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PREFACE AND ACKNOWLEDGEMENTS

This master's thesis is written as part of the two-year Master of Science program within Marine and Offshore Technology at the Department of Mechanical and Structural Engineering and Materials Science. The study was conducted at the University of Stavanger (UiS) during the spring semester of 2021.

Energy resources, with a focus on renewable energy, have long been an interest of mine that my studies have allowed me to pursue during my time at the University of Stavanger. With this being said, it was considered a great opportunity and intriguing challenge to write my final thesis on a subject involving floating offshore wind turbines. I am very thankful for all the knowledge and insight that has been shared with me on the subject over the past year from supervisors, lecturers, and industry contacts.

A large amount of time was spent on researching the topic and reviewing previous research findings. Due to a minimal amount of available information and a lot of confidentiality surrounding the cost aspect of floating offshore wind projects, the research presented some difficulties. Limitations regarding the cost aspect were implemented as a result of this. Through using the Shoreline simulation tool, which proved to be very useful in my comparison cases, I have learned a lot about simulation modeling and the organizational structure of floating wind construction.

I am very thankful for everything I have learned and gotten to experience over the past two years of my master's degree. I would like to thank my supervisor, Associate Professor Charlotte Obhrai, for trusting me with this project and for continuous help, insight, and advice during the writing process. I would also like to extend a special thanks to Tore Kolnes at NorSea Group for assisting me with valuable insight into the plans for WindWorks Jelsa and helpful feedback on my results. Ph.D. candidate Afolarinwa David Oyegbile has been very helpful with problems and input regarding Shoreline. Further, my co-students deserve a special thank you for the valuable working environment that has opened for helpful discussions and guidance during my writing process.

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Martin Skår

ABSTRACT

The increasing interest and demand for renewable energy in Europe have supported trials and developments of floating offshore wind turbines in deep waters. It is already well established that about 80% of Europe's potential wind resources are located in waters deeper than 60 meters, but significant investments and improvements in the infrastructure and supply chain will have to be realized to meet the projected installed capacity of floating offshore wind[1]. This paper aims to determine how the increased interest and demands within FOW can be met by changing the assembly and installation procedures. Current planned developments lack efficiency by relying on too many locations during the construction and installation phase; this report explicitly investigates the effects of transitioning to a single multipurpose onshore site that can optimize these processes.

The research question asks how the construction phase of FOW can be optimized, and by doing so, securing Norway a leading role in Europe's floating wind industry. To answer this question, the Shoreline simulation tool was utilized to compare the installation of planned future floating wind projects with the new methods and locations proposed in this study. This was included in a comprehensive case study. Based on the literature study performed in this thesis, it was decided that a location study was required to find a suitable location for an installation hub that could serve Utsira North, Sørlige Nordsjø II, and many future developments.

The simulation results showed that by adapting to a more centralized installation hub, there was a potential of reducing the project duration by 52% on average. This confirmed the hypothesis stating that the downtime and installation process will drastically improve if the assembly and installation process is centralized and moved entirely onshore. Other results demonstrated that the seasonal change in weather has dramatic effects on the overall project duration of smaller floating wind developments, an effect that proved to be less significant for more extensive and more realistic projects. These results suggest that targeted investments in infrastructure specific for the installation of floating offshore wind can have a considerable effect on the installation time and cost of floating wind developments. By taking advantage of the knowledge and experience gained from floating structures in the offshore oil and gas industry while utilizing the industrialization on onshore steel tower sections, the results indicate that a transition to this model could advance Norway into a leading role in the FOW market.

