Uncertainties related to metocean conditions and structure responses can extend construction schedules and increase installation costs.

Heavy lift operations are required both when handling and installing a spar-type and a semi-submersible FOWT. If not using a dry-dock or a semi-submersible cargo vessel, the steel-type spar could require a lift from quay and into the water. During early stages of construction, both the concrete-type spar and the semi-submersible foundation are in the literature only mentioned using dry-docks. However, the literature mentions crane lifts related to mating of turbine and foundation for both spar-types and for the semi-submersible type. Identified challenges relates to uncertain dynamic motions and responses by the floating foundation and the crane vessel.

Due to high draft, a spar-type foundation could require a fjord operation phase in a deep-water area where the turbine is mated and mounted onto the floating spar. According to Equinor sources, a turbine could be fully assembled at quayside and then lifted from the quay and to the floating spar positioned in the deep-water area. According to Ramachandran et al., the spar can be unstable during mating and has tighter weather constraints compared to other foundations. The semi-submersible type foundation has low draft and mating of turbine can typically be executed at quayside. A fixed shore crane can lift the turbine onto the floating foundation positioned along the quay. In order to utilize crane capacity, the turbine is usually mounted in one corner or on one side of the semi-submersible foundation.

The literature indicates that a spar-type foundation could require a fjord phase which includes a mating operation that could require a floating vessel to execute the lifting of turbine onto the spar foundation. A topic addressed by Guachamin-Acero & Li is the challenge of assessing right winch speed related to how a floating vessel respond to wave actions. Unexpected vessel responses due to wind and swell is a challenge. If the winch speed is too high during an unexpected vessel response, the impact force between the turbine and foundation can cause damage to structures. The literature suggest that the impact velocity must correspond with the allowable limit of an impact force.

To predict metocean conditions and plan for a safe marine operation, it is recommended to conduct marine operational analysis before commencing an operation. This is to determine operational and allowable limits, including safety margins that also should take wind, current and human decisions into account. For the floating heavy lift crane analyzed by Lee *et al.*, it was recommended to have a weather limit of Beaufort scale 5 or less. If weather exceeds the limit, lifting operation is not recommended. A challenge related to weather is the fact that analytical wave spectra could deviate from the actual forecasted or measured spectra in reality. This could lead to lower safety level than expected. The literature also mentions challenges related to waves being reflected by the quay or waves disturbed by tugboats, causing unexpected conditions to the crane. If the crane does not have adequate distance to the quay, risk of contact increases.

4.3 WindWorks Jelsa

One challenge is predicting what type of foundation to invest and facilitate for as the bottom-fixed type is still the common choice (Cecchinato et al., 2021, p. 15-18). The floating wind industry is still small, and it is lacking standards, methods and strategies to how one should invest, plan, execute and optimize relevant processes including marine operations (Barter et al., 2020, p. 7).

According to NorSea, the WindWorks Jelsa project is first and foremost assessing spar and semi-submersible type foundations. If choosing spar foundations, these will be made of concrete and require a fjord phase in order to complete the slip-forming. This type of foundation requires a minimum draft of 98,5 meters in addition to a safety margin. The spar characteristics allows WindWorks to produce more foundations compared to using a semi-submersible type. The below figure is provided by NorSea and illustrates semi-submersible types in the dry-dock above and spar-types in the dry-dock below. Due to more units, the spar will include high traffic in the area of Norsk Stein Jelsa. If choosing semi-submersible foundations, their foot-print is bigger and the number of foundations produced per year will be significantly lower compared to the use of spar. This will also cause less load on the

Sandsfjord because the complete FOWT can be fully assembled in the dry-dock before tow-out to the offshore site (NorSea, personal communication, April 7th 2022).

