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Master's Thesis

Optimization of marine operations for the assembly and installation of a new floating wind concept

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University of
Stavanger

Abstract

The assembly and installation phases are relevant stages in the whole process of the life of a floating offshore wind turbine. Currently, there are multiple competing concepts aiming to make a significant impact in the offshore wind market. They have the objective of reducing the levelized cost of energy to make this technology competitive compared to other types of energies that are well established. The key consideration is identifying the concepts that can be assembled using an industrialized procedure in usual ports, allowing access to wind resources in the international market.

In this project, a comprehensive review of the state of art of various types of floating structures has been conducted. The technical aspects, installation procedures, fabrication, supply chain and port requirements have been described. Furthermore, a logistics study using the software Shoreline has been carried out. This study consists of the assembly and installation of the Moreld Ocean Wind semisubmersible concept in Utsira Nord. The wind farm consists of 25 floating wind turbines each with 20 MW capacity and their respective mooring systems. Moreover, a comparison between the assembly port of Wergeland Base and Wind Works Jelsa has been done. For this study, it is assumed that all the components are already at the ports and five different cases regarding different logistics have been simulated and compared.

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Chapter 1. Introduction

Currently, numerous countries are aiming to adopt various forms of renewable energy as a response to climate change and the need to reduce reliance on fossil fuels. Inshore renewable energy sources face limitations due to political goals, environmental restrictions and limited available space caused by human needs and environmental concerns. To address these challenges and achieve energy policy objectives while decreasing dependence on fossil fuels, offshore wind energy is being expanded. Offshore wind farms have emerged as a significant, dominant, and dependable source of renewable energy, supporting the transition to a low-carbon economy. The predominant technology employed in these farms is bottom-fixed structures, which have been adapted from onshore technology. This technology involves the use of: jackets, gravity structures, monopiles as well as tripod structures and is suitable for installation in coastal areas with shallow waters [1].

However, a major constraint is that these structures can only be utilized in water depths of approximately 50-60 meters. This limitation is not feasible for many countries with deeper continental shelves, making the deployment of this technology impractical and challenging technically. In order to harness wind energy in deeper waters, floating offshore wind technology has been developed. The use of floating structures introduces additional complexities due to the platform’s motion provoked by environmental forces. These motions need to be controlled to ensure proper installation, safe operation, meeting overall safety targets, and maintaining the position of the turbines. The most efficient types of floating structures include tension leg platforms, spars, and semisubmersibles. These different floating platforms offer both advantages and challenges compared to bottom fixed structures. Extensive research is being conducted to develop optimal and efficient floating offshore wind platforms, resulting in the emergence of several innovative concepts. Moreover, numerous demonstration and pilot projects featuring floating wind concepts are operational in various locations worldwide. In order to facilitate the successful development of floating wind farms, a significant reduction in the levelized cost of energy is crucial throughout all stages of construction [2] [3]. More precise, during the assembly and installation process where ports, cranes, towing vessels and anchor handling vessel will play a vital role in the assembly process and the installation on site, taking into account the weather restrictions and the overall cost of a project of this magnitude.

Chapter 2. State of art

2.1 Offshore wind market

In 2021 new projects were put into action in the floating offshore wind industry. One of those was Kincardine in Scotland, the largest farm with a capacity of 50 MW. Furthermore, China had demonstration project with a capacity of 5.5 MW and in Norway a demonstration project of 3.6MW with the TetraSpar concept was deployed [1].

Nevertheless, a large number of operating farms are bottom fixed structures, as depicted in figure1, where monopiles account for 64.4% of installed projects and Jacket structures only for 11.6%. This trend is gradually changing due to the need to access deeper waters. In the global market for offshore wind structures, the monopiles are expected to decrease substantially to 56.6% with 50MW of new announced capacity. The semisubmersible concept will occupy the second largest market sharing 16.2% and a capacity of 14MW approximately.

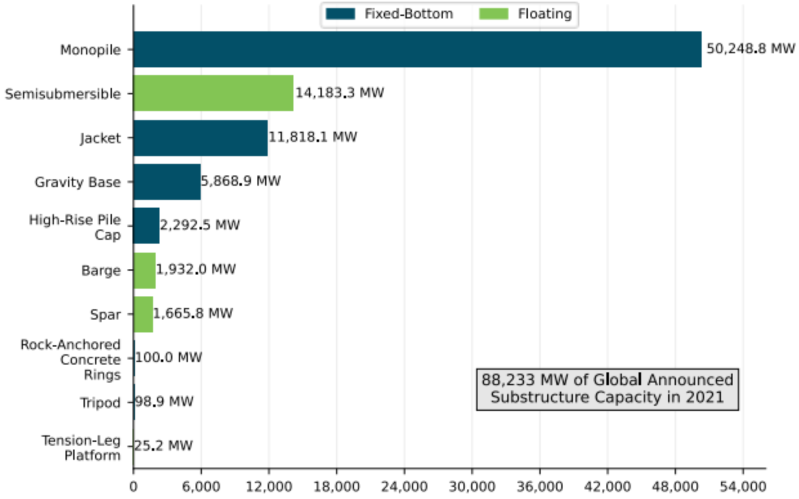


Figure 1. announced offshore wind substructures in future projects [1].

The following figure 2 depicts the incoming capacity in MW in 2021 and, the already installed capacity for various floating wind concepts. The majority of the floating wind projects employ semisubmersibles, accounting for 79.6% of the market. Although the floating wind market has been developing in recent years, its size is not large enough to get the benefits and advantages of a supply chain or large-scale industrial production to reduce costs. However, the levelized cost of energy predictions indicate a decline over time because of scaling up of floating wind technology and the learning curve [1].

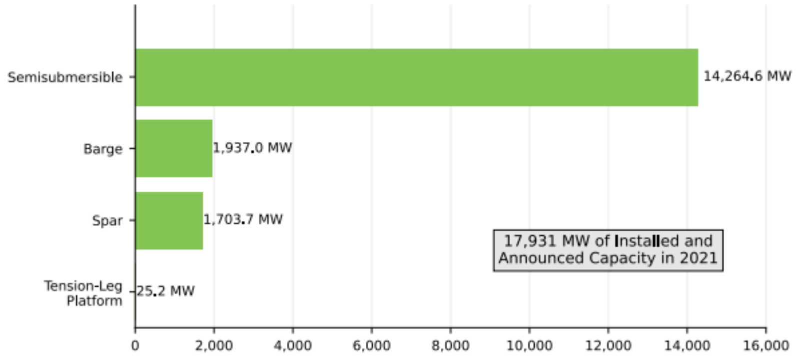
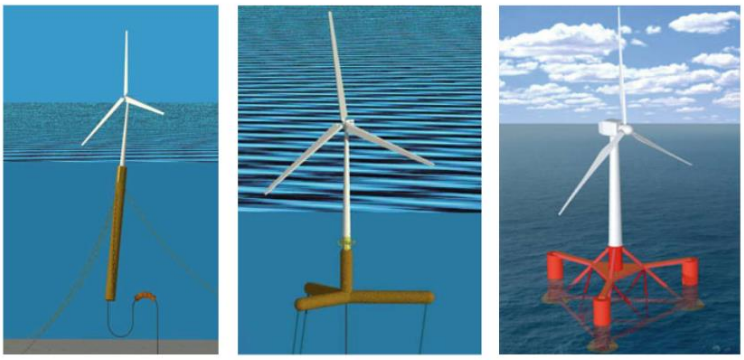


Figure 2.Offshore wind volume installed and announced projects [1].

2.2 Concepts in the floating wind industry

The use of floating structures comes with both advantages and disadvantages. Among the advantages are the ability to choose from a wide range of locations, grater flexibility in construction of the assets, installation, and easier decommissioning. However, challenges include managing the dynamics of the foundation to minimize motion, as well as dealing with wave loads, currents, thrust and torque. Additionally, more complex design is required for the modelling of the electrical infrastructure, coupled system, installation of the platform, operation and maintenance methods [2].

Floating wind structures can be divided into several components, the mooring system for connecting the floater to the anchors, the anchoring system for connecting the mooring system to the seabed, the floater for providing structural integrity and buoyancy, and the electrical cable to transport the electricity. The platform must also provide a stable base for the wind turbine to face the different loads and maintain its position. Figure 3 shows the different types of floating concepts available, including spar that the ballast provides the stability, TLP that the mooring provides the stability, semisubmersible and barge, each stabilized by the buoyancy of the floater [3].



Spar Class
(Ballast Stabilised)

TLP Class
(Moorings Stabilised)

Semi-Submersible Class
(Buoyancy Stabilised)

Figure 3. Floating wind concepts [4]

2.2.1 Ballast stabilised type

The cylindrical Spar design ensures stability by placing the centre of gravity lower than the centre of buoyancy. Ballasting water in the bottom part of the cylinder creates a righting moment and high inertia resistance to motion. Although it is relatively simple to construct, transportation, assembly and installation can be difficult due to the large draft needed. This design is only suitable for deep waters exceeding 100 meters and a deep-water port is necessary to install it. Additionally, towing it back to the port for repairs can be challenging due to its substantial draft [5].

2.2.2 Buoyancy stabilised type

The floating wind platform is held in place by mooring lines anchored to the seabed and obtains its stability through buoyancy. This design offers versatility with options for variations in configurations and number of mooring lines, as well as the placement of the wind turbine on the columns. The platform can be constructed with heave suppressing discs and either three or four columns. Although the platform requires a heavy and large structure to maintain stability, it has the advantage of a short draft, which simplifies logistics. The platform can operate in both deep and shallow waters and can be assembled inshore using basic tug vessels. However, some potential drawbacks include the need for a costly ballast system, a complex steel structure, and high structural mass [3].

2.2.3 Mooring stabilised type

This idea is based on a vertical platform that is permanently moored using tension legs to ensure stability. When the tension legs are fully installed, they provide the most stability. The mooring lines are rigidly arranged, and the platform is mainly affected by: little pitch, roll, heave, surge, sway and yaw motions [2].

However, this concept presents challenges during the installation phase, which is more difficult than other concepts. The tension leg floater is unstable during installation and requires buoyancy items during tow-out. The foundation if this idea relies on the tendons, and loss of tension due to changing water levels or tendon failure could result in loss of stability or capsize. Unlike the inherently stable semisubmersible or spar concepts, the stability of the tension leg floater depends entirely on the mooring system [6] [7].

2.3 Floating wind concepts in pre-commercial status

This section will cover a range of floating wind concepts, including concepts that are still in development and concepts that have been implemented. These concepts include WindFloat semisubmersible, that was done by Principle’s Power, the Hywind Spar, which was developed by Equinor, the Goto Island concept built in Japan, Floatgen, TetraSpar and the Moreld Ocean Wind floater.

2.3.1 Windfloat

The WindFloat is a semisubmersible platform with three legs, on onw of which the wind turbine rests. Heave plates are positioned at the bottom of the columns, as shown in figure 4, and the platform has a conventional mooring system with drag embedment achors. This design provides inherent stability, enabling assembly and commissioning to be carried out at the quaydide. The platform has a low structural weight, resulting in a significant reduction in the levelized cost of energy. Additionally, the platform has a shallow draught, allowing it to transit from regular harbours or shipyards. Assembly and commissioning can be performed onshore, reducing costs and assembly time, as weather constraints are less of an issue. Furthermore, all installation operations are reversible if the platform needs to be towed back for port repairs, resulting in lower OPEX [4]. The Windfloat concept has been used for a 25 MW wind farm off the coast of Portugal and a 50 MW wind farm (Kincardine) offf the coast of Scotland, where the floaters were constructed in Spain and transferred to Rotterdam each with a dimension of 9.6MW.

Figure 4. Windfloat overview [4]

2.3.2 Hywind Spar

Equinor developed the Hywind Spar concept, which was initially tested in Norway’s west coast with a 2.3 MW capacity shown in figure 5. Afterwards, Equinor installed a wind farm off the coast of Scotland with five turbines, each having 6 MW capacity using the same concept. The installation of this concept requires a deep draft offshore assembly in shelterd waters near the port.

The mooring system comprises of a three-point spread mooring system and a drag-embedded anchors deployed first. Subsequently, the spar structure was toed to a shelterd area using tugboats. The upending of the floater was accomplished using water ballast, which was later pumped out. Next, the rock installation vessel loaded magnetite into the structure and a heavylift vessel connected the wind turbine to the floater. Finally, the structures were towed to the wind farm location, connected to the mooring system and using salt water, ballasted [8].

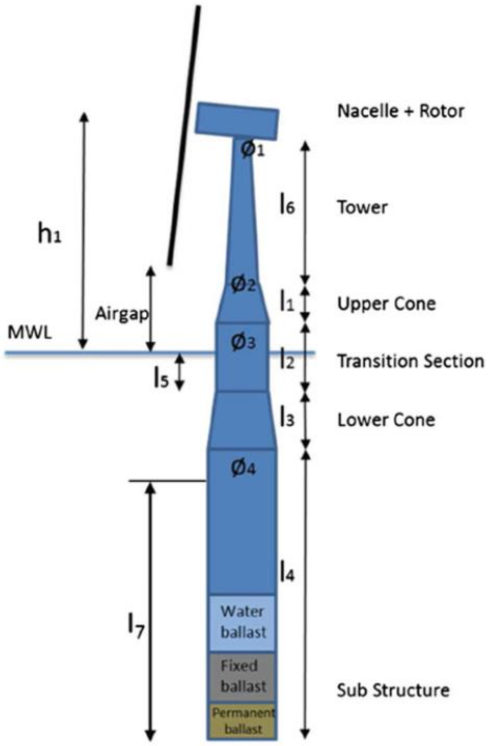


Figure 5. Hywind Spar overview [4]

2.3.3 Goto Island

This initiative was originated in Japan and constitutes a hybrid Spar design. The lower part of the Spar is composed of pre-stressed concrete, while the upper portion is made of steel, and it can generate 2MW of power. Figure 6 displays the perspective of the half-scale model. The concrete foundation is crafted to contain sea water and solids to raise the center of gravity above the center of buoyancy. The mooring system is made up of three catenary chains, two of which carry clamps weights, and drag-type anchors. Both the steel and concrete parts were fabricated simultaneously, and the steel section was transferred to Matsura quay by barge, where the concrete element was placed, and the entire structure was assembled. Once the concrete component was completed, a floating crane was employed to connect the upper steel structure to the concrete foundation. Later, the structure was towed to the island Kabashima, where the wave height is less, to accomplish subsequent installation tasks. Then, using a floating crane, the structure was turned upright and filled with seawater for ballast purposes. Later, the structure was loaded with solid ballast, and a portion of the water ballast was replaced. Finally, the wind turbine was assembled using a floating crane and towed by two tug boats to the location where it was connected to the mooring system [4].

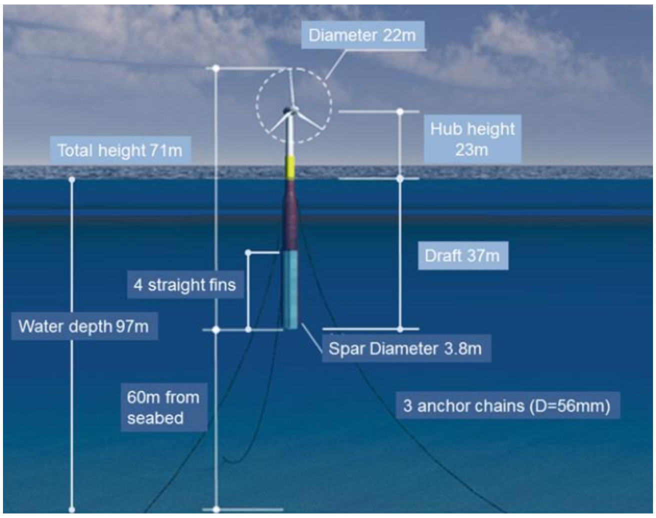


Figure 6. Goto island overview [4].

2.3.4 TetraSpar

This is a fully industrialized floating structure that comprises of modular components that are readily available in the wind energy industry's supply chain. This feature makes it possible for the structure to be deployed on a large scale while keeping costs low, ultimately reducing the levelized cost of energy. The design of this structure is focused on industrialization, which enables it to benefit from economies of scale and learning curve effects. Additionally, it reduces the amount of work required at the port by allowing for a fast assembly, eliminating the need of using specialized vessels. This floater can entirely be assembled utilizing cranes at the port.

The concept consists of ten components arranged in four structural elements, as seen in figure 7. The keel is constructed using three cylinders that are suspended from the structure with synthetic ropes. Furthermore, it utilizes a three-line mooring system [9].

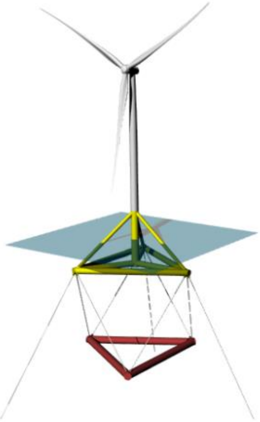


Figure 7. TetraSpar overview [9]

2.3.4 Floatgen

The first offshore wind turbine ever built and installed in France is IDEOL's Floatgen concept. This concept is a square concrete platform with a substantial gap in the middle, on one end of which the turbine is located, illustrated in figure 8. The patented "damping pool" design takes advantage of this gap to reduce the platform's motions. Polyamide mooring lines and the type of anchors are the drag embedment, that connect the floater to the sea floor. It was deployed in shallow waters (35 meters) in the northern Gulf of Biscay and has a 2MW power capacity [10].

Figure 8. Floatgen overview [10]

2.3.5 Moreld Ocean Wind

The Moreld Ocean Wind is a semi-submersible platform consisting of three legs, with the turbine situated at the center of the floater as shown in figure 9. The design of the platform provides inherent stability, allowing for easy assembly and commissioning at the quayside. This concept is focused on industrialization, where all the parts of the floating foundation and wind turbine can be assembled at the port and then towed out to the wind farm. This approach results in significant cost reductions as the onshore costs are lower, the assembly time is reduced, and the weather constraints are less problematic compared to other concepts. Additionally, the Moreld Ocean Wind floater can be made in most ports due to an easy installation and to the small draught.

Figure 9. Moreld ocean wind assembly overview

2.4 Mooring system in floating wind structures

The most commonly used mooring systems in floating offshore wind are the catenary mooring system, which is used in the spar platform and the semisubmersible. Other concepts may use a semi-taut mooring system or a taut spread as a mooring system [3], [2].

- The catenary mooring method: this method is made up of steel chains and wires that use the weight of the mooring to keep the structure in place, with the lower part resting on the seabed to support the anchor. This system is easy to install and part of the lines are on the seabed, which reduces the loads on the anchors. The point of anchoring experiences horizontal loading and some degree of horizontal displacement.

- The taut spread mooring method: it relies on the platform’s buoyancy and a strong anchoring to the seabed to achieve stability. This system is typically made of wire or usually, synthetic fiber. The anchoring point experiences a vertical load, and the anchors are subjected to significant loads. The process of installation is more complicated than the catenary mooring system and needs a high tension to limit the movements.

- The semi taut mooring method: is made up of usually, wire or fibers that are synthetic and is connected to a turret that joins several mooring lines to the seabed. The anchoring point experiences a loading typically at a 45 degree angle and the loads on the anchors are less than in a taut spread method. The installation process is simple, but since it has a single point connection, the platform is more susceptible to wave motions.

There are several factors that determine the choice of anchor, such as the holding capacity needed, conditions of the seabed, and the mooring configuration that can have different direction forces that will act in the anchor. Generally, hard clay and sand provide greater holding capacity than soft clays but may require more effort to penetrate. The main types of anchors usually used are [3]:

- Gravity anchor: this anchor performs well in vertical loading and the angle which the force is acting does not affect the output. It can be set up in almost any seabed. However, it is bulky and heavy, making it difficult to extract during decommissioning.

- Drag anchors: these anchors are suitable for soft seabed’s like clay, sand, gravel and silt. They provide horizontal loading and have a simple installation and decommissioning procedure.

- Suction Pile: this type of anchor can provide either horizontal or vertical loading but may not be suitable for stiff or sandy soils. It has a simple installation and removal process.

- Driven Pile: this type of anchor can be used in a variety of seabed conditions and can provide either horizontal or vertical loading. However, it requires hammer piling and may be difficult to extract during the decommissioning process.