ABBREVIATIONS

BFOW	Bottom-Fixed Offshore Wind
CAPEX	Capital Expenditures, investment costs
EU	European Union
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
GW	Gigawatt
HAWT	Horizontal Axis Wind Turbine
LCOE	Levelized Cost of Energy
MW	Megawatt
NCS	Norwegian Continental Shelf
OPEX	Operating Expenses, operational costs
O&M	Operations and Maintenance
VAWT	Vertical Axis Wind Turbine
WOW	Waiting on Weather
WTG	Wind Turbine Generator

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1 INTRODUCTION

1.1 BACKGROUND

Norway is currently in a position where they want to reduce their annual carbon emissions and help other European countries achieve the same goal. This means that the extraction of hydrocarbons will have to be drastically reduced over the following decades, leading to less activity in the oil and gas sector and potentially high unemployment rates in the affected sectors. It's believed that these unemployment rates can be avoided if Norway starts transitioning more over to sustainable energy and use the experience and knowledge from the oil industry to become a leading nation in floating offshore wind technology.

Over the past decade, floating offshore wind (FOW) technology has seen a significant increase in both confidence and feasibility. With increased public and financial trust, the technology quickly evolved from various demonstration projects consisting of one single floating turbine to Hywind Scotland Pilot Park, the world's first pilot wind farm, with five 6 MW turbines located just off the coast of Scotland[2]. The first pilot park has been successfully operating for four years and has, according to official UK offshore wind capacity factors, been outperforming expectations and operating on consistency levels higher than bottom fixed wind[3]. The success of these pilot projects has resulted in the start of a new industrial era where floating offshore wind technology is unlocking the possibility of extracting wind energy resources in hard-to-reach places, such as deep waters.

In the European Union (EU), a large share of the member countries has turned to floating offshore wind to cut carbon emissions and become climate neutral by 2050[4]. Due to their history in the oil and gas industry, Norway is arguably one of the European countries with best prerequisites of taking a leading role in the floating offshore wind market, something they are determined to utilize. In June of 2020, the Federation of Norwegian Industries received funding from the Ministry of Petroleum and Energy for the project "Delivery models for offshore wind"[5]. The project has engaged several industry clusters and significant companies in the supplier industry, contributing to mapping and describing the opportunities for Norwegian suppliers. The project will provide recommendations for how supplier companies can obtain contracts and market shares in offshore wind and how marine operations, ports, technology, and the supply chain can transition to the offshore wind era.

1.1.1 NEW CONCESSIONS ON THE NORWEGIAN CONTINENTAL SHELF

On the 1st of January 2021, the Norwegian government opened the areas "Utsira Nord" and "Sørlige Nordsjø II" for offshore renewable developments, including floating offshore wind power[6]. This means that contractors can now start submitting license applications for offshore wind farm projects[7]. The area of Utsira Nord has an average water depth of 267 meters and is, therefore, most suitable for floating offshore wind installations. The relatively close proximity to the mainland makes it less complicated to transfer the energy to the mains supply[7]. The near-shore location also ensures that the distances for towing and time spent on the open ocean are kept as low as possible. Locations like these are very valuable for FOW developments, and this is where the technology will see its first large-scale developments that can set an example for future developments that will be needed to reach the climate goals by 2050.

If floating offshore wind is going to help European countries reach their climate goals, it will require a substantial amount of installed capacity by the year 2050. This means that fundamental processes such as assembly, deployment, and installation must be optimized and tested to yield satisfying and cost-reducing results. At the time of writing, there are a couple of locations that have been used for the assembly and deployment of floating wind turbines in Norway, but the procedure is yet to be optimized, and there is a lot of improvements that can be made. This thesis will focus on how these operations can be improved, particularly by centralizing the assembly process and using software to simulate virtual construction cases.

1.2 PURPOSE OF STUDY AND MOTIVATION

The purpose of this study is to explore how to optimize and refine the procedures involved in the assembly and installation of future FOW developments in Europe. While doing this, the thesis will shed light on Norway's potential of taking a leading role in European floating offshore wind developments, partially by serving as a central hub for manufacturing/import, assembly, and installation of future floating offshore wind projects. This is to be done through qualitative location studies and simulations using Shoreline.

Considering the short amount of time that floating offshore wind farms have been part of the renewable energy sector, there are some uncertainties and a considerable amount of untapped potential. Norway is in a unique position when it comes to experience within offshore and subsea operations. The past few decades have seen an exponential increase in oil and gas demands, putting Norway at the forefront of offshore technology solutions. This thesis will, amongst other things, explore how the knowledge and solutions from the Norwegian oil and gas industry can be put to use in the renewable energy sector.