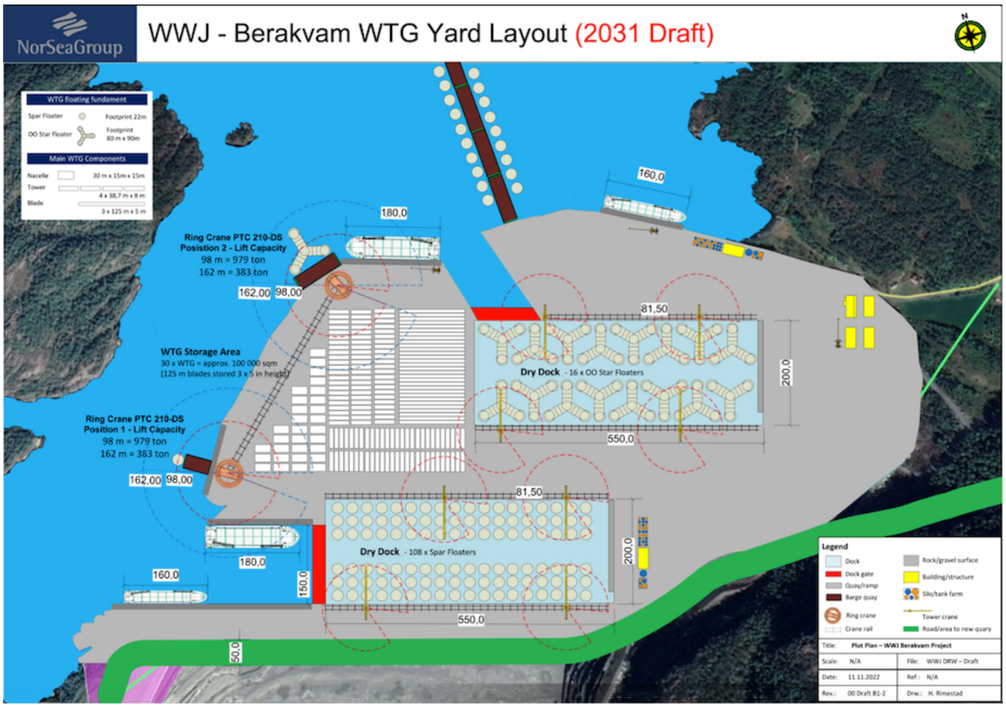

Figure 9. WindWorks Jelsa - Layout draft. Credit: NorSeaGroup (2022)

According to NorSea, WindWorks Jelsa is applying for change of fairway for the tow-out operation using a strait with the name Midtsundet instead of the strait called Straumbergsundet. If this is not approved, the fairway will take a right after the Kvite Islet as shown in the figure below provided by NorSea (NorSea, personal communication, April 7th 2022).

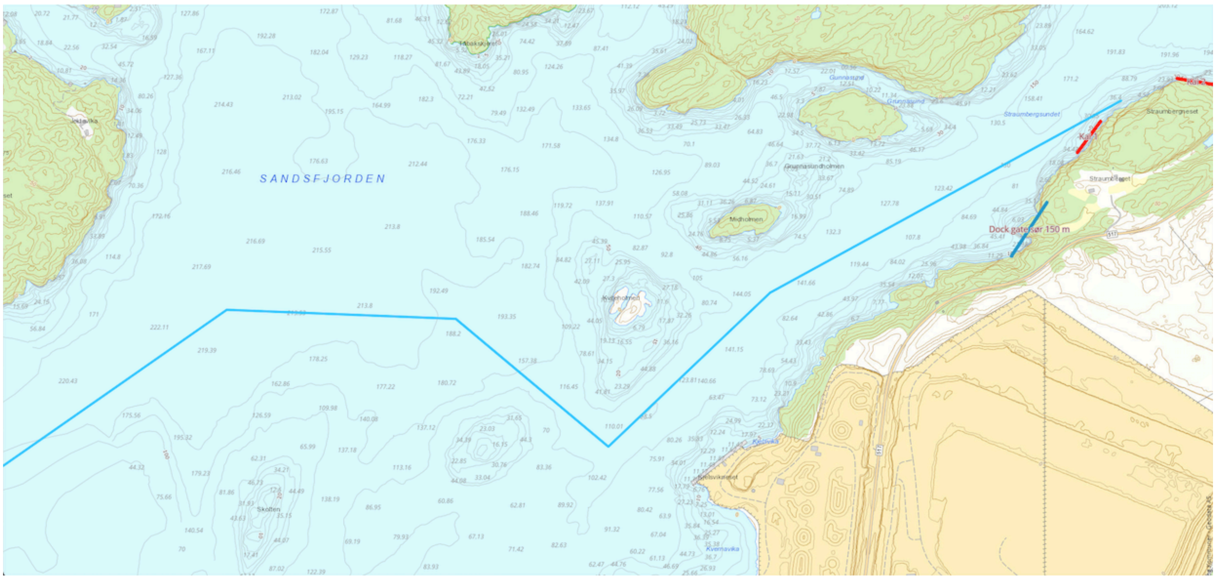

Figure 10. WindWorks Jelsa - Change of fairway. Credit: Norsea (2022)