2.5 Installation process of floating wind turbines

The wind industry in the offshore sector is distinguished by relatively small suppliers and manufacturers that are driven by the growth potential of the market, short-term planning, and a project-based approach. This industry is heavily impacted by weather uncertainties and the high costs of resources such as installation vessels, which can only be rented for a limited time span [11].

The installation phases of offshore wind projects in the overall supply chain often create a bottleneck due to potential weather interruptions. Manufacturers continue to produce components on schedule, but installation may be delayed [12]. Adequate port logistics are also necessary for the storage of large structures. To minimize delays, multiple structures, components and turbines should be assembled and prepared prior to loadout. When weather conditions are favorable, loadout should occur quickly and take advantage of the available weather window, which is limited usually by wind speed and wave height.

Floating wind turbines often have the floater and the turbine preassembled prior to the towing to the wind farm. This helps to minimize the offshore wok time, allowing the installation to be completed within the limited available weather windows.

The floating support for wind turbines consists of a floating foundation, anchoring system(to anchor to the seabed), and mooring lines (to connect the floater with the anchors). The anchoring system has four types: driven pile, gravity anchor, suction bucket, and drag-embedded. Meanwhile, the mooring lines have three types: tether mooring, taut mooring and lastly, catenary mooring. In addition to the mooring lines, the mooring system also has buoyancy and gravity attachments, as well as fairlead equipment and winches [13].

To install a floating wind turbine, the first step is to transport and install the anchoring and the mooring system onto the seabed. Then, the installation can follow a partially integrated and integrated method shown in figure 10. In the partially integrated method, the floating foundation is first transported and installed, and then the wind turbine is installed on it. Alternatively, the integrated installation method involves transporting and installing the floater and the wind turbine jointed [14].

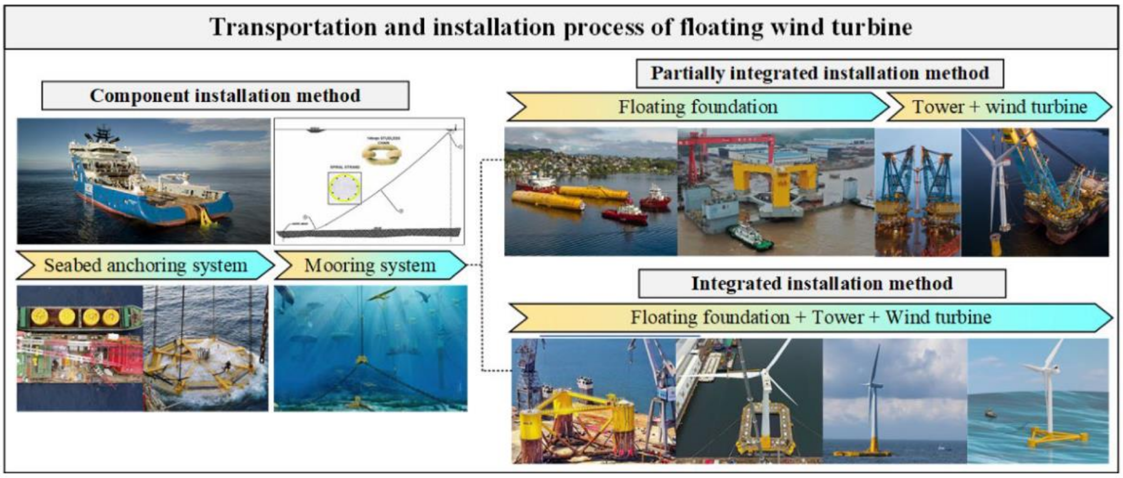


Figure 10. Phases in transport and installation [14]

The installation process for a floating wind turbine is illustrated in figure 11. It begins with the towing vessel being mobilized to the port location, followed by loading the structure onto the vessel and the towing to the wind farm. Then, the installation of the asset (hook-up) is carried out. Finally, the towing vessel comes back to the loadout port and the process is repeated until all assets are deployed and completed.

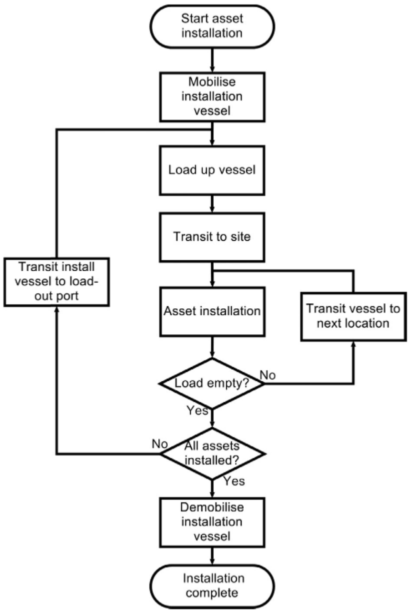


Figure 11. Installation chart [15]

2.6 Installation of Spar floater

The first ever Spar floating wind turbine was the Hywind Demo, which was installed in 2009. The installation process began with the foundation being wet towed from Finland to Norway. The Spar was then upended, solid ballasted and the parts of the wind turbine (tower and rotor) were assembled by a heavy lift crane offshore. After this, it was towed to the final position and hooked-up where the mooring system was already installed. At the end, it was linked to the mooring system and the final ballast modifications were made. The success of this concept led to the development of another different project called Hywind pilot park in Scotland. The installation steps for this project, shown in figure 12, were essentially the same as those for Hywind Demo, except for the use of a semisubmersible crane vessel during the assembly of the wind turbine.

One of the challenges related to the installation of the Spar design is the impact of wave-induced motions, which is a crucial factor during this stage. Therefore, it is preferable to upend and assemble the wind turbine in protected or sheltered waters.

A different approach is to use an onshore crane to assemble the wind turbine on the floater. The installation process is similar, beginning with building the Spar substructure if the port has sufficient space. If not, the substructure has to be transferred to the port via wet or dry towing. The subsequent steps include upending the floating structure, ballasting, and assembling with and onshore crane the wind turbine parts. The complete structure is then towed to the wind farm, joint to the mooring system, and final ballast adjustments are checked and made [3].

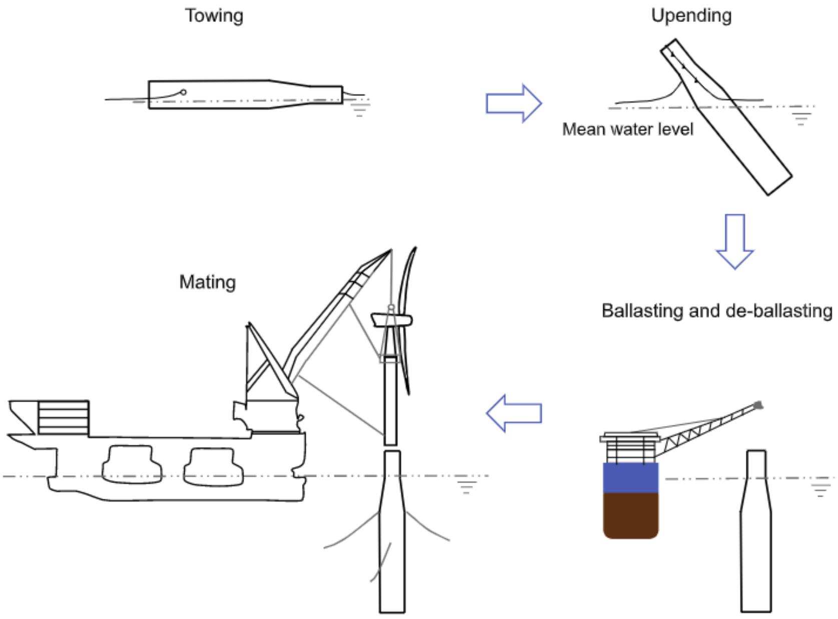


Figure 12. Installation of Spar floater [5]

2.7 Installation of semisubmersible floater

The semi-submersible concept offers several advantages over the Spar design, such as a larger waterplane area that provides greater stability and a better structural stiffness to face wave loads. Additionally, it can be towed more easily, making installation and decommissioning not complicated. The entire structure, including the wind turbine, can be assembled onshore, requiring less transportation and simplifying the process [14] . The integrated installation approach is commonly used for this concept, which is considered cost-effective due to the simplicity and lower cost of installing the mooring lines compared to other designs. Maintenance is also relatively easy, as the structure can be towed to a dry dock if necessary. However, finding the appropriate weather window for towing can be challenging due to the sensitivity of the process due to the wave height [5].

As an example, the WindFloat concept, which had a 2 MW capacity, was installed off the coast of Portugal and remained operational for five years. The assembly process was conducted in a dry dock and involved constructing the hull, tower, and at the end, the wind turbine. The fully assembled structure was then towed to the installation place and connected to the pre-existing mooring system using three tugboats and an anchored handling vessel to assist with the hook-up. Figure 13 shows the process of towing the structure to the site.

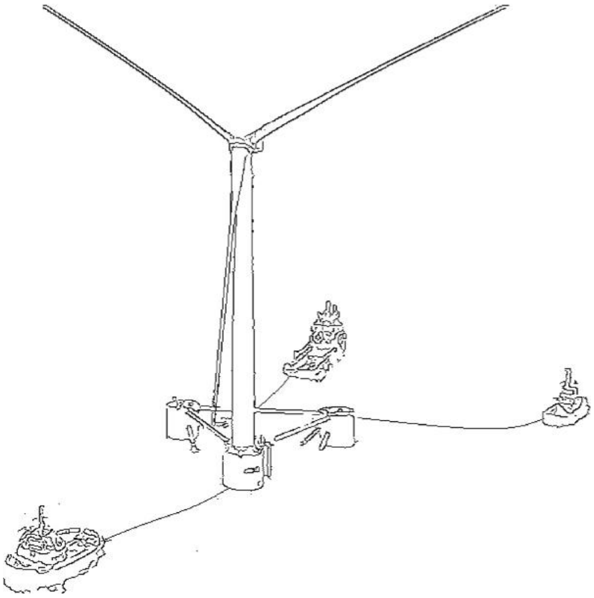


Figure 13. Installation Semisubmersible [5]

2.8 Floating offshore wind requirements

In order to get the best potential and profit from offshore wind the wind farms, they have to be built in the best possible sites [16].

-Wind speed: the most important factor in the levelized cost of energy is the wind speed, the larger the more power output. Even though, large wind speeds produce an increase in the capital expenditure due to the rise in loads and the increase of the dimensions of the structure, it is negated by the increment of power output. This results in a reduction of the levelized cost of energy.

-Water depth: some floating concepts need deep water such as the Spar concept but most of the concepts need around 40 meters depth as a minimum. The ideal depth should be around 100 meters due to the cost effectiveness related to the mooring system. If the depth is increased to 150-200 meters there would be an increment in the total mass of the mooring system and therefore, the overall cost.

-Geotechnical conditions: these conditions are an important aspect to determine the type of anchors that are going to be used. To get the maximum holding capacity the best type of soils are the cohesive ones. This soil is not excessively stiff to difficult the penetration on the seabed and is not excessively to loosen to restrain the resistance of the seabed.

-Weather conditions: the weather conditions will determine the design of the floating structure. The most important factor is the wave height. The larger this factor is, the more conservative the design will have to be, which will raise the weight and the costs of the structure. It is preferred that the wave height is as low as possible, but this factor is usually correlated with the wind speed. Furthermore, better weather conditions make the installation and maintenance preferable.

-Distance to the grid connection point: the wind farm should be as close to shore as possible. This would reduce the cost of the transmission cables and the losses of the transmission.

-Distance to the port: the distance to the port is an important factor. This will impact CAPEX due to the costs of transit to install the assets and the available weather windows. Also, it will impact OPEX due to the distance to reach the wind farm and perform the maintenance.

-Port facilities: the port plays an important role in the costs of CAPEX and OPEX. It will provide storage, assembly and installation. The size and the capability of the port will determine the time and costs of the project. Dry docks are preferred for floating wind because they allow assembly and the posterior launching by flooding the dock. One of the problems is that this type of facility is designed to construct and repair ships. That means that the offer is limited and could provoke bottlenecks when adopting an industrialized process in the assembly.

-Proximity of suppliers: If the suppliers are close to the port, it will reduce the overall costs of the project. Depending on the distance it will influence the logistics of the transport of components for assembly to the port.

2.8.1 Vessel requirements

One of the benefits of floating wind turbines is the cost saving due to the type of vessel used. For bottom fixed the need of expensive vessels such as dynamic positioning vessel or jack-up that increases the cost substantiable. For floating wind, tug vessels are required that are around 80% cheaper [16]. Furthermore, tug vessels and cable lay vessels are needed in all types of different floating concepts. The Semi-submersible is the concept that requires less vessels for its installation, usually four. The Spar concept needs heavy lift dynamic vessel for the assembly of the turbine and barges that transport the structure to shelter waters to be erected. Also, TLP needs barges to transport the structure. In the following figure 1, the different number of vessels for each concept is shown.

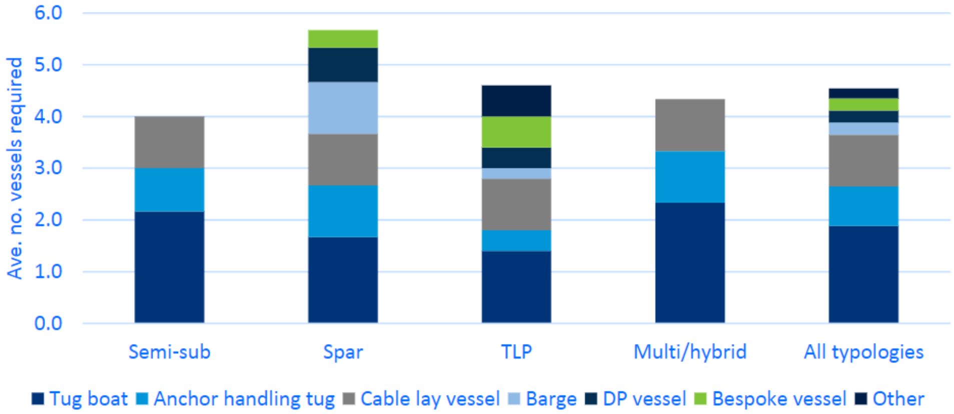


Figure 14. Vessel requirements for different concepts [16].

The vessels used in the installation process of the floating wind turbines are of maximum importance in the overall cost of the project. The main costs are the personnel and the charter of the vessels. They are highly dependent on the port location with respect to the wind farm and the weather.

For bottom fixed turbines the vessels must transport the wind turbines to the site and perform the installation process. As a result, highly specialized vessels must be used. This type of vessels have a large impact on the installation cost. On the other hand, floating wind does not need this kind of vessel since all the construction is done at the port. Simpler tug vessels can be used to transport the whole structure to the site which is cheaper to use. If the number of vessels and the specialized vessels are reduced this could decrease substantially the installation phase in the offshore wind industry.

Anchor handling vessels have to be used to install the mooring system and to perform the hook-up. Furthermore, the charter costs of these vessels must be considered, since the charter rates fluctuates excessively, and it is hard to know during the planning of the project [17].

2.8.2 Draft requirements

Draft requirements will vary depending on the different concepts and the type of operation (assembly, transport and installation). Generally, the semi-submersible has a need for more depth at the port and transit, around 10 meters because of the heavier mass of the floater. Spars and TLP usually use barges for transit that need low draft, around 7 meters. Spar concept can also be assembled at the port which would require a draft of around 12 meters or more. Depending on the draft of the port facility, the appropriate concept should be chosen. For installation, the Spar to upend and ballast needs a substantial draft, around 90 meters. TLP requires an installation draft of approximately 50 meters. The semi-sub is more flexible and can either be installed in deep (100 meters) or shallow waters (35 meters) [16].

2.8.3 Met-ocean conditions

The weather limitations are relevant to reducing the amount of time used for installation. If the concept can perform in larger wave heights it is less likely that the installation will be stopped by the weather. For the semisubmersible the wave height for transit is around 2.5 meters and for installation 2. For TLP transit is approximately 4 meters and installation 1.5 meters. For Spar concept assembly wave height is 1 meter, transit is approximately 5 meters and installation 2 meters [16]. Semisubmersible concept is the most flexible concept due that it not being constrained by depth and handles a larger wave height overall.

2.9 Fabrication of the structure

Nowadays, there haven’t been major bottlenecks due to the reduced size of the floating wind projects. In the future, there will be potential bottlenecks due to the commercial scale of wind farms. These bottlenecks will depend on the transport of components, assembly and installation of the wind turbines.

As a difference with bottom fixed wind turbines, where the heavy lift vessel and other vessels have an important role because it is needed for installation. For the floating wind, the vessels availability is not a problem. Tug vessels and anchor handling vessels are usually available for the installation.

The fabrication of the floating structure is very similar to shipbuilding. Therefore, this makes it possible for manufactures to exploit the existing facilities with the necessary modifications for a serial production process [16].

2.9.1 Steel

Most of the concepts use steel as the main material for fabrication of the floater. In steel structures, the components are transferred to the port, subsequently the assembly of the components takes part. Some concepts have taken in modular designs where the structure will be fabricated and assembled in different sections. This approach makes the assembly more effective and lessens the requirements of a heavy lift crane at the port. When the assembly is finished, the floater is either skidded over a slipway or lifted into the water. Following that, the wind turbine will be assembled on it.

Some of the advantages of using a steel floater are the following [17]:

- This material is well established in the industry, and it is known and proved by its relevant standards.
- The structure is going to be lighter than the concrete one.
- The assembly process can be rapid since all the components can be transported and assembled at the port only positioning the components and performing the welding operations.

Some of the disadvantages are:

- The planning of the process can be difficult since the price of the material can fluctuate and can be expensive.
- To do the modular assembly large cranes and specialized welding equipment are needed. Also, enough space to do the whole assembly of the structure.
- The dimensions and the heaviness of the components can be large which can be difficult for industrial scale production. Furthermore, transporting these components and storing them in large amounts can be challenging.

2.9.2 Concrete

So far in the wind floating market only six floaters have been constructed using concrete. In concrete platforms the fabrication process will be different. It will be necessary to find local reinforced concrete suppliers, and the platform will typically be built using a slip form method, in which concrete is constantly poured to create a continuous individual structure with no joints. A sizable set-down area and dock with enough load bearing to support the weight of the structures are required for the procedure. There won't even be a need for large onshore fabrication facilities because the concrete structure can be built on an installation barge [16].

Some of the advantages of using a concrete floater are the following [17]:

- This material has a low cost, it does not require specialized equipment, local workforce and supply chain can be used, the concrete is adaptable locally for the project needs and conditions. Moreover, this material does not need a large storage area at the port since it is ready-mix concrete.

Some of the disadvantages are:

- This material has not been used that many times compared to steel, this results in having less experience. Since the dimension of the floater is large, the port will require a large space to construct in mass production.
- The weight of the floaters can be really large, and it can result in restrictions due to bearing capacity of the ports.
- These concrete platforms have weather restrictions when they are being constructed.
- Further steps need to be taken since tension loads are not suitable for this material.
- Due to the fact that the mixing process is done at the site it can be inaccurate, so it needs extra quality checking.

2.9.3 Limitations of construction

The availability of draught and beam at port-side are another factor to take into account in order to facilitate assembly and transportation to the site. A dry dock also has the advantage of being flooded to the ideal level for turbine installation before being floated away. Furthermore, the dry dock accessibility can cause bottlenecks for large scale wind farms.

Even though, the selection of material can cause different constraints, there are general limitations that are caused by the general fabrication of the structures. The main ones are the float-out and transport in the port. The transport of the materials and components and the related tasks must be considered. Also, the constraints that can be caused by the continuous supply to the port. The production of the floaters must require cranes to do the fabrication and the posterior assembly. The requirements of the crane depend on the type of floater that is being constructed and the weight of the parts that need to be assembled. Cranes can cause a limitation in the construction process, and they vary from port to port. This can cause that some ports will be not applicable for these projects.

Another possible limitation can be the float out which is going to be dependent on the port. The dry dock is the simplest option if the asset is constructed there. It only requires flooding the dock for the float out. Another option is the construction on a barge which is also efficient. It consists of submerging the structure to a specific draft, then the barge sinks until the structure is lift off from the barge. Moreover, the structure can also be constructed on the quayside which will have to be transported for the float out. This needs to be properly planned to avoid bottlenecks [17].