Major energy companies like Equinor and Aker BP have announced upcoming floating wind projects, and with this, also released detailed plans regarding the operations. When studying these plans, it becomes clear that there is significant room for improvement; today's solutions for assembly and installation rely on several different locations, offshore lifting operations, and a lot of seaway transportation during the construction and assembly phase. The wind turbine technology itself and its ability to efficiently harvest energy is rapidly evolving yearly, and this report will therefore not focus on these potentials. This study, on the other hand, will focus on the improvements that can be made within the assembly process and the potential upsides that can be achieved by developing a multipurpose assembly and storage facility. It will also explore if Norway has the potential to act as central manufacturing, assembly, and installation hub for coming FOW projects in Europe.

1.3 RESEARCH QUESTION

Based on the topics and challenges discussed in the above subchapters, I have formulated the following main research question for this thesis:

How can we optimize the construction phase of FOW and help Norway venture into a leading role in the European floating offshore wind market?

Answering this question is an extensive task. To address the challenge, there has been developed a series of hypotheses that will be confirmed or disproved through the course of the thesis to assist in concluding an answer for the research question.

HYPOTHESIS 1

The downtime and installation process will drastically improve if the assembly and installation process is centralized and moved entirely onshore.

HYPOTHESIS 2

The future trends and potential for floating offshore wind in Europe put Norway in an ideal position for acquiring a leading role within the industry.

HYPOTHESIS 3

The estimated goals for installed capacity will not be reached unless industrialization of floating offshore wind is seen in Norway.

1.4 FOCUS AREA

There are many challenges to overcome, and many exciting focus areas need to be explored before developments at Utsira North and Sørlige Nordsjø II can be executed. This thesis will explore the various positive effects of executing as much of the installation work as possible on the mainland before towing the finished structure out to its operating destination. The study will therefore include a location study used to find an ideal location for mainland construction and assembly. An ideal location demands a deep-water quay, a crane with sufficient reach and capacity, proximity to the offshore wind farm location, accessibility, and more. The gathered information will be processed through a software called Shoreline, which can simulate an endless number of complex O&M, supply chain, or cost efficiency scenarios in a risk-free virtual environment[8].

In order to correctly understand Norway's position in the European floating offshore wind market, it is essential to develop a better understanding of the strategies and future plans of other key nations in Europe. Therefore, a lot of the research will focus on planned developments and potential onshore assembly locations in countries such as France, UK, and Denmark, which are seen as Norway's main competitors.

Figure 1.1, which is seen below, illustrates a forecasted cost reduction trajectory based on analysis by BVG and Catapult[9]. The measurement primarily used for the LCOE for offshore wind is million NOK per megawatt, which lies at around 60-65 when this report is written. Expert estimates from IEA floating wind and DNV GL predict that this LCOE will be reduced by 50-69% by 2050, as discussed in WindEurope's "Floating Offshore Wind Vision Statement" and DNV GL's "Energy Transition Outlook"[9][11]. The most significant reductions are expected to be seen within fixed costs (manufacturing, vessels, labor, etc.) and operating and maintenance (O&M). By running cost efficiency simulations in Shoreline and finding the ideal onshore installation methods, this report could potentially assist in strengthening the grounds on which the below trajectory is based.