Norsk Stein at Jelsa claims to be Europe's biggest quarry, exporting millions of tons of split aggregates each year. According to the leader of the Norsk Stein ship agency, the quarry had about 860 port calls in 2020 and about 730 port calls in 2021. A ship inbound from the North Sea will typically take pilot at *Skudefjorden 2* pilot station when calling at Norsk Stein Jelsa. The quarry has two main shiploaders (*North* shiploader and *South* shiploader), and an additional berth used for self-loading (*Timber berth*). The port area has no ice limitations and the flow of ships is consistent throughout the year. However, the seasons from spring to fall can be described as high seasons (Norsk Stein ship agency department, personal communication, May 7th 2022). According to NorSea, a challenge of accomplishing an efficient production at Jelsa is related to the limited window to when it is possible to conduct tow-out operations. Today, this window is from April to August and is the same for both the spar and the semi-submersible type (NorSea, personal communication, April 7th 2022).

5. Discussion

This chapter discusses the identified challenges from the previous chapters, including topics concerning ports, towing operations and lifting operations related to the floating offshore wind industry. The discussion is divided in two parts; The first part discusses marine operational challenges related to floating offshore wind turbines in accordance with the limitations stated in the method chapter. The second part implements topics from the first part into the setting of WindWorks Jelsa for further discussion.

5.1 Part 1

What are the marine operational challenges related to installing floating offshore wind turbines using spar and semi-submersible foundations?

5.1.1 Port

In order to develop competitive and large-scale floating offshore wind farms, it seems like ports play a key role (Cecchinato, 2021, p. 7-8). The industry needs relevant ports to support the projects by offering suitable berths, quays, fairways, sheltered areas, logistical facilities and services, including marine support and local guidelines to ensure safe and efficient installation and handling of FOWTs. However, it can be challenging to know how to invest and facilitate when the floating wind industry is still in beginning stages. Which FOWT types will be most relevant in the future? How big will they be and where will they be installed offshore? Identified literature and challenges suggest that spar types and semi-submersible types are two popular concepts which has seen positive results in pioneering projects. Based on earlier trends with constant increasing structural sizes, we can speculate that these trends may continue in the future as the technology advances. According to outlooks, the North Sea seems to still be a popular area for installation due to favorable winds and shallow waters (Cecchinato, 2021, p. 14). Energy ports are already established in this area, supporting the petroleum industry. This can be an advantage.

The literature mentions a wide range of factors and characteristics which are recommended to be taken into account when evaluating port suitability. However, I think the first question should be; Does the port have adequate space and depth to handle the chosen FOWT in a safe and efficient way? This includes adequate access for relevant vessels and components coming to the port. It includes the safe maneuvering and handling of relevant vessels and components inside of the port. And it includes the safe maneuvering and handling of complete FOWTs departing from the port. If these basic conditions are not met, I believe the port is not suitable for the installation and handling of floating offshore wind turbines.

If above conditions are met, there are still many other factors that can have an impact on the suitability and performance level of a port in this context. Climate and environment, access to support services, adequate infrastructure, berths and quay conditions are some of the factors mentioned in previous chapters. For a floating entity to move into, inside and out of a port, I assume the fairway layout and complexity, as well as the level of traffic can have impact on the suitability. Characteristics such as length, breadth and shape of a basin or fairway can set physical limits to what is actually possible to execute inside a port, fjord or inshore waterway. Depths also seems to be a key limitation factor for some of the marine operations during the installation and handling of a FOWT. Ports should be elected based on the characteristics of the FOWT, which is why it is necessary to review and compare the spar-type and semi-submersible-type FOWT.

While the weight of a unballasted steel-type spar can range from 2500-5000 tons, a large-scale semi-submersible foundation seems to only weigh about 2.500 tons. This can be of relevance when evaluating quay strength and crane capabilities. But a more significant difference between the types of foundations seems to be the actual shape and size. A spar-type is characterized by its long, cylinder-shaped hull (see fg.1), while a semi-submersible type is shorter but characterized by its huge size and big foot-print. There are only a few spar-type projects completed at this time, but the data indicates that a steel-type spar has an overall length of 80-90 meters. This type of foundation is kept horizontal until the point where it is ballasted in a deep-water area. Data concerning the semi-submersible type does not discuss length as often because this foundation is in up-right position already in early stages of construction in the yard. Its height seems irrelevant and its draft is only about 10 meters during transport. However, it has a triangular foot-print with about 70 meters on each side, which require more space than the spar.