The main challenges when constructing a floating wind structure are the type of concept that will be used, the weather limitations at the assembly and installation place and the type of port where the project will take place and its infrastructure. Furthermore, the storage capacity, facilities and equipment and the option of making modifications or expanding the port for large scale projects. Also, the main characteristic of choosing the port will be the distance to the wind farm.

2.10 Logistics and supply chain

The cost of producing energy by floating wind turbines is influenced in different ways. The installation processes, weather conditions, the connection to the energy grid and the maintenance and operation of the wind farm. The total costs of the logistics of floating wind accounts around 5-10% of the whole investment cost. This is a 10% reduction in the cost of logistics for bottom fixed wind turbines [18]. The installation of the floating wind farm is really complex and it needs a proper collaboration of the whole logistics network. The networks consist of the method of installation, the characteristics of the port, the number and type of readily available spaces for construction and the transfer of components.

2.10.1 Transport and installation

The installation procedure starts when the manufacturers produce the components that are divided in: the mooring system, the components of the floater, the tower section, nacelle, hub and blades. After that, the logistics provider organizes the transport from the components manufacturer and the port. Subsequently, the port operator has the responsibility of handling and storing the components. Following that, the construction company handles the components and operates the vessels and installation process. In the end, the transport and installation of the components are carried by vessels [18].

Furthermore, the transport of the substation goes directly to the installation location because no assembly is required. Cabling-laying vessels with the loaded cables do not need port assembly. Once all the different components have been designed and manufactured, they have to be delivered to the harbor where the assembly will take place. Based on the location and the size of the turbines the transportation can either be done by land using oversized trucks or by sea using vessels. Moreover, depending on the port capacity not all the components can be delivered at the same time due to the limited space [19].

2.10.2 Supply chain

In the supply chain the following terms are relevant: [20]

-Constraints: this factor is caused when the capacity of producing certain elements in the supply chain is less than optimal.

-Bottlenecks: this factor is produced by the lack of balance in the supply chain. The demand of the market is higher compared to what can be produced.

-Barriers: these are parts that produce a slow development or blockage of the supply chain within the renewable and offshore wind industry.

The main bottlenecks and constraints that face this industry are the following: connection and expansion of the grid, storage of the produced wind energy, human skills and capital, government policies tariffs and subsidies, offshore deployment and logistics, investment resources and lack of new places to install a wind farm [20].

In the supply chain the main components of floating wind turbines are: the mooring system, floater components, wind turbine components, onshore/offshore substation and cables (array cables and export cables). Apart from the main components there are minor components, but these do not represent the vital part of the installation project. For every component the supply chain involves the infrastructure and equipment related to transport, storage, installation and the combined service providers. The supply of this infrastructure can either be done individually by firms or as a combined work packages (supply, transportation, and posterior installation of cables) [18].

To assess the configuration of the supply chain of an offshore wind farm it is divided into three levels shown in figure 15. First, the upstream that consists of: research and design, the manufacturing of the cables and its three stages (materials, parts, inter-array and export cables). Moreover, the offshore part has three stages (materials, parts, substation and foundation). In addition, it also includes the manufacturing of the turbine and its three stages (materials, parts, sub-components and turbine). The midstream phase includes the development of the wind farm and its services such as: construction, logistics, operations and installations. The downstream consists on the power companies and the users of the electricity [21].

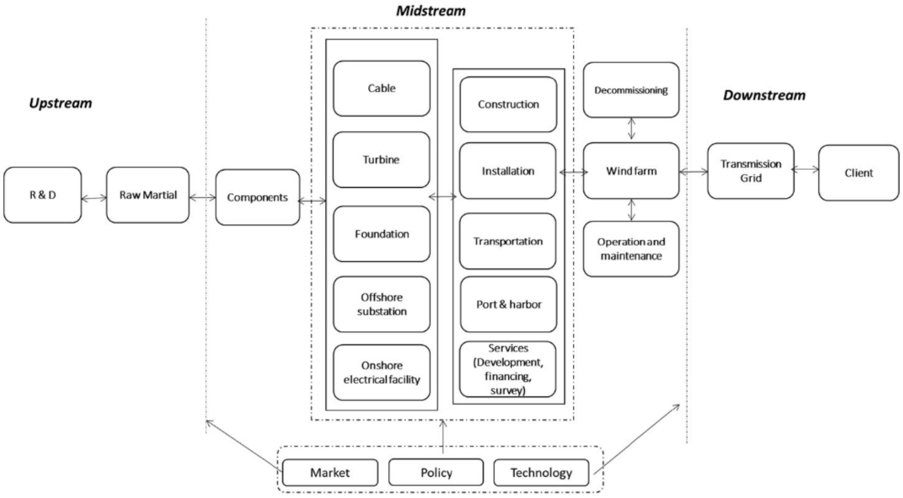


Figure 15. Upstream, midstream and downstream in offshore wind [21].

2.10.3 Phases in the supply chain

The offshore wind farm life cycle is usually divided in the following phases, seen in figure 16, and each phase has its own bottlenecks in the logistics and supply chain [20]:

- Development and consent: in this face a set of different surveys are carried out for the site planning. The surveys are done by survey vessels and normally are: geophysical, ornithological, geotechnical and others. These are performed to check if the area is suitable to install a wind farm and not affect wildlife and nature.

- Installation and commissioning: this face consists of two different supply chains. The outbound is based on the warehouses, ports, storage places. Furthermore, the components such as subsea cables, foundations and sub-stations. These parts have a different supply chain which acts as the lead for the installation and commissioning of the assets. The inbound, is based on the parts of the wind turbine like the blades, nacelle, foundation and tower. These are assembled using different logistics and manufacturing methods. For instance, the assembly of the nacelle that consists of 65,000 components is based on different sub-assembly procedures and on-site warehousing. The most important suppliers are usually located around the assembly plant for better factory logistics and to make sure that the transfer of different components and sub-assembled parts are done effectively.

- Operations and maintenance: this supply chain lasts as long as the wind farm is operational, 20 to 25 years. This phase uses a preventive approach of the supply chain that schedules the different tasks. Nevertheless, if an unpredicted event occurs there must be unscheduled maintenance that makes it more logistically challenging and more expensive. These tasks need technicians, tools spare parts and components that have to be transported to the wind farm due to the scheduled maintenance or emergency maintenance. To transport them, transport vessels such as crew transfer vessel, along with accommodation vessel or platform are used. To replace different components of the wind turbine smaller installation vessels are used. These marine operations don’t have to be done during rough seas because it would make technicians to be seasick and may have difficulties aligning the vessel to access the wind turbine.

- Decommissioning: the decommissioning phase of the supply chain is very similar to the installation phase because it usually requires the same logistics to carry on the process normally having the same constraints and challenges.

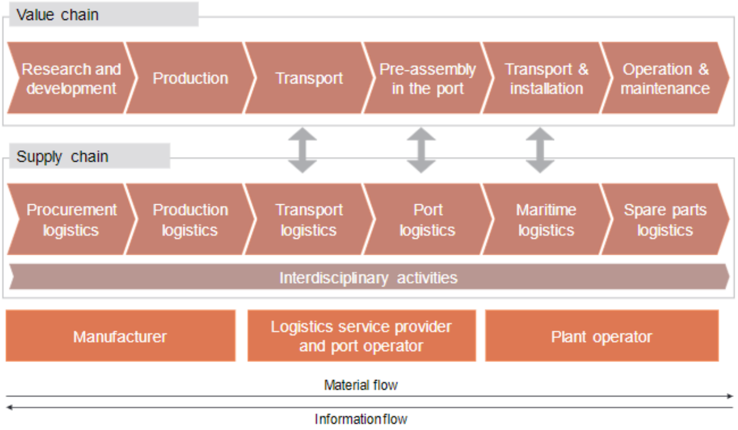


Figure 16. Value chain and supply chain in the offshore wind installation [22].

2.10.4 Logistics network

Offshore wind logistics are complex, and it is dependent on the environmental conditions. The offshore bottom fixed wind is mature compared to floating wind turbines. It is a new technology and there are only a few projects where most of them are individual prototypes.

The installation process and logistics for the floating wind are different than the bottom fixed. The majority of the processes are done in the port or shipyard than at sea and this makes the supply chain different [23]. In figure 17 the whole process of the logistics and installation of a FWT is shown.

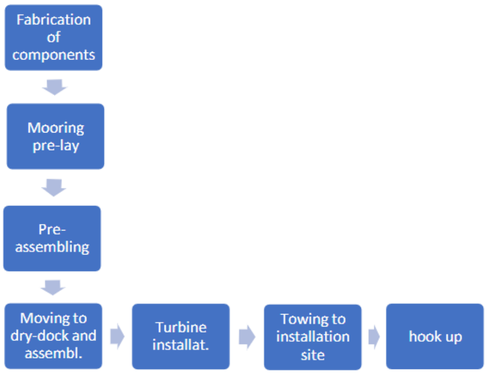


Figure 17.Process of installation of a floating wind turbine [23]

In contrast to traditional logistic chains, offshore wind requires a more complex resource planning due to the meteorological conditions. This stochastic factor makes it more difficult to transfer the knowledge of the supply chain of other industries. Therefore, it is of great importance to do the proper controlling and planning of the logistics chain that will contribute to cost savings.

The logistics chain in installation and production is aimed by a downward material flow from the manufacturer (source) to the installation place (sink). In figure 18 the supply chain for an offshore wind farm can be seen. It consists of the following: first, the raw materials and the semi-finished component suppliers start the supply chain. Subsequently, the manufacturers make the different components of the wind turbine and the fixed or floating structure. Then the transport of the components to the assembly port is usually made by vessels provided by the logistics services. Also, the raw materials and the semi-finished component are transported by the logistics service to their correspondent places. At the end, the different components are stored and assembled at the port and then transported and installed in the wind farm. The end of the supply chain corresponds to the installer that is the last customer [24].

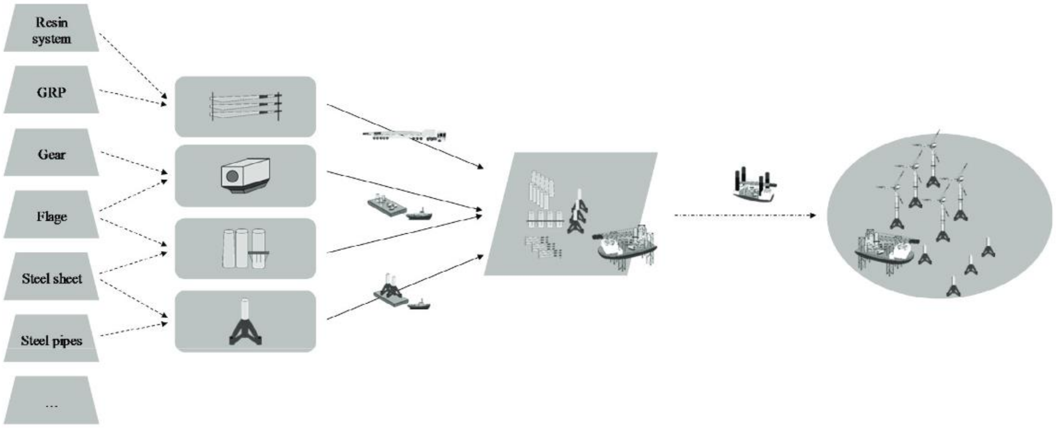


Figure 18. Supply chain for offshore wind [24].

2.11 Assembly site

Since the offshore wind industry extends in Europe and the world, the harbors (seen in figure 19) have become an important and strategic part in the whole process. Also, it is important in the supply chain because all the operations of the project are supported by it. For this reason, the proper selection of the port that is suitable for this industry to support all the required operation is an important decision. Ports in floating offshore wind have different functions: construction (the construction of a substructure in a shipyard, base for weather survey and geotechnical survey of the offshore site), manufacturing (blade manufacturing in a quayside factory, loadout quay for the parts of the turbine), assembly site, installation (laydown area for the different components such as mooring system, array cables or the floating structure) and maintenance (maintenance support port) [25].

The main port characteristics are the following [26]:

- Port's depth: this characteristic is important for substantial vessels with large drafts that can be used in the port. Also, it is crucial for the installation of different floating concepts such as Spar type that needs a large draft. Furthermore, for maintenance, small vessels with shallow drafts are required.
- Equipment to handle components: ports must have proper equipment to assemble and install the floater's structure or the wind turbine components using heavy lift cranes or other types of cranes.

- Loadbearing capacity of the quay: this capacity is characterized by the capability of ground surface to withstand the weight of a structure or component before failure. Usually, the capacity should be between 15-20 $tonnes/m^2$.

- Quay length: this parameter is relevant to assembling and deploying the different substructures.

- Distance to the wind farm: this parameter is the distance between the port and the wind farm for the installation and maintenance of the wind turbines. It influences the cost and time of the project.

- Road networks: the port should have access to roads due to some components may arrive by road from their place of manufacturing. Nevertheless, since the size of the offshore wind turbines are increasing it is more likely that the components arrive at the port by component transfer vessels.

- Component supplier's distance: the components are transported from the manufacturing place to the port where they will be stored and assembled before they are installed. If the distance is large, it can increase the costs and the time of the project.

- Storage availability: this parameter is relevant for industrialized processes of installation and assembly where large quantities of components must be stored after they are transported from the manufacturing site and later, they are assembled. Moreover, the layout of the harbor should be that the storage area is connected with the assembly site so the distance of transporting the components is not considerable. This storage area can be covered or open.

- Components assembly area: the area for the assembly of components of the floater and the posterior integration of the components of the wind turbine is critical to avoid bottlenecks.

- Manufacturing facility: to reduce the number and cost of the transportation of components and elude the loading and unloading of these components. Some ports in Europe have utilized this strategy and they have manufacturing facilities to produce wind turbines.

- Office and workshop facilities: for operations and maintenance ports the workshop facility is important to repair and make proper maintenance of the assets. Also, offices must be available at the port since they have the daily responsibility of the operations and maintenance.

- Expansion potential: ports that have expansion potential are considered better than those with restricted potential for the future developing of larger offshore wind farms.

Figure 19. Example of an assembly site [19].

In figure 20 the port interaction process is shown. To store the different components of the floater and the wind turbine (nacelle, blades, tower) a substantial area is needed. This area is dependent on the number of turbines to be installed, their size and the type of floating structure.

To assemble the different parts a set of different cranes or a large crane will be required. The crane must be able to lift the nacelle that is the heaviest and the tallest component. Once the turbine is integrated it needs to go through some tasks done by the technicians: bolt tensioning, painting, safety system and electrical circuits checks. The floater is wet stored until the turbine is integrated on it. Following that, the whole structure will be towed to the offshore location.

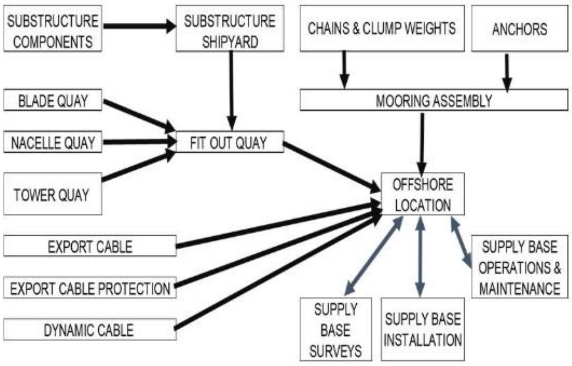


Figure 20. Port interaction process [25].

2.12 Processes of construction of the wind farm

2.12.1 Deployment of components from the ship

From various places around the world the different components that are part of the floating wind turbine are brought by ships. The type of ship depends on the type of components that are being transported. It can either be a Ro-Ro vessel that uses the stern or bow to deploy the components, or a cargo vessel seen in figure 21, that docks alongside the quay. Usually, the Ro-Ro vessel deploys the hub and the nacelle. The tower components and blades will be lifted from the cargo vessel using cranes [27].

Figure 21. Cargo vessel transporting components [28].

The hub can be mobilized from two types of vehicles, by self-propelled modular trailers (SPMT) from the Ro-Ro ship or from cranes from the cargo ship. The hub will be equipped with some monitors and a precise handling is required, nevertheless the size and weight of this component is low. The nacelle (figure 22) can also, be deployed by the two different types of ship. It has to be considered that the nacelle is the heaviest and most complex component. The deployment is helped by shock absorbing elements. After that, to transport the components the SPMT will lift them from below the supporting elements.

Figure 22. Deployment of the nacelle [28].

To deploy the tower sections (figure 23), the cranes from the vessel or the port, will lift (usually by two cranes) the different sections and land them on specified vehicles or area.

Normally, blades are transported in a pack of three for an easy deployment using cranes. Depending on the crane capacity, one blade can be lifted at a time or the full pack. Also, this part of the turbine is the lightest.

Figure 23. Deployment of the tower sections [28].

2.12.2 Loadout mooring system

The mooring system has to be installed in advanced before the turbine is ready for towing out. The anchors and the mooring lines will be transported by sea to the assembly port from their manufacturing place. A part of the mooring lines will be stored in vessels because they are made of steel wires rope and synthetic fibres. Specialized equipment needed will be at the port and ready to be placed onto the installation vessels. The mooring system follows these marine operations [25]:

-The crane from the manufacturing port loads the mooring anchors and lines on a component transfer ship.

-The crane from the assembly port offloads the mooring anchors and lines from the component transfer ship to the mooring storage facility.

-Load the mooring system onto an anchor handling vessel for their installation at the offshore site.

2.12.3 Loadout subsea cables

The subsea cables must be stored onshore before they are installed at the offshore site. Generally, these cables are installed before the wind turbine is hooked-up. The dynamic array cables are connected to the export cables that are buried [25].

2.12.4 Floating structure

The floating structure can be assembled at other port and transported by sea. When it arrives to the next port it will have to be installed in the dry-dock or along the quayside to do the integration of the wind turbine. If it left along the quayside, it will be moored.

If the floating structure is assembled at the same port, the different components will have to be transported from different parts and deployed at the port using a Ro-Ro or a cargo vessel.

2.12.5 Transportation and storing of components in the port.

Usually when the parts are deployed by the ship, SPMT (figure 24) or special vehicles will transport them depending on the characteristics of the elements. Generally, the hub and nacelle are going to be transited with a SPMT and the rest of the components such as blades, tower sections and other elements of the floater can be transported by SPMT or special trucks.

Figure 24. SPMT carrying the nacelle and the hub [28].

Nacelle and hubs need to be stored in covered places to avoid environmental stresses and avoid places where there is a risk of corrosion since these are to most delicate parts of the turbine. Furthermore, they should be kept above the ground for easy transportation.

Blades can be stored in frames horizontally in the storage area outdoors. It needs cautious handling due to its fragility. Towers are the most robust component and can be stored outdoors in horizontal or vertical position in a storage structure for its posterior transportation for assembly [28].

2.12.6 Transportation to assembly area

The transportation of the components from the storage area to the assembly area (figure 25) is similar to the transport from the quayside to the storage area. Depending on the component, SPMT, cranes or rolling trucks will be required. The blades will be carried by rolling vehicles, the hub and the nacelle, generally, by SPMT and the tower's sections will usually be lifted by cranes and left on SPMT or trucks [27].

Figure 25. Transport of the tower sections at the port [28].

2.12.7 Assembly of the turbine

Before starting the assembly process, the area needs preparation. The welding area needs to be clean of other elements, paints, rust, dirt, and moisture. In this area some of the components will be welded together. First, the tower section will be assembled. The surfaces will be prepared and rinsed. The ends of the sections require fixing and preparation, the bottom and the top of the sections will be the assembly points of the process. These parts will be joint by bolts and welded inside and outside in a symmetric way. Typically, on the port, the towers are assembled horizontally. To help the welding procedure and the tower's rotation, pipe turning rolls are utilized. To use these rolls the tower will be lifted by a crane from the SPMT onto the rolls.

Following that, the assembly of the hub with the blades will take place. The hub will be raised by a crane from its frame and left facing upwards. Then, the hub and the blade will be aligned using a crane. During the assembly the blades must be turned 90 degrees. After that, the blade will be connected to the hub with up to 128 bolts and the misalignment will be checked when the procedure is over. This process will have to be repeated for the three blades [27].

Figure 26. Assembly of the rotor [28].