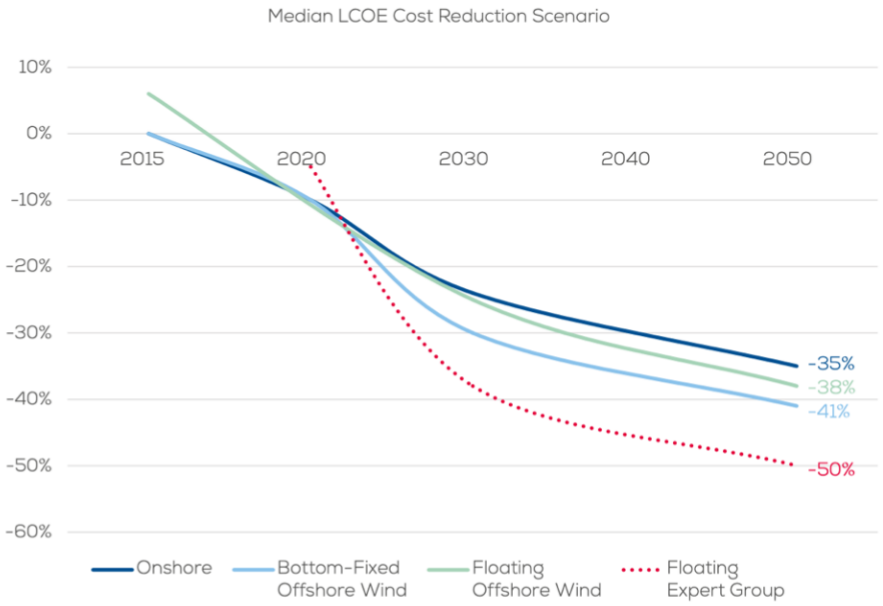


Figure 1.1 – Cost reduction trajectory for 2020-2050[9]

1.5 LIMITATIONS

The study's main focus area is floating offshore wind and the development and execution of this technology and Norway's position in the European market. Considering the vast scope of the mentioned industry, it becomes necessary to set some boundaries to limit the extent of the study.

1.5.1 THEMATIC BOUNDARIES

The floating offshore wind industry in itself is very promising, and there is a broad consensus that floating offshore wind will see a dramatic increase in developments and serve an important role when reaching future climate goals. Therefore, it is essential to clarify that this study investigates Norway's role in the floating offshore wind market and not the potential of the technology itself. The thesis will include some estimates on future installed capacity, but it will not discuss the technological advancements in detail.

1.5.2 GEOGRAPHICAL BOUNDARIES

Norway's potential in the floating offshore wind segment will be strongly affected by agreements made in the European Union. Decisions made in the EU can, for example, have an impact on which offshore areas are opened up for floating offshore wind developments. Many promising developments are happening globally, especially in Asia, where technology is developing very fast. But as current predictions say that the European floating offshore wind market will most likely not depend heavily on imported parts from Asia, this thesis will only focus on the European market.

Opening up new geographical areas for FOW developments will be necessary for reaching high enough levels of installed capacity. However, this responsibility lies with the respective governments in the participating countries, and the chance of this happening will not be discussed in this thesis. The thesis may instead suggest areas that need to be opened and discuss how large areas or how many turbines are required in order to reach Europe's publicly published goals.

1.5.3 INDUSTRY SPECIFIC BOUNDARIES

This study will only focus on the floating offshore wind segment. Offshore wind, in general, would also be very relevant to assess. Still, considering the fact that the most potent wind resources are located at depths where the bottom fixed wind can't reach, FOW is seen as the technology with the most untapped potential. The knowledge and experience gained within floating structures in the oil industry from the past decades put Norway in an excellent position for taking a leading role in the floating wind market. These are the main reasons why this study has chosen to focus on floating offshore wind.

1.5.4 BOUNDARIES AS A RESULT OF UNAVAILABLE INFORMATION

The high level of competition between the various organizations in floating offshore wind has had an impact on this thesis. It has proved challenging to gather exact information on the costs involved in FOW developments. These are confidential and not to be shared due to the risk of leaking and losing advantage. As a result, this thesis will not address the cost and general economy of the discussed developments.

As for the weather files used in the simulation scenarios, there were also some minor limitations due to unavailable data. Some of the wind farms simulated in the large-scale simulations had to be placed on locations where there, to this date, is not opened for floating offshore wind. Since the simulations predict developments until the year 2050, the thesis used locations that seemed reasonable and attractive for floating offshore wind developments. A result of this was that there was no available weather data for these locations. The nearest available data (Utsira North) was used to compensate.