When handling spar-type foundations in port, challenges can arise both when in un-ballasted and ballasted condition. The difference between a steel and concrete-type spar can also have impact. When un-ballasted, the steel-type foundation will be in a horizontal state and can therefore offer a challenge in port regarding its length on the surface of the water and in the yard or dry-dock. First of all, physical limitations in the port area and/or in the fairway, such as shallow areas and narrow and/or curvy layout of the fairway, can for instance have direct impact on the suitability of towing a spar foundation. The length of the tow may also be relevant but will be discussed in the next sub-chapter. If choosing a concrete-type spar, findings indicates that the structure will be slip formed vertically inside a dry-dock and then moved to a deep-water area for further slip forming. Based on this, towing in horizontal state seems to be avoided which eliminates some of the limitations in terms of length. However, structural draft and water depths must be addressed.

The steel-type spar has a diameter of 14-15 meters (Equinor, n.d.a). When floating horizontally in the water, the draft of the hull is not identified in the implemented literature, but I assume it is not more than 10-12 meters. In my view, this is not an unusual draft for a floating vessel/structure and should be suitable for many ports and terminals. In other words, if length is not an issue, a unballasted steel-type spar can be a convenient choice in regard to port handling. Depending on size, it can have similar length and weight as a small bulk carrier/tramp, and it should be possible to tow it to the preferred deep-water location in port or to the next port where the turbine is mounted. However, a berth and fairway area must still have enough width and underwater clearance in order to avoid grounding.

It seems like the main difference between a steel- and concrete-type spar is that the steel-type must be handled in horizontal state, which can set limits for instance when arriving to or departing from a berth or port. However, if long tow-length causes a challenge, this can be avoided by using a suitable mono-hull or semi-submersible cargo vessel. If using latter, the port must have adequate water depth in order for the vessel to discharge the spar foundations. Furthermore, the research did not disclose the typical height and draft of a concrete-type spar-section when ready for float-off and transport to the deep-water area for further slip forming. Maybe there is some flexibility in construction related to draft and local water depth at berth/dry-dock, but this was not confirmed.

It is however clear that a deep-water area is required both for the steel- and concrete-type spar when final stages begin. When in position, the steel-type will be made upright by adding ballast. When fully upright and the turbine is mated, the draft of the complete structure is about 78 meters based on data from Hywind Scotland. We could make assumptions that the draft of the spar is less before the turbine is mounted. In which case, the foundation could be ballasted in one place and towed to another where the turbine is mounted. Not sure if this would have any beneficial purpose but it might be possible to store one or several ballasted foundations in one area where depths are limited, and then tow one by one to a designated and suitable area for mounting the turbine.

5.1.2 Tug and tow

Based on the literature, it seems like one of the biggest advantages with floating offshore wind turbines compared to fixed offshore turbines is the difference in vessel requirements. Fixed offshore turbines are usually installed and assembled at sea using specialized and highly complex vessels. Jack-up vessels seems to be the typical choice but are limited to shallow waters and takes time to relocate. With the ability of fully assembling both the spar and semi-submersible type in port, the need for specialized and expensive offshore vessels is no longer the case. In terms of transporting a floating foundation or a complete FOWT, conventional tugboats seem to adequate. These are typically found in most port areas.

Just like any marine operations, proper planning and assessments must be conducted beforehand. Metocean conditions and uncertainties are relevant factors that must always be taken into account. We also know that predictions and forecasts may not always reflect the actual conditions, motions and responses. There is also the chance of something breaking or a human error occurring. This is why we implement safety margins to allow unexpected incidents to not exceed allowable limits. However, I think it should be mentioned that every marine operation, including tug and tow, are unique operations. Not to mention, the floating wind industry is just starting to grow and there is limited experience and standards for handling these specific structures. I agree to the recommendations of reviewing how the structures behave in the sea.

While tugboats are often used to assist and convey vessels weighing much more than 5.000 tons, it is somewhat different when assisting a floating structure that has no self-propulsion. All movements depend on the thrust and coordination of the tugboats. It was discovered that winds and currents can have more impact on a vessel or structure compared to wave motions. When operating in narrow ports or fairways, this could potentially cause a big challenge. High winds and strong currents do not just occur at sea but also in ports. If not having adequate thrust force to handle sudden external forces, the operation can lose control of the tow and in the worst-case lead to a total loss.