2.12.8 Transportation of the components to the quayside and integration of the wind turbine to the floater

When these parts of the turbine are assembled, they will have to be transferred to the quayside to assemble everything to the floating structure. First, the floater must be prepared, cleaned from rust, paints, grease and ready to for the welding and the fitting of the bolts. After that, the tower will be transferred with SPMTs to the quayside and the ends will be prepared to be joint with the floater. Simultaneously, the nacelle will be lifted and transported with SPMT to the quayside. The assembled rotor, since it is a large component must be transported carefully with SPMTs.

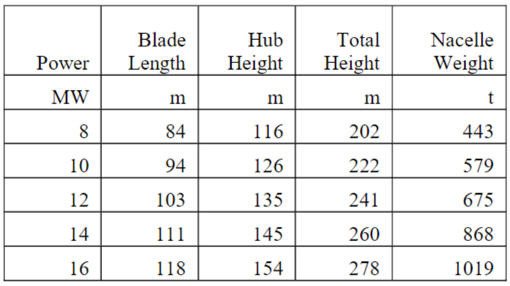
Subsequently, the components will be installed with a large crane that is capable of lifting to the required height and has a capacity to withstand the weight of the objects. First, the tower will be assembled onto the floater. There are various procedures to upend the tower in a controlled and safe manner. For instance, the J-hook that serves a s a guidance of the tower to avoid impact with the ground or other elements. This hook will raise to the tower from the bottom and the crane from the top. Then the guidance elements will make sure the tower is placed in the right position. Next, the nacelle will be lifted from the vehicle by the crane and positioned on the top of the tower. Eventually, the same procedure will be used to assemble the rotor to the nacelle. Another method could be to assemble the hub and the blades one by one, separately, lifting them from the vehicles and installing them on the nacelle in the floater [28].

2.13 Installation and requirements for floating wind turbines

One of the best characteristics of floating wind is the capability to avoid offshore operations (heavy lifts) that are weather dependent and highly costly. Doing the assembly at the port avoids these constraints, saving cost and time. The assembly port must be as close as possible to the offshore site for the towing of the turbines. This process is weather restricted. Nevertheless, the manufacturing port of the components or the construction port of the substructure can be a long distance.

Furthermore, the type of concept that will be installed is based on the capability of the fit out of the port and its water depth. Ports are crucial constraints in the installation phase. Since there are different concepts competing for the commercial market, the type of concept will need different port infrastructure. Most of the process is done onshore as a difference with bottom fixed wind turbines. As a result, the ports will require an expansion of their area for the cranes, assembly, storage of components and retrofitting for production as an industrialized process. Usually, ports with 80 meters depth can install Spar concept and ports with 15 meters depth can install TLP, barge and semisubmersible concepts. In addition, for the same dimensions concrete structures weight more than steel so they have a larger draft. [25].

In figure 27 the different heights and weights of the nacelle and blades can be seen. Usually, the height and weight of the different components of the wind turbine can cause constraints in the onshore cranes at the port or floating crane vessels if they do not have the proper capacity. Between the water line and the and the lowest rotation point of the blade should be 30 meters of distance.



Power	Blade Length	Hub Height	Total Height	Nacelle Weight
MW	m	m	m	t
8	84	116	202	443
10	94	126	222	579
12	103	135	241	675
14	111	145	260	868
16	118	154	278	1019

Figure 27. Heights and weights of the nacelle and blades [25]

Generally, the floating structure is constructed using concrete or steel and each type of material has its own advantages and disadvantages. Concrete has a low cost, no unusual equipment is necessary, the supply of concrete is adaptable and has local content. On the other hand, steel is established in the sector, due to a lighter structure the water depth of the port can be lower. The assembly of the pre-fabricated components can be done rapidly.

2.13.1 Planning tasks

The following planning task are described to ensure an efficient and proper installation of the assets [29].

- Supply chain and long-term production coordination: to accomplish a proper installation procedure a long-term planned coordination must be generated. In an industrialized process, a proper production plan is required to assure that all the components will arrive at the port at the right time. Furthermore, it has to be precise to avoid large and costly storage of the different components.

- Capacity planning in long-term: storage areas in the port and logistics such as vessels and cranes have to be rented prior to the operations so proper long-term planning is important. The production plan can be influenced due to disturbances in the lower levels of the supply chain. For instance, operations can speed up due to good weather or delayed by bad weather. Also, delays in the transfer of components oblige more storage time than expected. Usually, the logistics have to be rented in advance for a fixed amount of time.

- Transportation planning in mid-term: transport of components by transport vessels has to be planned in advance like the manufacturing of components. In addition, weather conditions can complicate transportation that can cause shortage of components at the assembly place.

- Execution and operations planning in short-term: long-term and mid-term planning relies on assumptions for the weather and availability of components and logistics. In short-term planning the operations are highly dynamic due to uncertainties of weather and the supply chain. If there are delays in the operations the changes have to be shown in the planning of higher levels for a smooth installation process.

- Scheduling and planning of the workforce: workforce must be planned like the operations. Qualified personnel and the crew vessels during commissioning have to be scheduled.

2.13.2 Influences in the installation process

In this section, the most critical influences on the execution phase are described [29].

- Weather: this is the primary influence and most crucial factor on the planning and the performance during an offshore operation. Furthermore, uncertainty of prediction of the weather can cause delays.

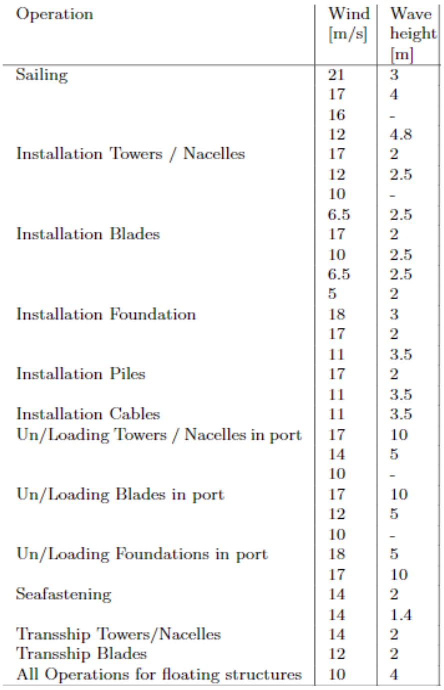
- Delays in transportation: the transport of components should be planned in advance. Some of the components can only be transported by some types of vessels due to their size. If there is a deviation of the planning schedule it could cause large delays in the supply chain.

- Damage of components: due that the logistics such as cranes or vessels need proper maintenance and breakdowns activities, this could cause delays that are not planned within the supply chain. Also, components could be damaged during the different operations the logistics must make.

- Production delays and missing of components: Some components can miss due to mistakes in the scheduling of production or damage, e.g., when orders are discordant, or components are delayed. Moreover, the wrong component delivery is caused by sub-optimal coordination and planning.

- Workforce qualification and scheduling: during commissioning, specialized technicians are needed and must be available to do the tasks. If the workforce lacks qualifications or is sick, this could cause uncertainties during the operations.

The supply chain is restricted due to the maximum wave height and the maximum wind speed. The operation must be stopped if either of these values are exceeded. In figure 28 the maximum values permitted for bottom fixed and floating wind turbines are shown (these values may vary depending on different factors and are not always the same).



Operation	Wind [m/s]	Wave height [m]
Sailing	21	3
	17	4
	16	-
	12	4.8
Installation Towers / Nacelles	17	2
	12	2.5
	10	-
	6.5	2.5
Installation Blades	17	2
	10	2.5
	6.5	2.5
	5	2
Installation Foundation	18	3
	17	2
	11	3.5
Installation Piles	17	2
	11	3.5
Installation Cables	11	3.5
Un/Loading Towers / Nacelles in port	17	10
	14	5
	10	-
Un/Loading Blades in port	17	10
	12	5
	10	-
Un/Loading Foundations in port	18	5
	17	10
Seafastening	14	2
	14	1.4
Transship Towers/Nacelles	14	2
Transship Blades	12	2
All Operations for floating structures	10	4

Figure 28.Type of operation and permitted values [29].

2.13.3 Installation floating wind concepts

Due to the uncertainties associated with the installation offshore of the turbines this can cause an increase in the capital expenditure of the project because of an extension of the schedules. Therefore, marine operations have a big importance in all phases of the wind farm cycle. The phases of installation from the port to the site have a lot of challenges since the turbines get larger and further offshore with an increase in the severity of weather. Additionally, the distance to get to the site increases and it makes a logistical challenge. Usually, installation accounts for 30% of the whole project [30].

Bottom fixed turbines depend on installation vessels that are limited to 60 meters. Currently, there are two concepts that are commercial, Principle Power and Hywind Spar. Also, eight demonstrator concepts have been deployed. The main obstacle is the commercialization cost of a full-scale floating farm. The installation of the mooring system takes approximately the same time as installing bottom fixed substructures. Bottom fixed is significantly less expensive than floating structures in manufacturing and assembly because they are not produced as an industrialized process.

One of the advantages of floating wind is the integration of the wind turbine that does not require expensive vessels and it can be done at the port in shelter waters. Except the Spar concept that is more costly because it requires offshore cranes and deep water. Furthermore, the vessels needed are less expensive than the ones for bottom fixed. One of the exceptions is the TLP that needs a bespoke installation vessel due to the instability during towing [30].

2.13.4 Construction and installation

The temporary phase starts with the floating from a dry dock or the loadout to the sea or heavy transport vessels and finishes whit the hook up of the mooring system and the installation of cables. The temporary phases consist on: the seabed survey (bathymetry, conditions of the soil), installation of mooring system, construction and assembly of the floater, construction and integration of the wind turbine, towing to the site, cable installation and burial.

Construction of the substructure:

-The substructure can be built on land in an average shipbuilding yard or offshore building site. The concepts that can be used in this way are semisubmersibles, barges and Spars.

-Construction in a dry dock: semisubmersibles and barges can be used. The constraints in this type of construction are availability and the water depth.

The substructure usually is made by steel tubulars that require assembly. For this case, the port needs the following features: a sizeable storage area and cranes for the assembly of the components. Since the structure needs a large space, it is difficult to build them in a serial process. Normally, the manufacturing facilities are spread over different locations and transport of the components to the assembly site is required [25].

The installation of the different concepts is described in the following paragraphs. [30]

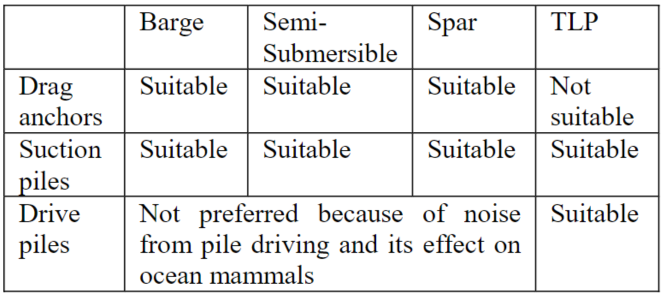
For the Spar concept the procedure is the following: horizontal construction of the structure in a shipyard, loadout using the modular self-propelled transporter, heavy transport vessel to transport to a deep site, pre-lay inshore mooring, floating-off, upending, connect to the pre-laid inshore mooring system, add solid ballast, integrate wind turbine, tow to site, connect to mooring system, add water ballast and connect to subsea cables.

For the TLP concept, the procedure is the following: vertical construction in land, loadout with a self-propelled transport onto a heavy transport vessel, transport to the port for the integration of the turbine, float off, mooring off the floater to the quay, perform the integration of the wind turbine, add temporary buoyancy, tow to site, connect with the mooring system, extract ballast and temporary buoyancy, connect to the cables.

Semi-submersible concept constructed on land: vertically construction of the structure on land, loadout with the self-propelled transporter, transport with heavy transport vessel, float off at the port for the integration of the wind turbine, mooring of the floater to the quay, add the turbine, transport to site, connect with the pre-laid mooring system, add water ballast and connect with the pre-laid cables.

Barge concept constructed in a dry-dock: construction of the pontoon barge, move to dry dock, separation of substructure from the barge, towing-out to of dry-dock, towing to the integration of turbine yard, mooring to quay, add the components of the turbine, transport to site, connect with the pre-laid mooring system, add water ballast and connect with the pre-laid cables.

Mooring system installation can be seen in figure 29. Anchor handling vessels can install small suction piles and drag anchors. Driven piles and large suction piles need a crane vessel for their installation and an anchor handling vessel for the installation of the mooring lines.



	Barge	Semi-Submersible	Spar	TLP
Drag anchors	Suitable	Suitable	Suitable	Not suitable
Suction piles	Suitable	Suitable	Suitable	Suitable
Drive piles	Not preferred because of noise from pile driving and its effect on ocean mammals			Suitable

Figure 29. Types of anchors with the different concepts [30].

To install the floating wind turbine generally, an anchor handling vessel is used to tow and another one follows the tow. Also, a remotely operated vessel connects the pre-laid mooring system with the floater. Subsequently, the anchor handling vessel does the tensioning of the system. At the end, a specialized cable vessel connects the subsea cables.

2.13.5 Substation installation and connection grid

To connect the wind turbines to the grid an adequate electrical infrastructure is crucial. If the wind farm is close to shore an offshore substation is enough but if it is far away an offshore and onshore substation is required. The substation includes: reactors, transformers, switchgear, fire protection, control and low voltage auxiliar systems [19].

The final step of the installation of the offshore wind farm is the cable installation. Based on the location and size of the wind farm the output power is connected by array cables to either two or one substation busbars. Following that, the high voltage electricity is transferred using export cables to the onshore substation and from there to the grid. The export cables and array cables are planned to reduce the total cable length and follow the marine restrictions and environmental laws [19]. Subsea cables have to be stored onshore before its deployment on the offshore site. The dynamic cables connect the floater with the export cables that will be buried. Normally, the export cables need special manufacturing facilities so both types of cables will be transported from another port. Furthermore, another facility will be needed to construct and store protection mats made of concrete to protect the export cables.

Chapter 3 Cases study in Shoreline

3.1 Shoreline

Shoreline is an online software that enables users to model and compare various building projects. This includes simulating and analyzing the entire process of installation, completion, commissioning, and testing. In addition, the software can evaluate costs and estimate the weather conditions required to carry out the operations. Moreover, Shoreline is capable of simulating the operations as well as the maintenance of wind farms to optimize management as well as logistics and enhance efficiency in every cycle [31].

3.2 Case study

The first port simulated is Wergeland base that is used as the port for the assembly of the floater and integration of the wind turbine. It will be assumed that all the components of the floater and turbine are already there. Furthermore, it will be the base used for towing the wind turbines to the wind farm. This base is situated at the coordinates 5.077233 longitude, 60.847017 latitude on Norway's west coast. The port has 10 slots for reparation and 3 berth spots available for loadout. Its capacity includes 200 mooring lines and 200 mooring anchors as well as 10 floating wind turbines spot. The chosen place to install the wind farm is Utsira Nord and the layout of the turbines has been left as a default spacing provided by Shoreline. The overview of the base and the wind farm can be seen in figure 30.

Equinor supplied the weather data utilized for the simulations in Shoreline at Wergeland base. The data was collected every ten minutes over a span of two years, ten meters above ground level, using a mast installed at the base. A modified version of this data was employed for the simulations, adjusting it to an hourly time instead of ten minutes. The reference height was modified to match the height of the wind turbine and the wind speed value at this new height was determined using the power law formulation.

Moreover, ERA 5 weather data is used for the location of Utsira Nord. This data set spans 19 years and includes information on wave height, swell and wind speed, all recorded at one-hour intervals. The weather data from Utsira Nord plays a crucial role in the installation of the mooring system and the wind turbines at the site. This data started being collected in 1979 and is a result of a reanalysis of climate data and weather. For the simulations in Shoreline the weather data has been generated as the increment start year approach for 10 years.

The second port simulated is WindWorks Jelsa (seen in figure 31). This port will be used as a base for operations, it is in the north of Stavanger making it an attractive site for the future development of floating offshore wind in the North Sea. All the components will be assumed to be there. The assembly of the floating structures will take place there and the installation to the wind farm. This port is located at latitude 59.375629 and longitude 6.050517. It is assumed that the number of repair sloths is 10 units, and the number of loadout berth capacity is 10 units.

The weather ERA 5 is not accurate to the location of this port, that could cause a significant modification of the results between the real weather and the simulated one. Since there is limited weather data from the precise location of WindWorks Jelsa, this will produce some limitations in the simulations. Due to that, the weather data used for this port has been ERA 5 in Stord location. This data was chosen due to the fact that it is the most approximated site to the assembly (around 50 km) and the location is similar. For the simulations in Shoreline the weather data has been generated as the increment start year approach for 10 years.

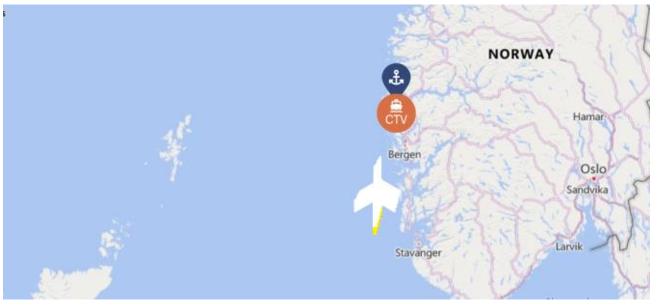


Figure 30. Overview of Wergeland Base and the wind farm

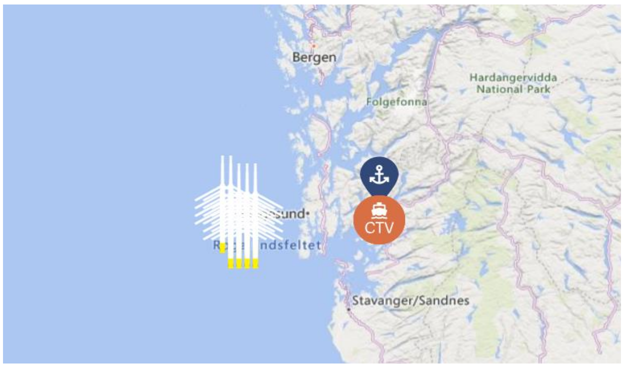


Figure 31. Overview of WindWorks Jelsa port and the wind farm

3.3 Logistics

The logistics used in the simulations can be seen in table 1 and table 2. The use of these logistics will depend on the type of cases explained in the following section. In annex 1 a further description of each logistic is shown.

- Cranes: the main crane employed is Mammoet PTC 200-DS. It is a stationary ring crane responsible for the assembly of the floater and the integration of the wind turbine. It has a lifting capacity of 1397 tons and can reach a maximum height of 205 meters. Furthermore, smaller cranes with different characteristics will be used to assemble the floater.
- Anchor handling vessel: this type of vessel is utilized for the transportation and installation of the mooring system.
- Swath trimaran: this type of vessel is employed to ferry personnel to the site of the wind farm.
- Towing vessel: it is used to tow the floating wind turbine to the wind farm and make the final installation with the mooring system.

Weather criteria		
Cranes	Wind speed (m/s)	Wave height (meters)
Large Crane (Mammoet PTC 200 DS)	12	0.5
Small crane	12	-
Anchor handling vessel	15	3
Towing vessel	13	2

Table 1. Overview of the cranes used.

Vehicles	Transit speed (kn)	Towing speed (kn)
Anchor handling vessel	15	5
Swath trimaran	20	-
Towing vessel	12	4

Table 2. logistics used.

3.4 Semisubmersible simulation

In the simulations Wergeland base or WindWorks Jelsa serve as the locations for assembling the Moreld Ocean Wind semisubmersible concept. These simulations assume that the various parts and components comprising the floating structure of the Semisubmersible and the wind turbine have already been manufactured and transported to Wergeland base/Jelsa for storage.

The simulations commence with the assembly of the floater performed by cranes, followed by its deployment into the sea. Subsequently, the wind turbine is installed onto the floater. This involves first, the assembly of the tower in two parts, the nacelle and finally, the three blades. Once completed, the entire semisubmersible, including the integrated wind turbine, undergoes pre-commissioning and preparation for the towing process. Following that, the floating wind turbine is towed and installed into the site. Simultaneously when the assembly of the structure starts, the anchors handling vessels start installing the mooring anchors and mooring lines in the location. Eventually, after the towing is finished the structure is hooked-up with the mooring system.