2 LITERATURE REVIEW

As this thesis is not the first to investigate the technology and advancement of floating offshore wind turbines, a literature review was conducted to get a proper understanding of the work that is already published. The main research topic for the literature review will be rooted in the underlying hypothesis that has been developed. Thus, extensive research has been carried out from a large variety of sources on the topics of future energy trends in Europe, the advantages of centralizing a construction process, and the effect of industrialization.

2.1 EUROPE'S FOW POTENTIAL

The EU has pledged a significant increase in the amount of energy each country should harvest from sustainable wind developments. A lot of these wind developments will be located offshore, and many of them will be floating. This means that the industry will see a significant increase in the demand for onshore wind turbine assembly locations. In order to solve this puzzle, countries will have to cooperate across borders to establish assembly locations that can be used for a large variety of wind projects.

The various energy trends in Europe will give a good indication of whether Norway has good chances of taking a leading role in the floating offshore wind market or not. The following sections will present findings from the literature review that can help answer the second hypothesis, which states that *the future trends and potential for floating offshore wind in Europe put Norway in an ideal position for acquiring a leading role within the industry.*

2.1.1 TRENDS IN THE EUROPEAN UNION

WindEurope's latest report states that if all European member governments implement their National Energy and Climate Plans (NECPs), Europe will have reached an increase of over 100% in sustainable energy capacity by 2030[12]. This implementation will also lead to an estimated 50% increase in jobs related to wind energy and ensure that Europe gets roughly 30% of all its electricity from sustainable wind power compared to today's 15%[12][13]. However, another scenario is represented in the same report; with the rate seen in today's developments, the National Energy and Climate Plans will struggle to deliver the promising scenario presented above. The report states that there is a lot of confusion regarding the auctioning of new potential wind farm developments and that governments are failing to simplify the process of getting permits for new wind developments. If these problems were not to be improved upon, it could potentially lead to an overall decrease in jobs related to the floating wind industry within 2030[12].

A report published by DNV GL in late 2020 projects that the global floating wind capacity will grow to reach 250 GW by 2050, compared to the current installed capacity of 100 MW; this represents a 2000-fold increase. Reaching an installed capacity of 250 GW would mean that floating offshore wind accounts for 20% of all offshore wind and about 2% of the global power supply[14].

The NECP goals referred to in this chapter are seen as feasible and affordable, and they would not have been signed if they weren't. It is a matter of initiative and willingness that's needed to take advantage of the significant resource that lies within European floating offshore wind. The following sections will explore the potentials that lie within establishing central ports for distribution, storage, and assembly of FOW throughout Europe and how this could help unlock the untapped potentials that have been explored in this chapter.

2.1.2 INTERNATIONAL DISTRIBUTION AND STORAGE PORTS

Availability and accessibility are of utmost importance if governments want companies to heavily invest in floating offshore wind, the industry needs to arrive at a point where a company can apply for a development license, plan a project, order the components and execute the operation in as few steps as possible to make it cost-efficient for the companies involved[15]. Today's situation involves too many intermediaries from start to finish, making the operation far more complex and costly than it needs to be. A solution to this problem could be to establish international distribution and storage facilities that are accessible and ready to deliver all components that a company might need in their project. The UK is at the forefront of these types of developments, and the planned Able Marine Energy Park (AMEP) is an excellent example of this[16].

The British-based company Able UK has recently opened up about their plans of constructing an ample storage, supply, and assembly port for offshore wind in the East of England[17]. The port's geographical location makes it a good supply base for wind developments in both the North Sea and more distanced projects. The thought behind the project is to create a multi-user-friendly facility, meaning that several companies can simultaneously rent space at the facility. The port will be specifically developed to handle the operations related to manufacturing, storing, assembling, and deploying offshore wind turbines. It's many thanks to the planned size of this project that makes it possible, with close to 1400 meters of deep-water quays.