It seems like the semi-submersible type requires less use of towing operations because the assembling happens quayside. However, if the foundation is built in one place and further mated with turbine in another, it needs to be transported from A to B. This could be executed by using a suitable cargo vessel. However, due to its massive footprint, there could be limited availability of such vessels. In which case, towing is one solution. But this type of foundation is more sensitive to wave height limits during towing (Ramachandran et al., 2021, p. 10). It has a low draft which could make it unstable in rough weather. To ensure a safe operation, allowable limits and safe weather windows must be identified. It is also recommended to define safe havens along the route in case actual weather is worse than predicted. However, when towing in port, waves are often minimal which makes this challenge less significant.

If having to transport a spar in any state from A to B, these operations can also be challenging and should be limited to only what is necessary. A steel-type spar could be transported by a vessel similar to what is mentioned for the semi-submersible type. This can eliminate some of the weather constraints and it will most likely be a more efficient mode of transport. However, once the spar is floating on its own, several tugboats including adequate thrust and coordination is required from this point out. Tugs must keep the spar in place during ballasting and mating of turbine. Wind and current can still offer unexpected difficulties which could force the operation to abort. Furthermore, when the complete spar-type FOWT is towed towards open seas, it is less sensitive to wave heights due to its high draft. However, it seems like the draft still makes the towing challenging and it could be related to the amount of thrust-force-coordination required.

5.1.3 Lifting operations

When installing a FOWT using a spar or a semi-submersible type foundation, heavy lift operations seems to be unavoidable and a central part of the assembly process. The actual lifting and lowering involves the moving and mounting of components. The components can include blades. tower sections and nacelles. It could also include lifting and lowering a steel-type spar from quayside and into the water or onto a cargo vessel or barge. With the semi-submersible foundation, it looks like the components can either be mounted one by one, or they can be assembled on-land before the complete turbine is mounted onto the foundation. This also applies for the spar-type where a fjord-phase typically involves mounting the complete turbine in one lift, while a deep-water phase close to land can allow piece by piece if crane capability is adequate. This research did not identify the actual weight and size of the turbine components, nor did it identify detailed challenges when assembling/mounting them. In reviewed cases, the complete turbines were lifted and mounted onto the foundations.

I acknowledge factors of the external environment including winds and motions of the sea to have direct or indirect impact on how vessels and structures behave and respond to each other. Waves can be caused by nature, but they can also be caused by structure responses and behavior or passing vessels. When performing a lifting operation using a floating crane, one must consider that both the crane and the floating foundation are moving by the laws of the sea and they can have different characteristics. During a spar-type fjord-phase, the foundation can tilt from side-to-side and up and down. The lowering must be conducted carefully in order to avoid a sudden impact between the foundation and turbine. Adjusting winch speed based on amount of movement can help adapt and avoid too strong of an impact. In order to mitigate the movement caused by the wave spectrum or other metocean conditions, using a semi-submersible type crane could be a safer alternative compared to a mono-hull type.

5.2 Part 2 – WindWorks Jelsa

A highlighted topic from key sources emphasizes the need for relevant energy ports including significant investments in order to make relevant ports able to support future projects and handle bigger structures. It is believed that the North Sea will continue to be a hub for offshore wind development projects, which means ports surrounding this sea is required. If approved, WindWorks Jelsa will be situated on the southwest coast of Norway in a sheltered area with close proximity to the North Sea. Its location includes a fairly accessible fairway leading in and out, a short distance to project sites offshore, and proximity to a strong and experienced maritime and oil- and gas cluster which can offer collaboration and support.

Based on information provided by NorSea, WindWorks Jelsa is first and foremost focusing on spar and semi-submersible foundations as base and direction for their plans in Jelsa. It is recommended to plan and invest in port development based on characteristics of the type and number of FOWT in future demand. According to the literature, the spar and semi-submersible types are reckoned to become typical choices in the future. This means

WindWorks Jelsa has a favorable starting point. It is however not known which type they will go for. A production line with both types could perhaps be evaluated.