Moreld Ocean Wind has provided the data for each assembly process and installation of the floater. Also, they have provided the data for the procedures and time that takes to install the mooring system. For each process the weather limitations (wind speed and wave height) have been provided. The specific details regarding the assembly and installation of the floater, mooring anchors, and lines have been kept confidential. The weather limitations, assembly time and integration of the wind turbine are shown in table 3 based on [32].

Process	Wind speed limit (m/s) (reference height 100 meters)	Wave height limit (meters)	Duration (hours)
Connecting the crane for each process	-	-	1
Disconnecting the crane for each process	-	-	2
Assembly of the tower part (2 parts)	12	0.5	6
Assembly of the nacelle	12	0.5	3
Assembly of the three blades	12	0.5	9
Transit to pre-commissioning station	-	-	3
Pre-commissioning	-	-	24

Table 3. Data integration wind turbine

3.4.1 Base case (Case 1)

For the Base Case 25 floating wind turbines will be installed in Utsira Nord. Each wind turbine with a power capacity of 20 MW. For this simulation it is assumed that all the components of the floater and components of the wind turbine are already stored at the base. The weather data for has been generated as the increment start year approach for 10 years.

The logistics used have been the following: 2 anchor handling vessels, 1 towing vessel, 2 swath trimaran, 2 small cranes for the assembly of the floaters (each small crane assembles one different floater simultaneously) and 1 large crane for the integration of the wind turbine. The large crane is Mammoet PTC 200-DS.

The workflow of this case can be visualized in figure 32. It is assumed that the floater components and the wind turbine components are already at the port. First, the components arrive at the assembly place where the cranes to assemble the floater are placed. They will start assembling at the same time and will usually finish on the same date. Then, the floater of the crane 1 will be transported to next assembly site where the large crane is placed. This crane will integrate the wind turbine. The different components of the wind turbine will be transferred to the large crane. The other floater assembled with crane 2 will wait in the storage area until the large crane has finished. When the large crane is done with the structure it will deploy it onto the sea in the floating storage area. Finally, the towing vessel will arrange the floating structure and will transport it to the wind farm where it will be hooked-up with the previous installed mooring system. This cycle will be repeated until all the 25 wind turbines are assembled and installed.

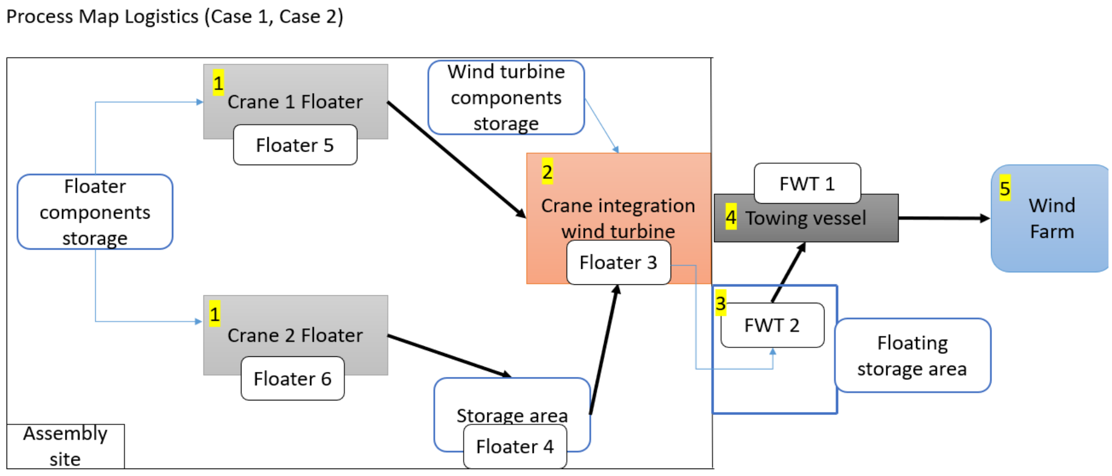


Figure 32. Flowchart Case 1

3.4.2 Case 2

For case 2, the wind farm is located in Utsira Nord, the wind farm has 25 floating wind turbines, each with a capacity of 20 MW. The logistics used in this case are the same ones as in the base case. In this simulation no weather constraints have been used. The process flow is the same as in case 1.

3.4.3 Case 3

In case 3, the location of the wind farm is Utsira Nord, with 25 floating wind turbines each with 20 MW capacity. The weather data used is the same as the base case and the logistics are: 1 small crane for the assembly of the floater, 1 large crane for the integration of the wind turbine, 2 anchoring handling vessels, 2 Swath trimaran vessels, 1 towing vessel. The flowchart can be visualized in figure 33.

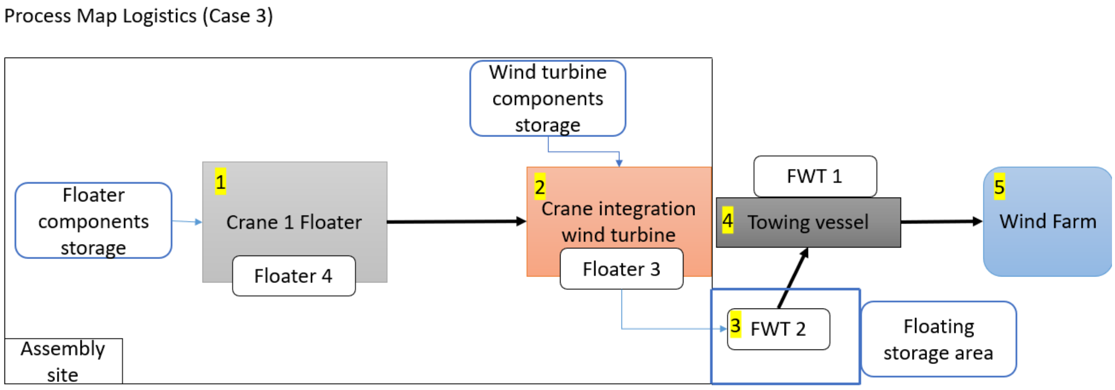


Figure 33. Flowchart Case 3

3.4.4 Case 4

For case 4, the wind farm is in Utsira Nord, the wind farm has 25 floating wind turbines, each with a capacity of 20 MW. The weather data used is the same as the base case. The logistics are: 1 large crane for the assembly of the floater and integration of the wind turbine, 2 anchor handling vessel, 2 swath trimaran, 1 towing vessel. The process map of the logistics can be seen in figure 34.

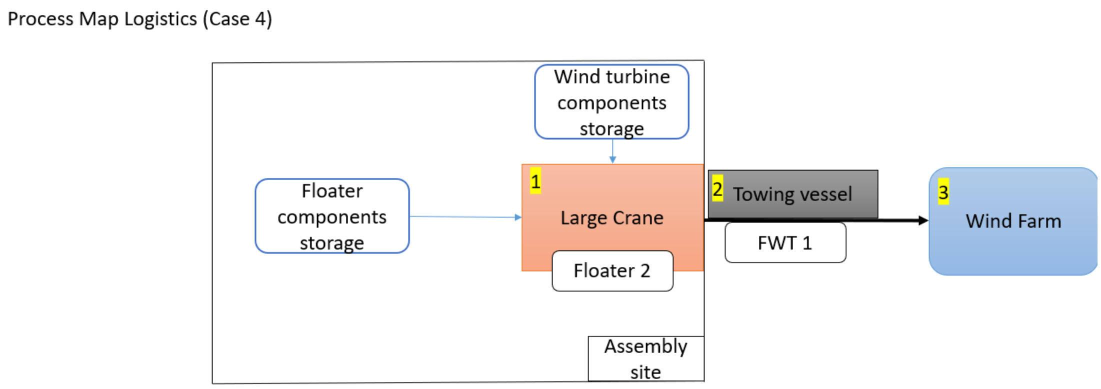


Figure 34. Flowchart Case 4

3.4.5 Case 5

In case 5, the location of the wind farm is Utsira Nord, with 25 floating wind turbines each with 20 MW capacity. The weather data used is the same as the base case and the logistics are: 2 small cranes for the assembly of the floater, 1 large crane for the integration of the wind turbine, 2 anchoring handling vessels, 2 Swath trimaran vessels and 2 towing vessels. The flowchart can be seen in figure 35.

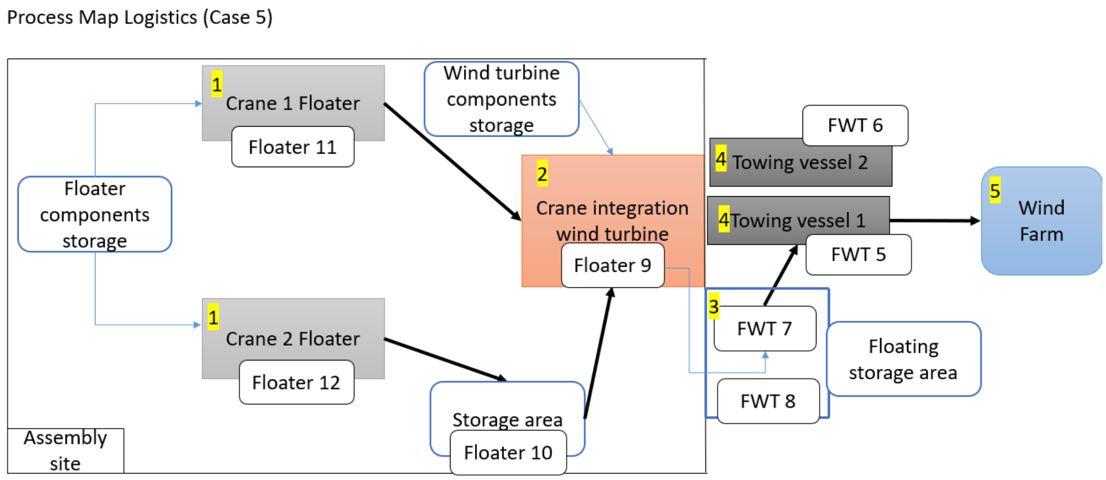


Figure 35. Flowchart case 5

Chapter 4. Results

For each case (base case 1, case 2, case 3, case 4, case 5) the results of the simulations are based first, as the total project time. The project timeline begins with the initiation of the project, marked by the anchor handling vessel starting the process of loading the mooring systems from the base and installing them at the site position. At the same time, the assembly of the first floaters takes place, followed by the installation of the wind turbine. The project concludes when the last turbine is successfully installed and connected to the mooring system, and the vessels return to the port. The assembly time includes the time that takes to assemble the whole floating structure and the wind turbine of each case. The costs section contains the spending costs needed for each case. The weather downtime of the cranes consists of the amount of percentage that the cranes will be unused due to the weather limitations for each case.

Moreover, for each case a weather analysis has been performed with 12 simulations, each starting every month of the year. The results of every case have been compared with the base case.

4.1 Project time Wergeland Base

In table 4 the overview of the weather analysis can be seen. The rest of the tables of the other cases can be seen in Annex B1. First, the Case 1 has been simulated from Wergeland Base. The initiation of assembly, following the installation have been performed as an average of the start of every month of the year with 453.8 days . It can be seen that the most effective month to start the project would be in April due to having less weather limitations with 415 days. The maximum project duration would be starting in November with a duration of 517 days. The standard deviation of Case 1 is 33.69.

	Total project time				
Month	**Case 1**	**Case 2 (Base case) (No weather)**	Percentage difference (%)	Days difference	Standard deviation case 1
January	466	160	65.67	306	33.69
February	438	160	63.47	278	Max
March	437	160	63.39	277	517
April	415	160	61.45	255	Min
May	416	160	61.54	256	415
June	423	160	62.17	263	
July	431	160	62.88	271	
August	448	160	64.29	288	
September	469	160	65.88	309	
October	499	160	67.94	339	
November	517	160	69.05	357	
December	487	160	67.15	327	
Average	453.83	160	64.57	293.83	

Table 4. Weather analysis

Case 2 is based on Case 1 with exactly the same logistics. The only difference is that for case 2 the weather data has not been added. The cranes and the vessels did not have weather constraints (wind speed and wave height) when performing their tasks. This can be seen in the left part of figure 36. Case 2 accounts for 160 days. The weather restrictions compared to the average of the results of Case 1 results in an addition of 293.8 days, 64.57% more.

In the right part of figure 36, a comparison between the average time of Case 1 and the average of all 12 months simulations of Case 3 can be seen. In this case the maximum project time is 623 days, the minimum is 484 days and the standard deviation of the simulation results in 48.96. It can be noticed that using only one crane for the assembly of the floater in Case 3 compared to two cranes assembling two different floaters takes 106.67 days more, 19.1%.

In figure 36 (left side) the comparison between the base case and case 4 can be visualized. Since Case 4 only uses a large crane to do the whole assembly process from the floater to the integration of the wind turbine, it is seen that the average duration is 904.08 days. The maximum time performed is 1002 days and the minimum is 811 days. The standard deviation has a result of 62.74 days. This results in an increment of 450.25 days, 49.8% compared to the base case.

The right side of figure 37 shows the comparison between the base Case 1 and Case 5. This case has an average project duration of 307.42 days, a maximum duration 342 days, a minimum duration of 256 days and a standard deviation of 23.51 days. In Case 5 two towing vessel were added compared to one in the base case. This modification produced an improvement of 146.42 days less, 31.71%.

In figure 38 an overview of the total project average time can be seen. It is noticeable that Case 5 is the most effective in terms of project time.

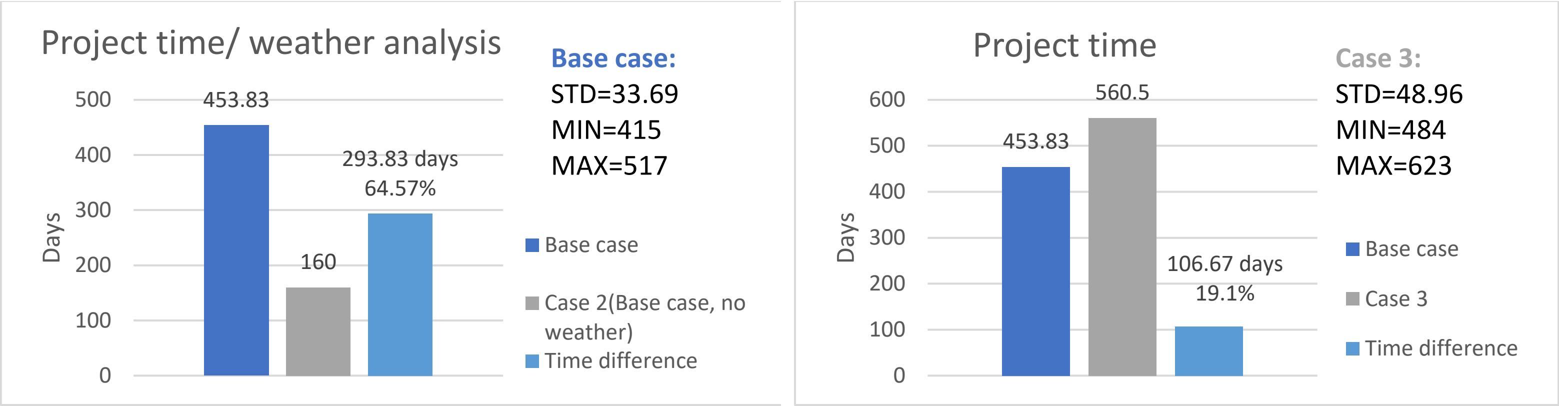


Figure 36. Total project time

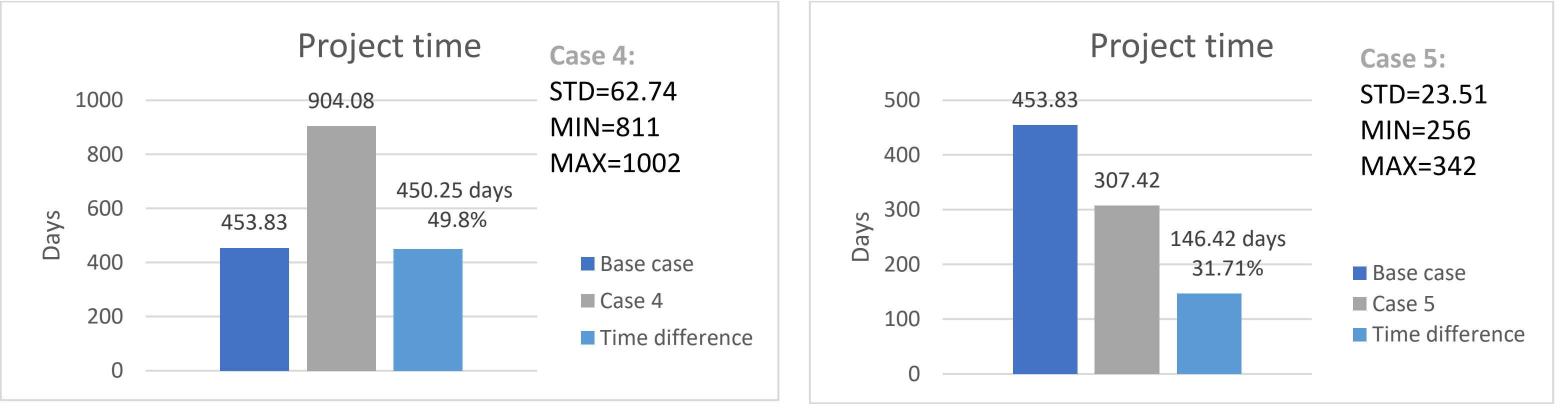


Figure 37. Total project time Case 4/Case 5

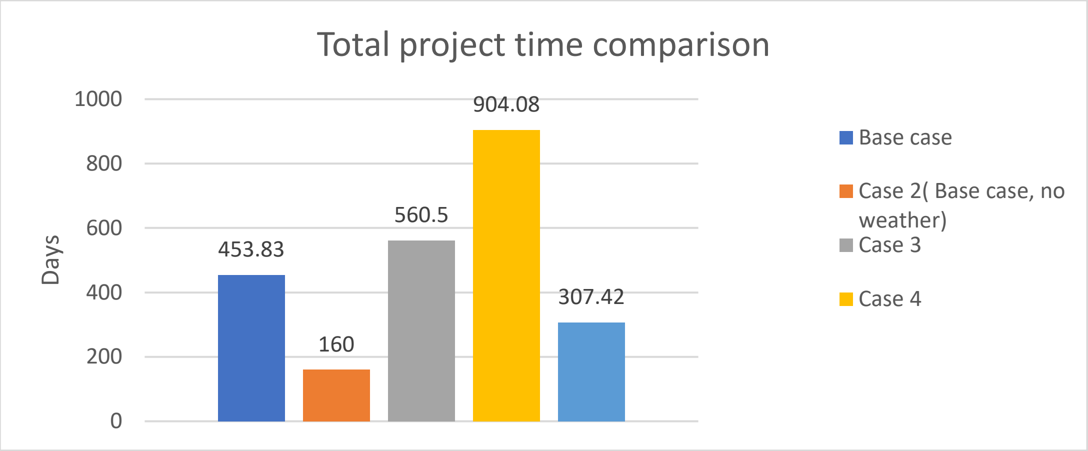


Figure 38. Total project time comparison

4.2 Assembly time in Wergeland Base

In this section a comparison of the overview of the simulated assembly time between all five cases has been performed. The assembly time is based on the starting of the first crane being mobilized to perform the first assembly process that starts with the floater. Following that, the deployment of the structure in the water is done, and it finishes with the integration of the wind turbine. For each case (Base Case, Case 2, Case 3, Case 4, Case 5) a weather analysis has been performed with 12 simulations, each starting every month of the year. The tables can be seen in the Annex B2.

In the left side of figure 38 the weather analysis between Case 1 (base case) and Case 2 is done. In Case 1 the average duration of the 12 simulations is 253.5 days. The maximum is 331 days, the minimum is 175 days and the standard deviation is 50.87 days. Since Case 2 has no weather restraints for the cranes the assembly time takes 155 days. This accounts for a delay of 98.5 days, 36.29% due to the weather. These restrictions are caused by the wind speed (12 m/s) in the large and small cranes and by the wave height (0.5 m) in the large crane.

In the right side of figure 38 the comparison between Case 1 and Case 3 can be visualized. The average assembled time in Case 3 accounts for 512.83 days. The maximum value is 550 days, the minimum is 447 days, and the standard deviation is 33.5 days. In this case, due to the use of one small crane to perform the assembly of one floater instead of two cranes to perform the assembly of two floater has an impact on the overall spent time. This produces an increased assembly time of 259.33 days, 50.73 %.