Establishing these types of ports in the UK and ultimately in other countries can bring many benefits to the industry. The industry allows for dramatic cost reductions related to transport and installation vessels by having these central hubs. By making the supply chain for components shorter, the journey from production to installation becomes drastically quicker, allowing for a reduced carbon footprint and also lowered costs.

2.1.3 INTERNATIONAL ASSEMBLY PORTS

Some assembly ports could easily be combined with a distribution and storage port, like the AMEP project discussed in the previous chapter. However, in many cases, there are limited locations available where one can find adequate accessibility, deep ports, and good enough space all in the same place. If the demands for wind energy continue to rise as projected, more assembly ports will have to be established, and these will have to be able to handle different types of buoyancy structures.

In Spain, the Port of Bilbao is in the process of establishing itself as one of the foremost hubs specializing in the construction, storage and installation of components for offshore wind. Official statements has announced that the 77 000m^2 large facility will be able to manufacture up to 300 offshore tower sections and 100 monopiles of 100 meter length per year at full production capacity[18]. The same port, which is one of Europe's largest wind tower and offshore foundation manufacturers, has been awarded a contract for the manufacture and assembly of Spain's first floating offshore wind turbine, the 2 MW DemoSATH project[19]. The Port of Bilbao is an excellent example of a centralized large scale installation hub that will be used for future European FOW developments, the success of these facilities will have big influence on the development of similar hubs in Norway.

2.1.4 COST TRAJECTORY OF FLOATING OFFSHORE WIND

Although the technology included in a floating wind turbine is not new or groundbreaking, combining a floating structure and a wind turbine of this size is something not tried until recent years. With this being said, solutions like this have not yet been put into mass production and will be of high cost in the first years of development. However, considering how undeveloped this technology is, there is considerable potential in technology development. This means that there is room for innovations that can lead to significant cost reductions. One example of this is design adjustments of the floating substructures contributing to lower costs.

The cost of floating offshore wind is expected to drop significantly in the years leading towards 2050[11]. This statement is backed by several companies and authorities, including DNV GL and Equinor. The positive cost trajectory also comes as an effect of the standardization and upscale in the production of turbines, towers, and floating substructures. Specialized vessels and procedures will continue evolving, leading to increased efficiency and lower cost of marine operations. As new developments are completed and the technology evolves, the companies and investors involved will get a better insight into the risk factors in floating offshore wind, causing the projects to be more predictable and lower in cost.

In writing time, Equinor's Hywind Scotland development is the world's largest floating offshore wind park; this is going to be surpassed by the future Hywind Tampen project if the current plans get realized. Using these two projects as an example for the cost trajectory, Equinor has estimated that the investment costs for Hywind Tampen have dropped by around 40% compared to Hywind Scotland[20]. An important driver for the cost reductions seen for Hywind Tampen is the increased turbine capacity which was 6MW for Hywind Scotland and now 8MW for Hywind Tampen.

Levelized cost of energy (LCOE), often also referred to as levelized energy cost (LEC), is widely used as a measurement to assess the profitability of different energy solutions. The LCOE of floating offshore wind technology is based on the average total cost of constructing and operating the asset, divided by the asset's total electricity production over an assumed lifetime.

2.1.5 FOW – SOCIAL ECONOMIC REPERCUSSIONS

This subchapter will further discuss the potential social-economic repercussions that can be expected in Norway if more floating offshore wind projects are completed, and the nation successfully secures a leading position within the FOW field.

These repercussions will be noticeable both as a short-term effect from the first floating wind park projects like Hywind Tampen and long-term if Norway can establish a competitive advantage in the floating wind industry.

2.1.6 THE VARIOUS FOW SEGMENTS

There are many segments within floating offshore wind, meaning that there is a lot of vendors in the offshore specific industry that can transition to becoming suppliers for the offshore floating wind segment. The following subchapters will explore the current presence of companies that can deliver components and systems to the floating offshore wind industry. Each segment will be rated from low, medium to high based on how big of a share of the production/involvement the Norwegian-based companies can expect as the floating wind industry expands. As Hywind Tampen is the first big floating offshore wind park that will be realized, this will be used as an example in the following segments. Some of the segments depend on how quickly the Hywind Tampen project is realized, considering that delays could weaken the advantage Norway has in experience and available technology.