Figure 9 shows a preliminary layout of the WindWorks Jelsa facility. This is provided by Norsea and is subject to change. The layout shows two dry-docks with different access points. A semi-submersible foundation has much bigger foot-print than the spar, which is clearly illustrated. The spar-type foundations used in this layout will be made out of concrete and are therefore constructed vertically, taking up less space than a steel-type would. However, it was discovered that a concrete-type spar requires a deep-water phase to complete the slip-forming before mating of turbine can be executed. Based on depth readings in the area, it would be challenging to do this at quayside. A fjord phase to do slip-forming could be necessary but can cause a challenge due to the complexity of tugboat operations and uncertainty in metocean conditions. An alternative is to use barges to create a more or less stable work environment to conduct final slip-forming. If having to use the Straumbergsundet or the Midtsundet for a tow-out/-in, a recommended minimum channel width of 90 meters is met in both cases (see fig.11).

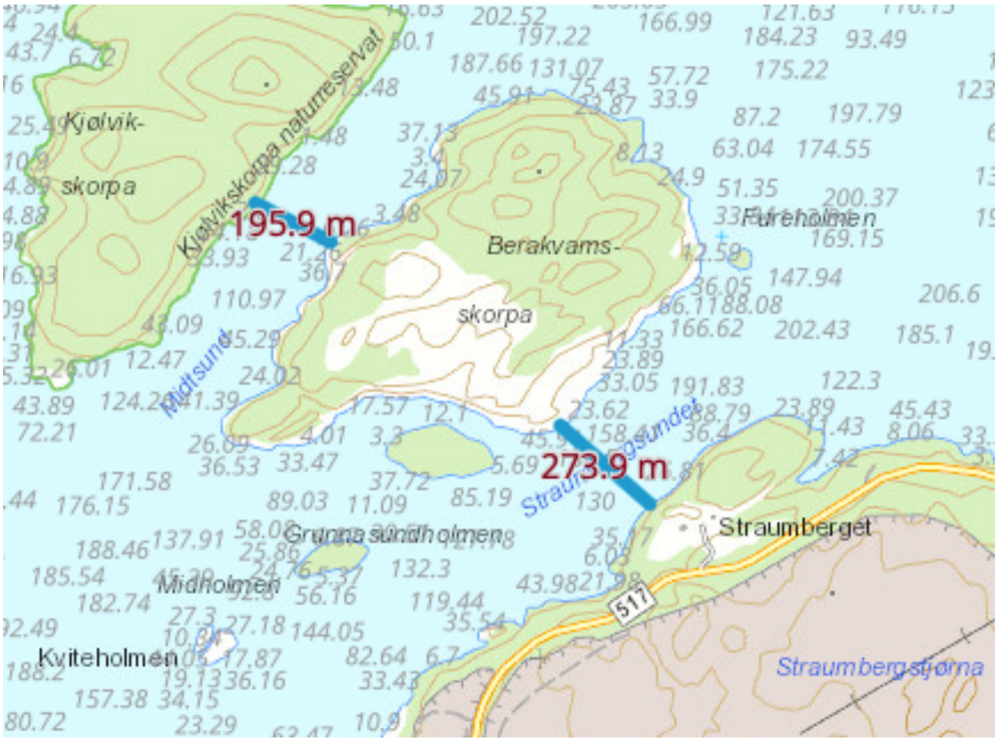

Figure 11. Personal sketch made at www.kystinfo.no (2022)

Towing operations are necessary when installing and handling both types of foundations. If doing final slip-forming of a spar on the inside of the straits, a tow-out with a 98,5-meter draft could be challenging due to areas in the straits with limited water depth. Any sudden responses to the structure and/or vessels could increase risk of damage/grounding. Local metocean conditions in the Jelsa area must be evaluated when planning these operations. Norway is a northern country but there are no ice limitations in this specific area. However, data from Hywind and NorSea suggest that tow-out operations should only be conducted from about April to about August. This can be related to force of winds, waves and uncertainties in the metocean conditions. The semi-submersible type has the advantage of being fully constructed and mated with the turbine in dry-dock or at quayside due to its low draft. This could limit the use of tugboats, associated risks and also load on the Sandsfjord area.

Both types of foundations still need a heavy lift crane to assemble and mate the turbine onto each foundation. Since the semi-submersible type has low draft, the mating could possibly be executed in the dry-dock or at quayside using a fixed crane onshore. A spar-type could be fully assembled at quayside if having adequate water depth. It is important that the floating structure and the fixed crane are close enough to each in order to have the most crane capacity available. However, if circumstances make it difficult to acquire a fixed crane due to costs or complaints from neighbors, a floating crane is needed. A semi-submersible crane vessel could for instance have an operating draft of 27,5 meters which could require some dredging at the preferred quay area. An alternative is using a mono-hull crane vessel or barge, but its operability could be limited.