In the left side of figure 39 the comparison between Case 4 and Base Case can be seen. Case 4 consists of only one large crane performing the whole process of assembly. This accounts for an averaged time of 869.5 days. The maximum is 946 days, the minimum is 803 days, and the standard deviation is 52.45 days. The use of one large crane to perform the assembly of the floater and the integration of the wind turbine produces an increase of 616 days, 70.97%, compared to Case 1. In the right side of figure 39 the comparison between the Base Case and Case 5 is visualized. Case 5 and Case 1 have the same assembly logistics, two cranes for the floater and one large crane for the integration of the turbine. This difference of 12 days, 4.52% is due to the difference outcome of the simulations due to the weather conditions.

Furthermore, in the last figure 40 of the section the overview of the spent assembly time is seen. The shortest assembly time is for Case 1/Case 5 and the longest for Case 4.

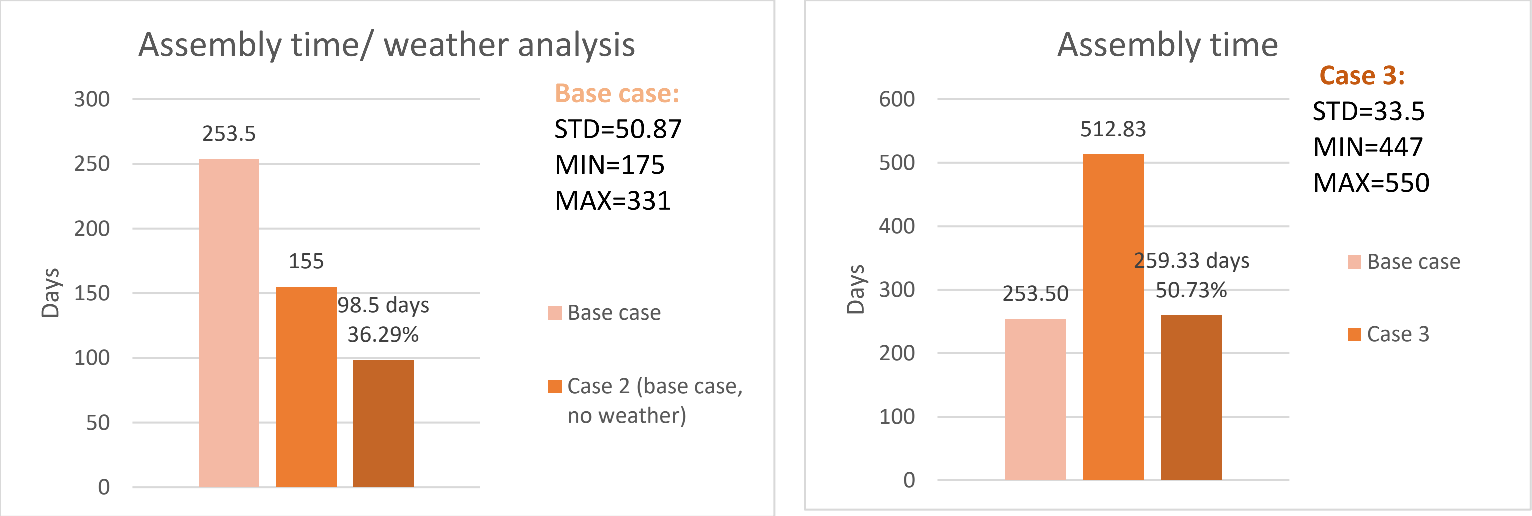


Figure 38. Assembly time Case 1/ Case 2/ Case 3

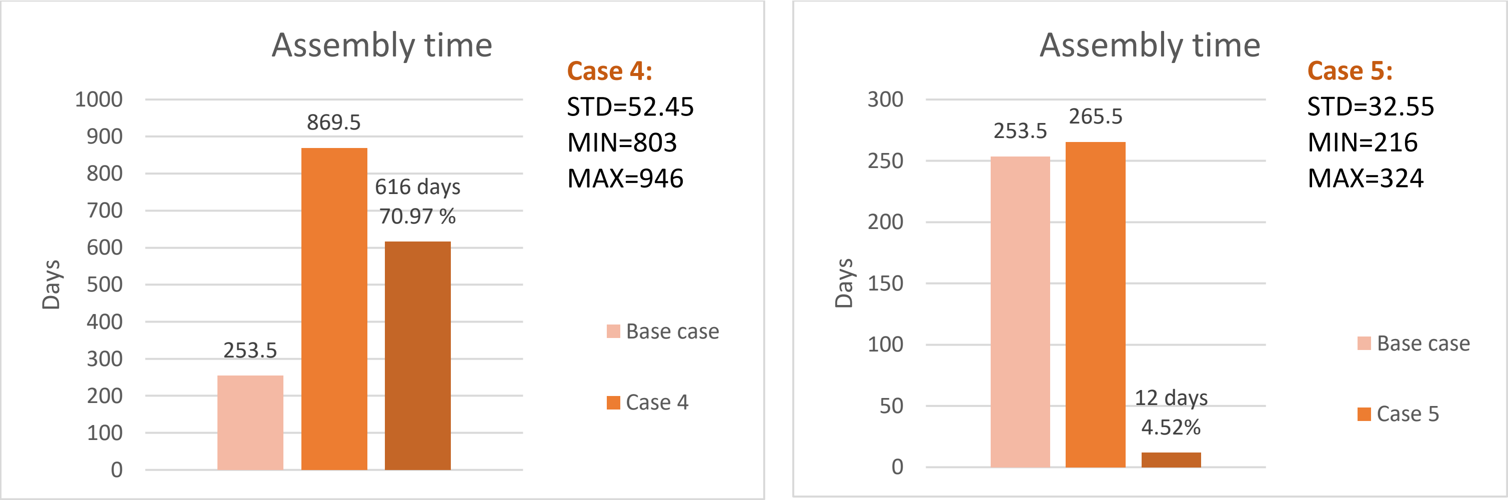


Figure 39. Assembly comparison Case 4/Case 5

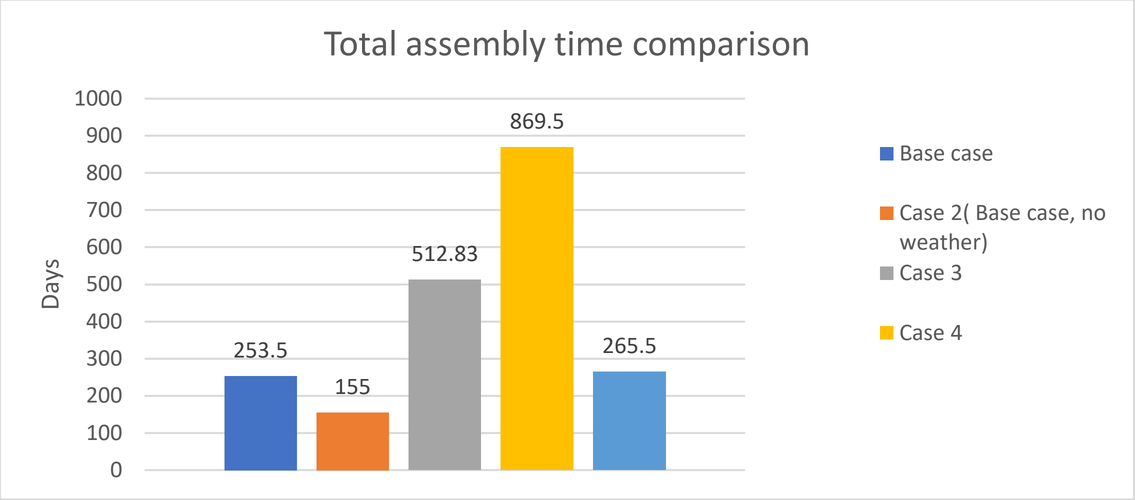


Figure 40. Total assembly time comparison

4.3 Project costs

The following section consists of a comparison between Case 1, Case 2, Case3, Case 4, Case 5 of the overall costs of the projects. These costs consist of the logistics costs and port costs (see Annex B3). The next table is the overview of the 12 simulations done, each starting every month of the year.

In the left side of figure 41 the weather analysis of Case 1 and Case 2 is compared. The first case has an average total cost of 397.23 million NOK. The maximum cost is 446.3 million NOK, the minimum is 359.3 million NOK. Case 2, without weather restrictions costs 243.8 million NOK. Waiting for weather has an increased cost of 153.43 million NOK, 38.25%. In the left side of figure 41 Case 3 is compared to Case 1. This case has an average cost of 426.82 million NOK, a maximum value of 464.7 million NOK, a minimum value of 379.5 million NOK and a standard deviation of 30.96 million NOK. The cost of Case 3 is 29.58 million NOK, 6.93% higher than the Base Case although it has one less crane. For Case 3 the expense is lower in the starting logistics because there is one less crane but that makes the project longer, increasing the cost.

In figure 42 the comparison between Case 1 and Case 4 is visualized. The average expenditure in this case is 622.47 million NOK, the minimum is 559.9 million NOK, and the maximum is 664.3 million NOK, the standard deviation is 34.53 million NOK. It has a 225.23 million NOK expense, 36.22% more than the base case. In the right side the comparison of Case 1 and Case 5 is seen. Case 5 has an average expenditure of 372.08 million NOK, maximum value of 392.8 million

NOK, minimum value of 349.2 million NOK, a standard deviation of 14.7 million NOK and a cost difference of 26.64 million NOK, 6.38%. These results are because the project time in Case 5 is lower due to having two towing vessels instead of one even though the expense of having two vessels is higher.

In the last figure 43 of the section the overall costs of the different cases can be seen. Case 5 stands for the cheapest case and Case 4 for the most expensive case due to the amount of project time required.

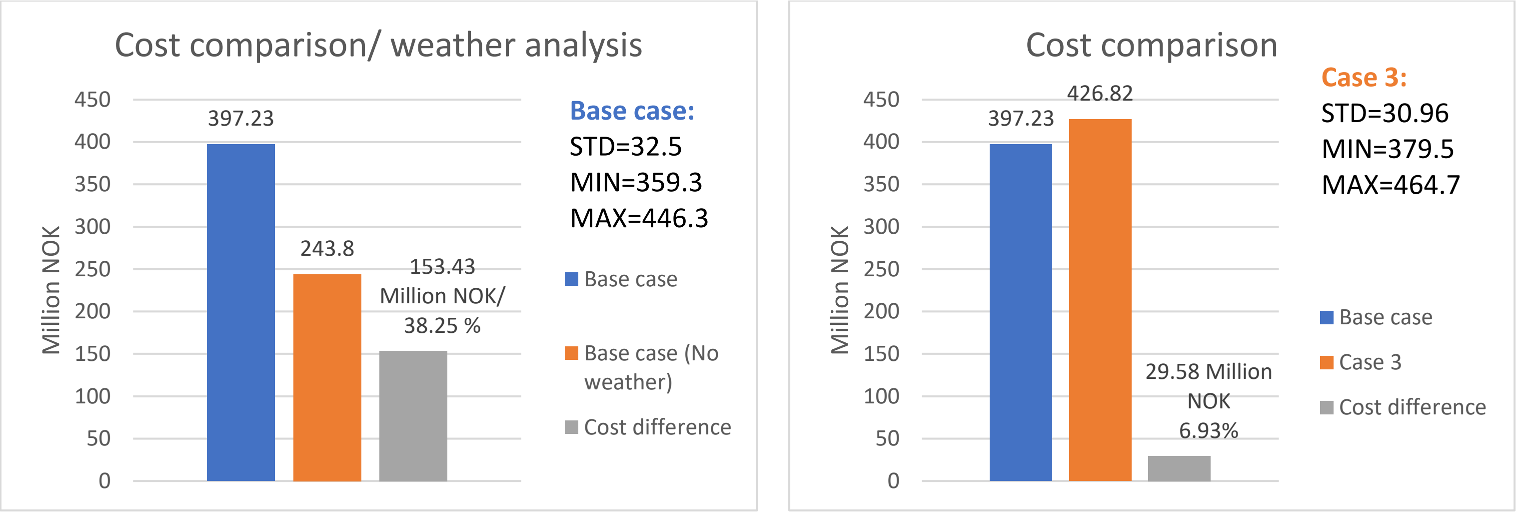


Figure 41. Cost comparison Case1/ Case 2/ Case 3

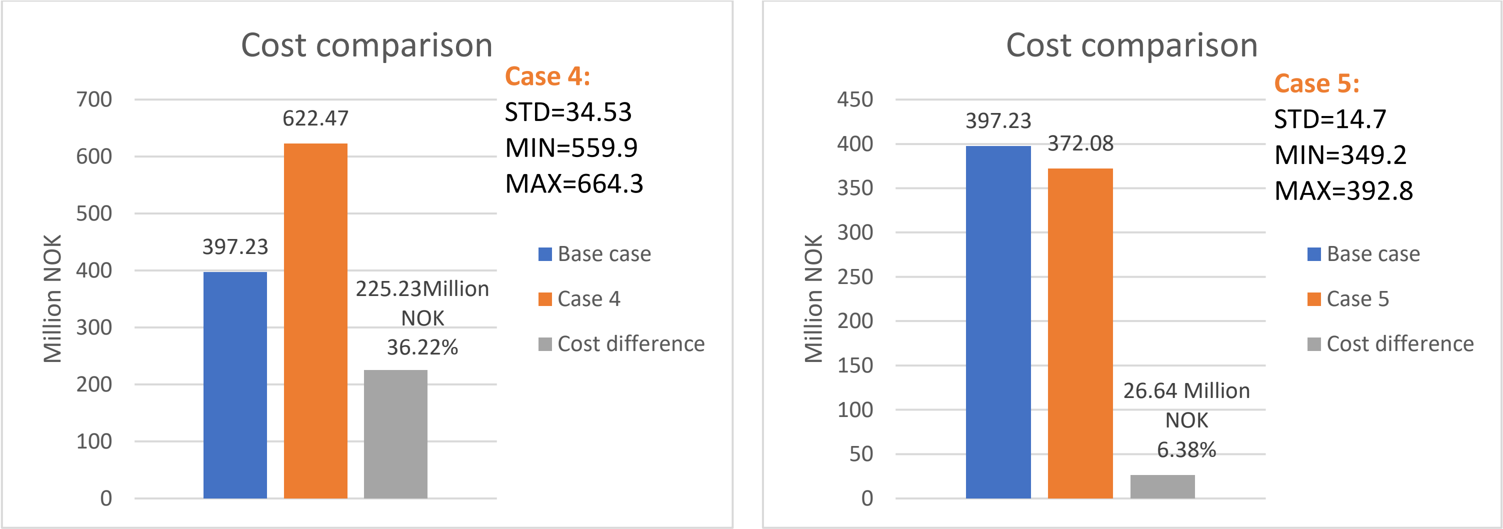


Figure 42. Cost comparison Case 4/Case 5

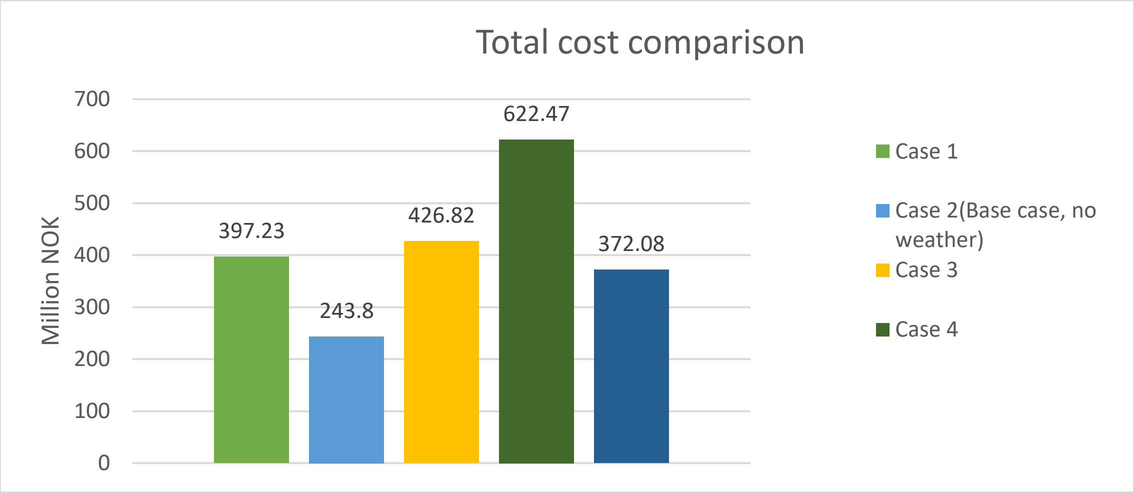


Figure 43. Total cost comparison

4.4 Crane weather downtime

In this section a crane weather downtime study analysis from every case (Case 1, Case 2, Case 3, Case 4 and Case 5) has been performed. In the following figures, the overview, and the average of the 12 simulations, each starting every month of the year for every case can be seen. The detailed information of every case can be found in Annex B4. The aim of this section is to have a general outlook of the percentage of the total time of the project that the cranes cannot function due to the weather conditions (wind speed, wave height).

In the left side of the next figure 44 the weather downtime of the three cranes of Case 1 can be visualized. The small cranes that take part in the assembly process of the floater have a weather downtime of 41.43%, crane 1 and 41.67% crane 2. These cranes only have the wind constraint of 12 m/s since the assembly is being performed in the quay.

For the large crane the weather downtime is around 42.45%. This slight increase is due that this crane, apart from the 12 m/s wind limitation a wave height of 0.5 meters must be considered. In the left side of the figure the weather downtime of Case 3 is shown. Crane 1 of the floater has a weather downtime of 41.6% and the large crane of around 46% because of the information mentioned before. In the left side of figure 45, the crane weather downtime of Case 4 is seen, and it accounts for 56%. This is due to the fact that the large crane has to do all the assembly process and is more exposed to weather constraints. Furthermore, since the length of this case is longer, that will also result in more downtime for the crane. In the right side the weather downtime of the cranes in Case 5 is presented. For the floater cranes the downtime is really similar because of the same weather conditions and the same timing process of assembly. This accounts for 42.46% for the first crane of the floater, 42.20% for the second crane of the floater and the large crane has a downtime of 42.45%.

In figure 46 the overall weather downtime of all the cranes utilized in all the cases is presented.

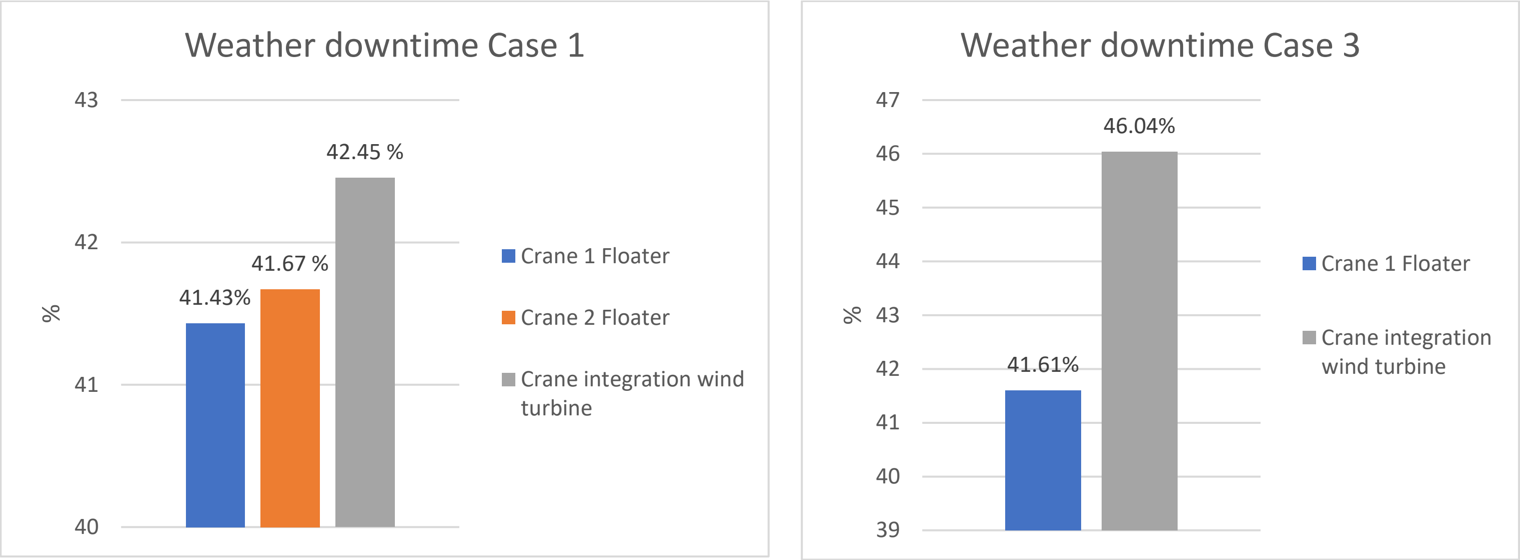


Figure 44. Cranes weather downtime Case 1/ Case 3

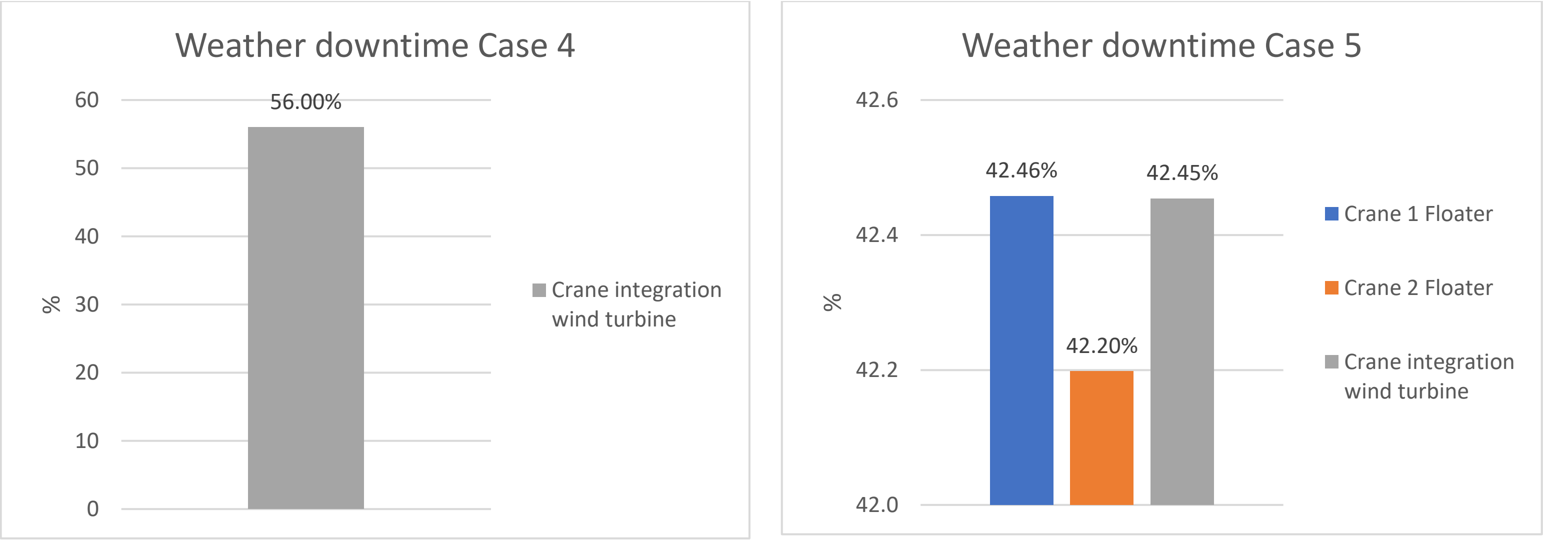


Figure 45. Cranes weather downtime Case 4/Case5

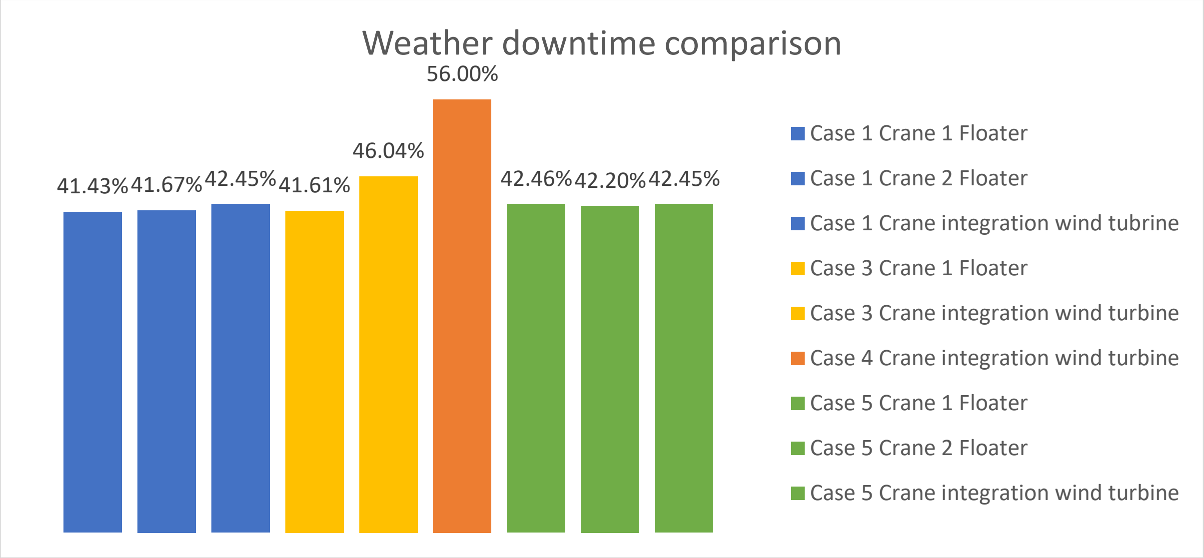


Figure 46. Cranes weather downtime comparison

4.5 WindWorks Jelsa project duration

In this section the results of the simulations performed in Shoreline are presented with the assembly base changed to WindWorks Jelsa. For each case (Case 1, Case 2, Case 3, Case 4, Case5) a weather analysis has been performed with 12 simulations, each starting every month of the year. The logistics of all the cases remain the same. The tables with the detailed information of every month of the cases are presented in the Annex B5. Furthermore, the outcome can be visualized in the following pages with the average of each case compared to the Base Case, with the calculated percentage difference, days difference, maximum value, minimum value and the standard deviation.

In table 5 the overview of the weather analysis can be seen. First, Case 1 has been simulated. The initiation of assembly, following the installation have been performed as an average of the start of every month of the year with 413 days. It can be observed that the most effective month to start the project would be in December due to less weather limitations with 365 days. The maximum duration would be starting in January with a duration of 454 days. The standard deviation of Case 1 is 23.31.

	Total project time				
Month	**Case 1**	**Case 2(Base case) (No weather)**	Percentage difference (%)	Days difference	Standard deviation case 1
January	454	159	64.98	295	23.31
February	430	159	63.02	271	Max
March	424	159	62.50	265	454
April	406	159	60.84	247	Min
May	408	159	61.03	249	365
June	405	159	60.74	246	
July	400	159	60.25	241	
August	408	159	61.03	249	
September	443	159	64.11	284	
October	418	159	61.96	259	
November	395	159	59.75	236	
December	365	159	56.44	206	
Average	413.00	159	61.39	254.00	

Table 5. Weather analysis Case1/Case 2 WindWorks Jelsa

Case 2 is based on Case 1 with the same logistics. The only difference is that for case 2 the weather data has not been added. The cranes and the vessels did not have weather constraints (wind speed and wave height) when performing their tasks. This can be seen in the left part of figure 47. Case 2 accounts for 159 days. The weather restrictions compared to the average of the results of Case 1 results in an addition of 254 days, 61.39 % more.

In the right part of figure 78 a comparison between the average time of Case 1 and the average of all 12 months simulations of Case 3 can be seen. In this case, the average project time is 547.92 days, the maximum project time is 607 days, the minimum is 499 days and the standard deviation of the simulation results in 37 days. It can be noticed that using only one crane for the assembly of the floater in Case 3 compared to two cranes assembling two different floaters takes 134.92 days more, 24.3%.

In figure 48 (left side) the comparison between the base case and case 4 can be visualized. Since Case 4 only uses a large crane to do the whole assembly process from the floater to the integration of the wind turbine, it is seen that the average duration is 1130 days. The maximum time performed is 1187 days and the minimum is 1088 days. The standard deviation has a result of 32.33 days. This results in an increment of 717 days, 63.46% compared to the base case.

The right side of figure 48 shows the comparison between the Case 1 and Case 5. This case has an average project duration of 325.58 days, a maximum duration 286 days, a minimum duration of 354 days and a standard deviation of 21.57 days. In Case 5 a towing vessel was added compared to the base case. This modification produced an improvement of 87.42 days less, 20.87 %.

In figure 49 an overview of the total project average time can be seen. It is noticeable that Case 5 is the most effective in terms of project time and Case 4 the less attractive.

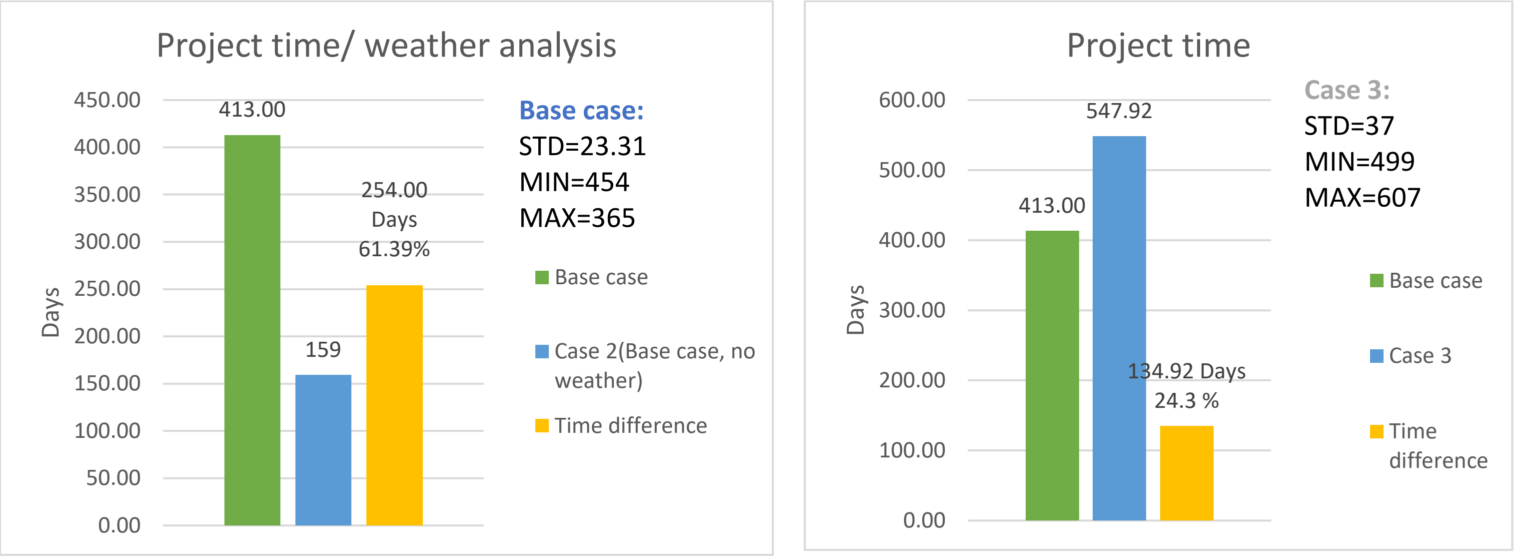


Figure 47. Project time Base Case/ Case 2/Case 3

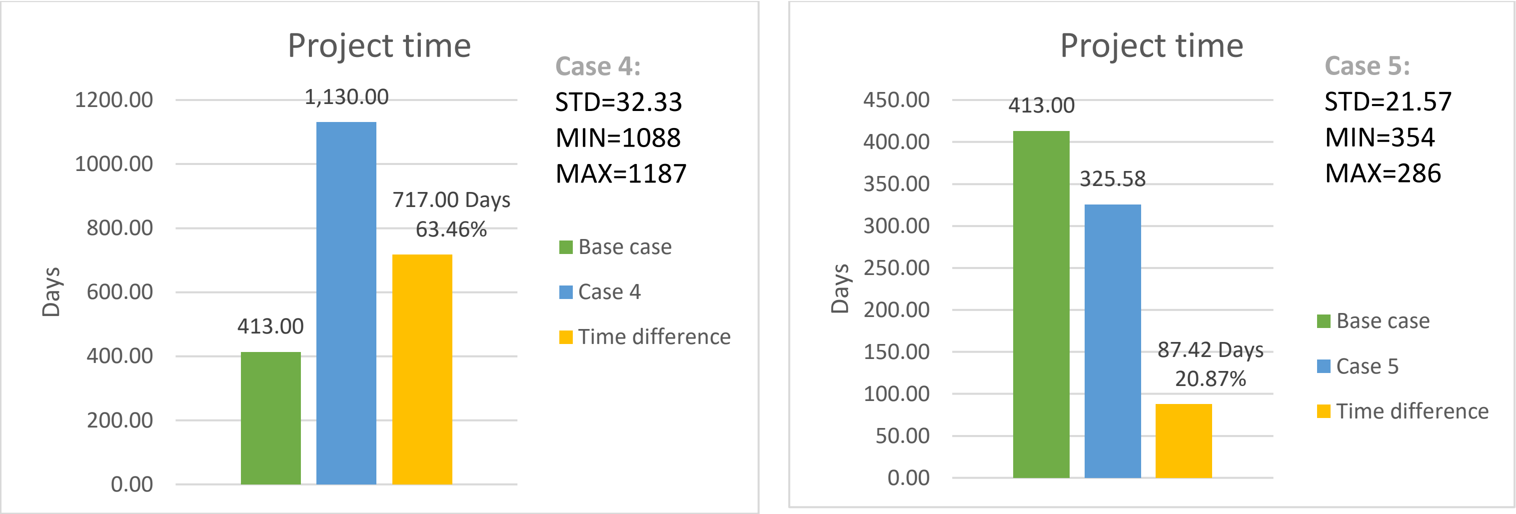


Figure 48. Project time Case 4/ Case 5

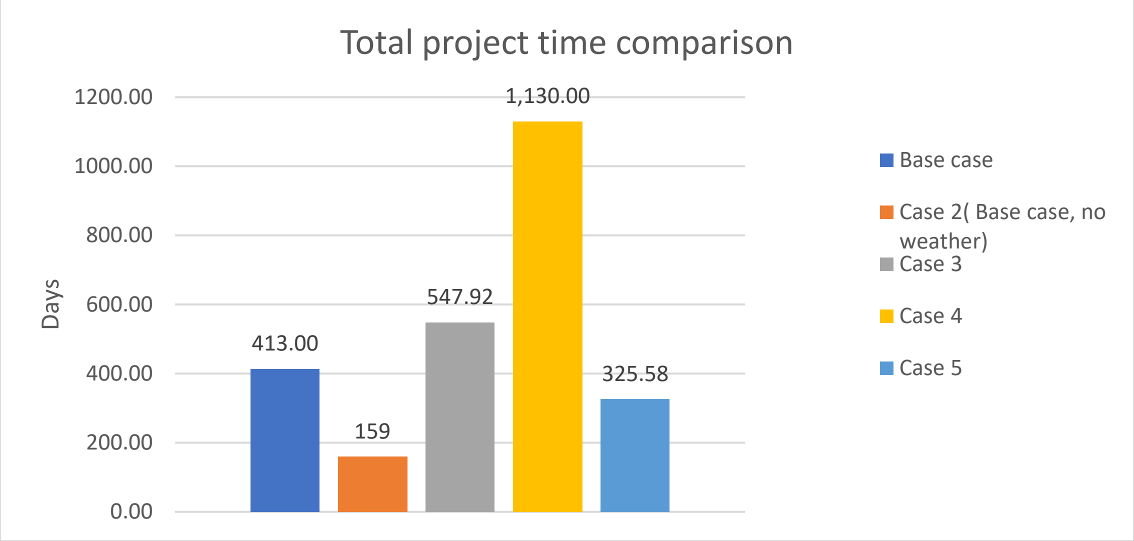


Figure 49. Total time comparison

4.6 Assembly site comparison

In this section the comparison between the assembly site of Wergeland Base and WindWorks Jelsa has been performed. Since the logistics are the same in both cases the only two variables that can affect the project duration are the weather conditions of each site and the distance to the wind farm. In figure 50, the difference in total project time is shown. In Case 1 the reduction in percentage accounts for 9% if the assembly takes place in WindWorks Jelsa. In Case 2 were there is not weather input the duration is very similar with a difference of 0.62%. That means that the outcome is very alike and slight changes in the weather can make either location with an addition of downtime due to bad weather. In figure 51, these changes between each case can be seen depending on the weather simulated and the amount of logistics used. Furthermore, there is not a clear place where it would bring an extensive advantage to situate the assembly operations due to similarities and changes between cases. Also, the most efficient case would be Case 5 in both ports in terms of project time. This case being done in Wergeland Base is reduced by 5.57% in the overall time compared to WindWorks Jelsa. In addition, other characteristics of the port should be considered, like the overall installation costs, assembly space and logistics.

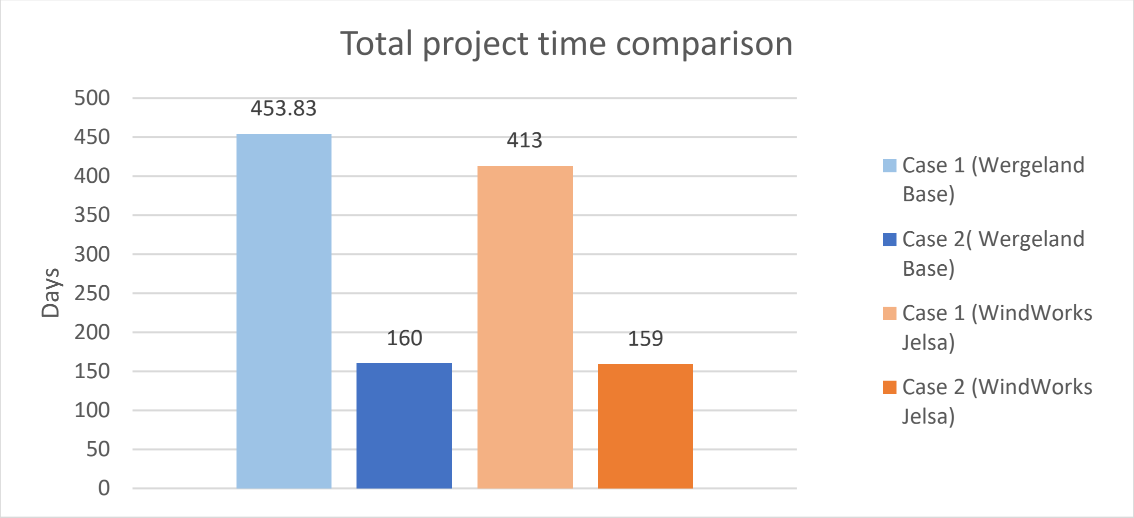


Figure 50. Total project time comparison Wergeland base/ Windworks Jelsa

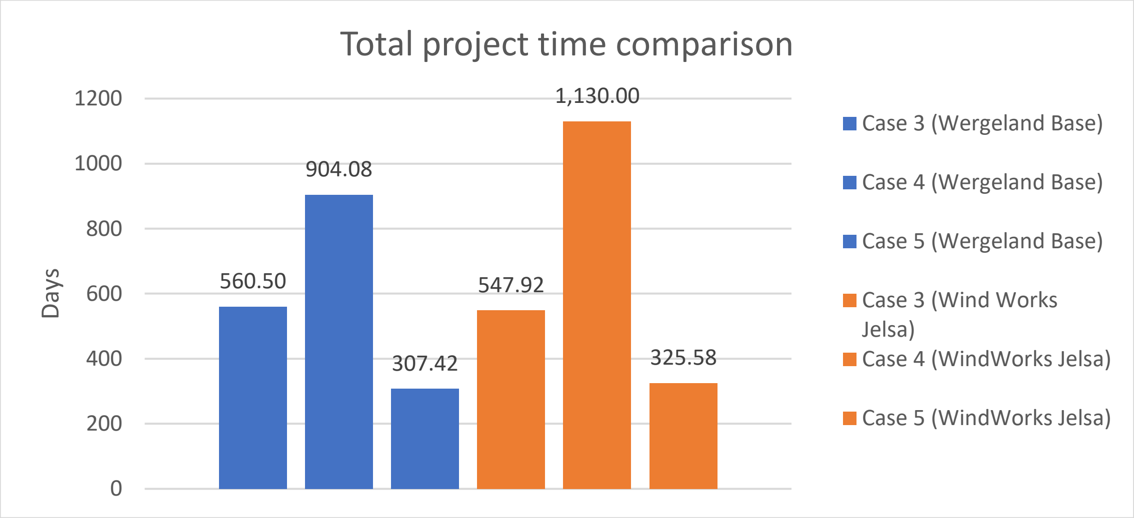


Figure 51. Total project time. Assembly site comparison

Chapter 5. Conclusion

The floating offshore wind industry is rapidly increasing to meet the net-zero policies that most of the developed nations are aiming to accomplish. Furthermore, different concepts are being developed but since this date only the Spar concept (ballast stabilised) and the Semisubmersible concept (buoyancy stabilised) seem to be economically and technically feasible compared to others, due to their characteristics and the different projects that have already been installed or are in the process such as Hywind Spar. This experience has given to the industry good feedback for the future to see which concepts are better in terms of cost and which have good versability to be assembled, installed, and used around the world in an efficient manner.