According to the discussion-paper by the EAWE, the spar-type structure requires offshore assembly (Ramachandran et al., 2021, p. 3). Based on depths in Sandsfjord, assembly in the fjord could be possible. However, there must be adequate water depths and safety margins, as well as enough room for several tugboats and for the floating crane to navigate and operate safely. Based on figure 10, the Sandsfjord seems to be fairly wide and if deviating from the main fairway using the path to the right after the Kvite Islet, marine operations avoid using the fairly busy and narrow shipping lane at Straumberg (see fig.12).

According to NorSea, their hope is to enable an alternative fairway using the other strait with the name Midtsundet (see fig.11). This could be in order to mitigate the use of the shipping lane and any risks or bottlenecks in this regard. According to Norsk Stein ship agency, vessels calling at Jelsa quarry will approach using the Sandsfjord and one of the three berths (see fig.12). It seems like the main fairway continues through the Straumbergsundet and ends in Sauda. Based on above findings, there is a steady flow of ships calling both at Jelsa quarry and in Sauda throughout all seasons. This could cause a problem related to floating lift operations, tow-in/-out operations or just general supply of cargo/components at WindWorks Jelsa.

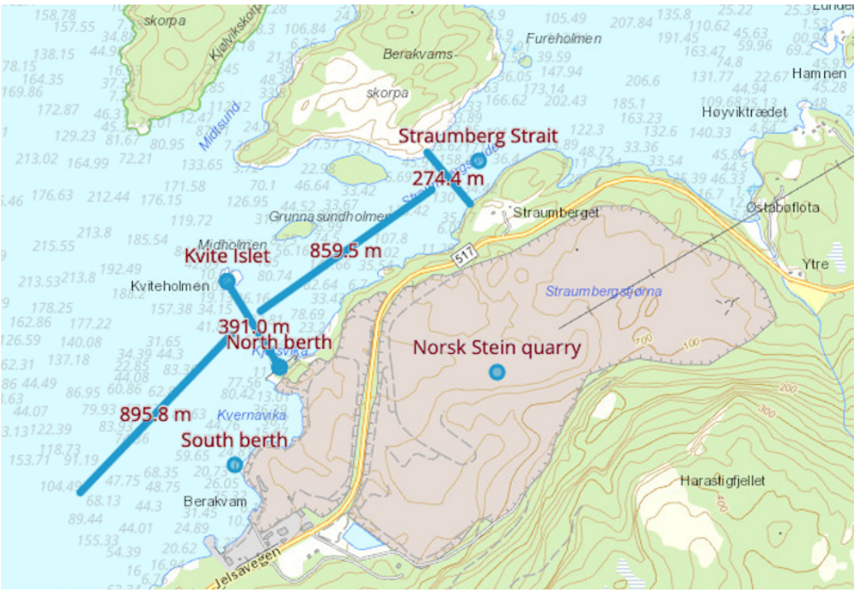

Figure 12. Personal sketch made at www.kystinfo.no. (2022)

According to NorSea, the number of units will be much higher if producing spar foundations instead of semi-submersible foundations. More unit also means more marine operations, which means the choice of fairway and amount of other traffic could have higher impact compared to using semi-submersible foundations. It was also mentioned by Norsk Stein ship agency that their high season could be from spring to fall, which seems to correspond with the allowable weather window for tow-out operations. The below figure (13) shows a rough sketch of the area where WindWorks Jelsa plan to develop, including rough estimates of where the dry-dock access points will be situated based on the layout in figure 6.