The way of construction of the floater or assembly play an important role in terms of time. Concepts that are assembled in a modular way as an industrial process will have advantage over others that need to be constructed in one piece. In the present, this industrialization of the floating offshore wind carries a lot of uncertainties due to the novelty of the technology compared to the bottom fixed turbines that has a more mature market. Nevertheless, the expected growth and the profit of the floating wind is substantial compared to the bottom fixed or land wind turbines.

The supply chain will be important in future projects where the quantity of wind turbines will be very high to make sure all the components arrive to the port at the expected time. Moreover, the ports will be essential in these projects, they have to be suitable to accommodate all this material flow, unloading from the transfer vessel, storing it, having the right cranes with enough height or capacity to perform the assembly of the floater and the posterior integration of the wind turbine and the deployment onto the water.

In addition, a logistics study in Shoreline has been conducted. This study consists of five different cases with different types of logistics (Case 1, Case 2, Case 3, Case 4 and Case 5). Also, a weather analysis has been done for each case, starting each simulation each month of the year to see what month was most effective. A comparison between all the assembly times of the different cases has been carried out and a cost analysis. Furthermore, a weather downtime of the different cranes was done and a comparison between the assembly site of Wergeland Base and WindWorks Jelsa was performed. The details can be found in Chapter 4 and in Annexes. The following conclusions regarding the simulations and the analysis were made:

- The weather analysis carried out for every case shows that usually starting in springtime lowers the project time and as a consequence the total cost of the project.

- The weather analysis comparison between Case 1 and Case 2 that is the same case but the second case without weather constraints, shows that the effect of the weather in these projects cause an average delay of 293.8 days,64.5 %. Also, this increase on time causes a rise in the expenditure of 153.4 million NOK ,38.2%.

- The most efficient case in terms of total project time is Case 5 with 307.2 days due to have the same combination of cranes as the base case and two towing vessels instead of one. The longest case is Case 4 with 904 days because the whole assembly of the floater and the integration is performed with one crane and only one towing vessel.

- In terms of assembly time and overall costs the best crane configuration is two small cranes for the assembly of the floater and one large crane for the integration of the wind turbine. This configuration is used by Case 1 and Case 5 and the output is 253.5 days and 265.5 days respectively. Case 1 have an improvement of time of 616 days, 70.9% compared to Case 4 that takes the longest assembly time with 869.5 days.

- Costs have a bigger impact with respect to the project duration rather than amount of logistics. This can be seen in the sightliest saving when using one more towing vessel lowers the project duration in Case 5 (372.08 million NOK) compared to Case 1 (397.2 million NOK) with 26.64 million NOK difference, 6.38%. On the other hand, the highest expense is done by Case 4 with 622.4 million NOK.

- In the study of the weather downtime of the cranes, the amount of percentage the cranes cannot be used because of wind speed limitations and wave height is around 42,5% as an average off all the cranes and cases, except in Case 4 that the weather downtime is 56% due to a longer duration. This downtime will cause a delay in the project and a rise in the overall costs.

- The same simulations for all the cases have been performed for the assembly site WindWorks Jelsa and the total project time has been compared to the total project time of Wergeland Base. First, in the simulations without weather conditions the total project time is very similar 160 days in Wergeland Base and 159 days in WindWorks Jelsa, 0,62 % difference, this makes the weather an important variable deciding which port is a better choice. For the same cases with the added weather constraints the difference is about 9 % with the port in Jelsa being the fastest to complete the project with 413 days compared to 453.8 days in the other location. In the other cases, the most effective is Case 5 with the lowest time employed in the project, 307.42 days for Wergeland Base and 325.5 for Jelsa, the longest case is Case 4 with 904.08 days in Wergeland and 1130 days for Jelsa. When having an overall comparison, the time taken when doing the project from these different ports is really similar between all the cases and a more specific analysis should be done with more accurate weather data closer to the location to have a better understanding of the outcome. As a first conclusion, it can be seen that the weather limitations in WindWorks Jelsa are slightly higher than compared to Wergeland Base with a small increase in the total project time.

5.1 Future work

Since the software has some limitations due to the availability of logistics data and exact weather data location for some sites, some future work is recommended. First, a good analysis of the supply chain from all the components loaded from the construction port and transported to the assembly site for every case could give a more detailed and realistic results to have an overview off the whole process of the supply chain. Also, a comparison between more cases with different combination of logistics (cranes, vessel) could give a better understanding of the different variables and future improvements in assembly and installation in an efficient way. Furthermore, a study of different types of concepts in different assembly ports could result in knowing which concepts have more advantages and are more effective than others.

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Annex A. Data Simulations

Two anchor handling vessels (Mooring system)		
Fuel consumption in transit (loaded)	0.025637	ton/km
Fuel consumption in transit (empty)	0.025637	ton/km
Fuel consumption when cable laying/burial	0.5	ton/hr
Fuel consumption during disconnect/hook up	0.5	ton/hr
Fuel consumption while installing mooring line	0.5	ton/hr
Fuel consumption while towing	0.025637	ton/km
Costs		
Day rate	700,000	NOK
Fuel cost	12,310	NOK
Port fee	1,544	NOK
Mobilisation cost	–	NOK
Towing speed	5	Kn
Transit speed	15	Kn
Capacity	3 mooring systems	

Weather criteria	
Wave height (m)	3
Wind speed (m/s)	15

Large Crane (Mammoet PTC 200 DS)		
Used for the integration of the Wind turbine		
Capacity of 1397 tonnes at 205 meters height		
Fuel consumption	Wergeland data	ton/hr
Assembly capacity	Wergeland data	
Costs		
Day rate	Wergeland data	NOK
Fuel cost	Wergeland data	NOK
Mobilisation cost	Wergeland data	NOK
Port fee	Wergeland data	NOK

Weather criteria	
Wave height (m)	0.5
Wind speed (m/s)	12
Ref. Height (m)	136

2 small cranes These two small cranes assemble two different floaters simulaneously			Weather criteria Wind speed (m/s)	12
Fuel consumption (load), diesel, 250Te	Moreld Data	ltr/hr		
Fuel consumption (load), diesel, 500Te	Moreld Data	ltr/hr		
Costs				
Mobilisation cost 250Te	Moreld Data	NOK		
Mobilisation cost 500Te	Moreld Data	NOK		
Day rate 250Te	Moreld Data	NOK		
Day rate 500Te	Moreld Data	NOK		

2 Crew transfer vessels		
Capacity	12 technicians	
Cruising speed	20	kn
Significant wave height access limit	2.25	meters
Fuel consumption		
Fuel consumption in transit	0.004499437	ton/km
Fuel consumption when pushing on asset	0.16647919	ton/hr
Fuel consumption when idle offshore	0.16647919	ton/hr
Cost		
Day rate	37500	NOK
Fuel cost	12310	NOK
Mobilisation cost	–	NOK
Port fee	1000	NOK
Activity durations		
Connection time	5	Minutes
Disconnection time	1	Minutes
Personnel transfer time per technician	5	Minutes
Equipment transfer time	10	Minutes
Mobilising time per port visit	30	Minutes
Demobilising time per port visit	30	Minutes

Towing vessel	Weather criteria

Transit speed	12	kn
Towing speed	4	kn
Capacity	1 FWT	
Fuel consumption		
Fuel consumption in transit	0.025637	ton/km
Fuel consumption while towing	0.5	ton/km
Fuel consumption during disconnect/hook up	0.5	ton/hr
Costs		
Day rate	137,150	NOK
Fuel cost	12,310	NOK
Mobilisation cost	5,000	NOK
Port fee	1,500	NOK

Wave height (m)	2
Wind speed (m/s)	13

Annex B. Results simulations

B.1 Project duration

	Total project time				
Month	**Case 1**	**Case 3**	Percentage difference (%)	Days difference	Standard deviation case 3
January	466	542	14.02	76	48.96
February	438	525	16.57	87	Max
March	437	512	14.65	75	623
April	415	484	14.26	69	Min
May	416	492	15.45	76	484
June	423	599	29.38	176	
July	431	615	29.92	184	
August	448	623	28.09	175	
September	469	606	22.61	137	
October	499	592	15.71	93	
November	517	581	11.02	64	
December	487	555	12.25	68	
Average	453.83	560.5	18.66	106.67	

	Total project time				
Month	**Case 1**	**Case 4**	Percentage difference (%)	Days difference	Standard deviation case 4
January	466	877	46.86	411	62.74

February	438	856	48.83	418	Max
March	437	828	47.22	391	1002
April	415	811	48.83	396	Min
May	416	863	51.80	447	811
June	423	868	51.27	445	
July	431	956	54.92	525	
August	448	1002	55.29	554	
September	469	982	52.24	513	
October	499	964	48.24	465	
November	517	933	44.59	416	
December	487	909	46.42	422	
Average	453.83	904.08	49.71	450.25	

	Total project time				
Month	**Case 1**	**Case 5**	Percentage difference (%)	Days difference	Standard deviation case 5
January	466	309	33.69	157	23.51
February	438	308	29.68	130	Max
March	437	291	33.41	146	345
April	415	308	25.78	107	Min
May	416	319	23.32	97	256
June	423	345	18.44	78	
July	431	335	22.27	96	
August	448	324	27.68	124	
September	469	311	33.69	158	
October	499	297	40.48	202	
November	517	286	44.68	231	
December	487	256	47.43	231	
Average	453.83	307.42	31.71	146.42	

B.2 Assembly time

Month	Assembly time case 1	Assembly time case 2	Percentage difference %	Days difference	Standard deviation case 1
January	224	155	30.80	69	50.87
February	266	155	41.73	111	Max
March	269	155	42.38	114	331
April	175	155	11.43	20	Min
May	175	155	11.43	20	175
June	289	155	46.37	134	

July	288	155	46.18	133
August	305	155	49.18	150
September	285	155	45.61	130
October	331	155	53.17	176
November	227	155	31.72	72
December	208	155	25.48	53
Average	253.5	155	36.29	98.5

Month	Assembly time case 1	Assembly time case 3	Percentage difference %	Days difference	Standard deviation case 3
January	224	517	56.67	293	33.50
February	266	476	44.12	210	Max
March	269	478	43.72	209	550
April	175	447	60.85	272	Min
May	175	484	63.84	309	447
June	289	525	44.95	236	
July	288	548	47.45	260	
August	305	550	44.55	245	
September	285	543	47.51	258	
October	331	528	37.31	197	
November	227	538	57.81	311	
December	208	520	60	312	
Average	253.5	512.8	50.73	259.33	

Month	Assembly time case 1	Assembly time case 4	Percentage difference %	Days difference	Standard deviation case 4
January	224	849	73.62	625	52.45
February	266	832	68.03	566	Max
March	269	805	66.58	536	946
April	175	803	78.21	628	Min
May	175	825	78.79	650	803
June	289	858	66.32	569	
July	288	946	69.56	658	
August	305	926	67.06	621	
September	285	913	68.78	628	
October	331	936	64.64	605	
November	227	905	74.92	678	
December	208	836	75.12	628	
Average	253.5	869.5	70.97	616	

B.3 Total project costs

	Million NOK				
Month	**Case 1**	**Case 2 (No weather)**	Percentage difference (%)	Costs difference	Std Case 1
January	407.7	243.8	40.20	163.9	32.50
February	386.1	243.8	36.86	142.3	Min
March	369.5	243.8	34.02	125.7	359.3
April	359.3	243.8	32.15	115.5	Max
May	361.6	243.8	32.58	117.8	446.3
June	367.5	243.8	33.66	123.7	
July	371.6	243.8	34.39	127.8	
August	399.7	243.8	39.00	155.9	
September	434.8	243.8	43.93	191	
October	446.3	243.8	45.37	202.5	
November	441.6	243.8	44.79	197.8	
December	421.1	243.8	42.10	177.3	
Average	397.23	243.8	38.25	153.43	

	Million NOK				
Month	**Case 1**	**Case 3**	Percentage difference (%)	Costs difference	Std case 3
January	407.7	431.4	5.49	23.7	30.96
February	386.1	409.4	5.69	23.3	Min
March	369.5	391.8	5.69	22.3	379.5
April	359.3	379.5	5.32	20.2	Max
May	361.6	380.9	5.07	19.3	464.7
June	367.5	421.2	12.75	53.7	
July	371.6	427.3	13.04	55.7	
August	399.7	446.5	10.48	46.8	
September	434.8	458.4	5.15	23.6	
October	446.3	464.4	3.90	18.1	
November	441.6	464.7	4.97	23.1	
December	421.1	446.3	5.65	25.2	
Average	397.23	426.82	6.93	29.58	

	Million NOK				
Month	**Case 1**	**Case 4**	Percentage difference (%)	Costs difference	Std Case 4
January	407.7	619.4	34.18	211.7	34.53
February	386.1	595.2	35.13	209.1	Min
March	369.5	572.2	35.42	202.7	559.9
April	359.3	559.9	35.83	200.6	Max
May	361.6	606.8	40.41	245.2	664.3
June	367.5	620.6	40.78	253.1	
July	371.6	622.1	40.27	250.5	
August	399.7	654.3	38.91	254.6	
September	434.8	660.8	34.20	226	
October	446.3	664.3	32.82	218	
November	441.6	657.9	32.88	216.3	
December	421.1	636.1	33.80	215	
Average	397.23	622.47	36.22	225.23	

	Million NOK				
Month	**Case 1**	**Case 5**	Percentage difference (%)	Costs difference	Std Case 5
January	407.7	385	5.57	22.7	14.70
February	386.1	349.2	9.56	36.9	Min
March	369.5	366.8	0.73	2.7	349.2
April	359.3	349.2	2.81	10.1	Max
May	361.6	370.5	2.40	8.9	392.8
June	367.5	364.6	0.79	2.9	
July	371.6	366.2	1.45	5.4	
August	399.7	378.8	5.23	20.9	
September	434.8	388.1	10.74	46.7	
October	446.3	392.8	11.99	53.5	
November	441.6	388.4	12.05	53.2	
December	421.1	365.3	13.25	55.8	
Average	397.23	372.075	6.38	26.64	

B.4 Weather downtime of the cranes

	Crane 1 Floater	Standard deviation case 1
Month	**Case 1** Downtime percentage %	6.00
January	32.93	Max

February	40.60	51.98
March	39.76	Min
April	30.53	30.53
May	38.86	
June	44.71	
July	51.98	
August	46.52	
September	46.08	
October	44.60	
November	42.82	
December	37.78	
Average	41.43	

	Crane 2 Floater	Standard deviation case 1
Month	**Case 1** Downtime percentage %	5.73
January	32.93	Max
February	37.52	49.98
March	39.76	Min
April	32.03	32.03
May	46.20	
June	44.71	
July	49.98	
August	46.52	
September	45.92	
October	44.60	
November	42.82	
December	37.06	
Average	41.67	

	Crane Integration turbine	Standard deviation case 1
Month	**Case 1** Downtime percentage %	10.97
January	31.83	Max
February	27.39	56.67
March	27.19	Min
April	27.19	27.19
May	54.56	
June	48.04	
July	46.48	
August	46.53	
September	45.10	
October	47.53	
November	50.93	
December	56.67	
Average	42.45	

	Crane 1 Floater	Standard deviation case 3
Month	**Case 3** Downtime percentage %	3.97
January	43.14	Max
February	39.68	48.24
March	39.24	Min
April	36.05	35.320
May	35.32	
June	42.75	
July	46.41	
August	48.24	
September	44.77	
October	43.32	
November	41.86	
December	38.49	
Average	41.61	

	Crane Integration turbine	Standard deviation case 3
Month	**Case 3** Downtime percentage %	8.08
January	44.25	Max
February	38.68	56.02
March	36.01	Min
April	36.01	36.01
May	36.71	
June	40.95	
July	49.01	
August	56.02	
September	53.76	
October	52.92	
November	53.75	
December	54.45	
Average	46.04	

	1 crane floater/integration turbine	Standard deviation case 4
Month	**Case 4** Downtime percentage %	4.38
January	52.28	Max
February	51.11	60.21
March	49.89	Min
April	49.21	49.21
May	54.11	
June	57.32	
July	60.00	

August	58.43
September	59.07
October	60.21
November	60.20
December	60.17
Average	56.00

	Crane 1 Floater	Standard deviation case 5
Month	**Case 5** Downtime percentage %	6.89
January	32.93	Max
February	37.52	52.46
March	39.76	Min
April	30.53	30.53
May	52.46	
June	47.89	
July	49.98	
August	46.52	
September	46.08	
October	45.96	
November	42.82	
December	37.06	
Average	42.46	

	Crane 2 Floater	Standard deviation case 5
Month	**Case 5** Downtime percentage %	6.12
January	33.10	Max
February	40.60	51.98
March	39.76	Min
April	30.53	30.53
May	46.81	
June	44.71	
July	51.98	
August	46.57	
September	45.92	
October	44.60	
November	44.01	
December	37.78	
Average	42.20	

	Crane Integration turbine	Standard deviation case 5
Month	**Case 5** Downtime percentage %	10.97
January	31.83	Max

February	27.39	56.67
March	27.19	Min
April	27.19	27.19
May	54.56	
June	48.04	
July	46.48	
August	46.53	
September	45.10	
October	47.53	
November	50.93	
December	56.67	
Average	42.45	

B.5 WindWorks Jelsa total project time

	Total project time				
Month	**Case 1**	**Case 3**	Percentage difference (%)	Days difference	Standard deviation case 3
January	454	540	15.93	86	37.00
February	430	518	16.99	88	Max
March	424	513	17.35	89	607
April	406	499	18.64	93	Min
May	408	501	18.56	93	499
June	405	523	22.56	118	
July	400	562	28.83	162	
August	408	584	30.14	176	
September	443	607	27.02	164	
October	418	590	29.15	172	
November	395	572	30.94	177	
December	365	566	35.51	201	
Average	413.00	547.92	24.30	134.92	

Total project time

Month	**Case 1**	**Case 4**	Percentage difference (%)	Days difference	Standard deviation case 4
January	454	1178	61.46	724	32.33
February	430	1147	62.51	717	Max
March	424	1126	62.34	702	1187
April	406	1095	62.92	689	Min
May	408	1103	63.01	695	1088
June	405	1105	63.35	700	
July	400	1119	64.25	719	
August	408	1187	65.63	779	
September	443	1162	61.88	719	
October	418	1132	63.07	714	
November	395	1118	64.67	723	
December	365	1088	66.45	723	
Average	413.00	1130.00	63.46	717.00	

	Total project time				
Month	**Case 1**	**Case 5**	Percentage difference (%)	Days difference	Standard deviation case 5
January	454	286	37.00	168	21.57
February	430	299	30.47	131	Max
March	424	322	24.06	102	354
April	406	354	12.81	52	Min
May	408	344	15.69	64	286
June	405	353	12.84	52	
July	400	339	15.25	61	
August	408	336	17.65	72	
September	443	336	24.15	107	
October	418	316	24.40	102	
November	395	314	20.51	81	
December	365	308	15.62	57	
Average	413.00	325.58	20.87	87.42	