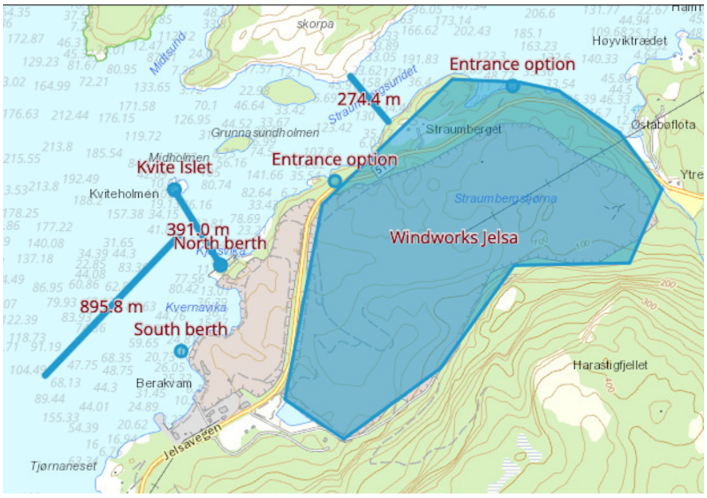

Figure 13. Personal sketch made at www.kystinfo.no. (2022)

When tow-out is conducted from the lower entrance point, the main fairway through the Straumbergsundet could be blocked during this operation. Towing of a floating foundation require precision and usually fairly slow moves to avoid incidents. Ships arriving to or departing from Sauda might need to wait for the tow to clear the shipping lane when approaching the Straumberg area. The Norsk Stein North berth seems to be the one closest to a tow-out operation. However, there is still adequate channel width and WindWorks plan to take a right after the Kvite Islet (see fig.10 & 12). The semi-submersible type has low draft during transport, and I don't see any significant challenges related to depths in this area. But if towing a complete concrete-type spar from any of the dry-docks, depth readings in the area indicates that there could be some shallow areas along the fairway. If tow-out of a spar, the need for extra tugboat force could be required in order to stay on the designated path.

5.3 Limitations

Due to a wide range of topics and challenges related to installing floating offshore wind turbines, I had to limit my research. Based on screening searches, what seemed to be unique with a FOWT compared to fixed turbines was topics related to the floating foundations. The research was therefore limited to marine operations related to handling the foundations. This includes tow-in/-out and mating of turbine and foundation. The actual transport at sea, operations related to ballasting and offshore anchoring operations were excluded from this research. While several FOWT concepts have been introduced to the industry over the recent years, scoping searches indicated that the spar-type and semi-submersible were favorites. The research was therefore limited to these two types to keep the research simpler and easier to follow.

6. Conclusion

The purpose of this systematic literature review was to identify marine operational challenges related to installing floating offshore wind turbines using spar and semi-submersible foundations. The results are related to operations when installing and handling FOWT foundations in port, including towing operations, mating of turbines and tow-out of complete FOWTs. In order to test and clarify some of the challenges, a development project called WindWorks Jelsa in Norway was used as contributing setting. The discussion pointed out three main topics containing challenges of various levels; challenges related to port characteristics, tug and tow operations, and mating of turbines using cranes.

First of all, challenges related to towing or lifting seems irrelevant if challenges related to basic port characteristics are not solved. In order to develop floating offshore wind farms, suitable ports are essential in order for projects to succeed. Suitable ports offer sheltered areas, quays and infrastructure to allow the construction, handling, storing and assembly of FOWT components, as well as waterways leading to the sea. Challenges arise when;

- Quay capabilities are not adequate to handle the number, size and weight of foundations.
- Berths are too narrow or shallow for foundations and/or floating cranes to safely operate.
- Fairways are too shallow or narrow, causing unsafe towing of foundations or of complete FOWTs.
- Local climate and regular metocean conditions make it unsafe to execute towing or to lift turbines onto floating foundations.
- Port and/or fairway has too much marine traffic, causing complex/unsafe passing/operations.

Furthermore, challenges related to towing and lifting must also be addressed when installing and handling FOWTs. There are obviously different challenges for the different types of foundations. However, some fundamental challenges seem to occur regardless of foundation type. The floating wind industry is in beginning stages which means it lack relevant experience in the field. This can make it challenging to perform adequate risk assessments, determine allowable limits and safety margins, as well as calculate coordination and adequate thrust force. Uncertain behavior and responses of foundations as well as unpredictable metocean uncertainties can also make towing and lifting challenging. Consequences can include;

- Unsafe towing or even grounding of foundation/FOWT due to sudden roll, heave or pitch motions caused by metocean conditions, tow-length, coordination of thrust force or waves by other traffic.
- Unsafe mating of turbine and foundation due to metocean conditions, lack of adequate crane capacity, or tugboats failing to keep foundation in position. Sudden responses by floating crane can increase G-force and payload weight, which can cause cable to break. Sudden responses can cause turbine and foundation to meet with too high velocity, causing damage to structures.

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