WIND TURBINE MANUFACTURING

As of today, there are no Norwegian-based companies that can deliver wind turbines for the offshore wind market. One of the largest European companies within wind is the Danish-based Vestas. They previously had a factory in Norway where they produced some of the turbine parts, but this was phased out about 10-years ago due to a decline in orders. Now, there are factories in Norway that can produce control systems, surface treatment, electrical components, and vessels needed for operations and maintenance; however, since there aren't any turbine manufacturers, the Norwegian share is set to low or non-existing in the construction phase.

FLOATING SUBSTRUCTURES

As discussed in previous chapters, several different types of substructures have been experimented with for floating offshore wind. The different types are usually separated by the water depth and environmental conditions they will be exposed to and the material used for construction (steel versus concrete). The concrete substructures can be, and already is, constructed locally, while steel foundations are for the most part produced in other locations/countries and then transported to an onshore base for finishing and assembly. A more significant share of the floater design is based on concrete, and there is a lot of sites, experience, and knowledge from offshore concrete casting that can be taken advantage of the thesis; therefore, consider the local/Norwegian share to be high when it comes to the production of floating substructures. However, the Norwegian percentage could be significantly decreased if the nation is unsuccessful in starting developments early and taking on a leading role.

INSTALLATION – FOUNDATION AND TURBINES

As previously discussed, the most efficient and cost-effective installation method is assembling the substructure and turbine onshore and then towing the fully assembled WTG out to the wind park. Based on these grounds, the thesis assumes that this is the method that will be most widely used in the coming years.

Through the last decades with very high offshore oil and gas activity, Norway has built up extensive knowledge and experience within marine operations. There will most likely be some competition from international companies within marine operations, but Norwegian companies are still considered to have a good advantage in this segment. The launch and installation of floating wind will, in some cases (spar buoys), require very deep waters in the ports that are used, which further improves the local advantage. Based on this, the thesis can assume that the installation work would lead to a high degree of Norwegian employment and market share. To fully take advantage of this lead, projects would need to quickly be realized since experience within the field is very important.

ANCHOR SOLUTIONS

A substantial share of the cost related to the anchoring solution is the procurement of the anchor chain itself. While there are some chain manufacturers in Norway, they are usually outcompeted by international companies operating in low-cost markets. A floating wind farm will require extensive amounts of anchor chains, and the additional cost of choosing a local manufacturer would not be accepted. There would, however, be opportunities for local/Norwegian market shares within the project planning and installation of both the anchor chain and the anchor, for example, suction anchors.

Experience will also be highly valuable on these occasions, so the competitive advantage will be increased if Hywind Tampen and other developments are realized early/as planned. Considering the local experience on fastening oil rigs using anchor chains and anchors, the potential share is assumed to be medium.

INTERNAL CABLES

The market for internal cables, known as array cables, has strong international competition and is heavily dominated by large and experienced companies. Compared to export cables that transport the produced power to the destination country, the internal array cables secure connection between the individual WTG's and control systems located in the offshore wind farms. Norwegian-based companies are experienced when it comes to installing these cables and systems, but not the production.

However, to lower the cost of floating offshore wind developments, there is a strong need for technology innovation within dynamic high voltage cables, especially regarding cost-effective and robust solutions for cable installation and integration in the substructures. Early experience in this field will be vital, meaning the potential advantage can be secured if Hywind Tampen and other floating wind developments are finished as early as possible.

EXPORT CABLES

The wind farms rely on subsea export cables to transport the generated electricity to its point of usage. Because of the high pressures and cold temperatures found on the seabed, the technology is far more complex than what's found in similar onshore solutions. Large international companies dominate the production of these cables, and it would be wrong to assume that this production could be done locally with a competitive cost scenario. However, similarly to some of the other segments explored in this chapter, the installation and maintenance of these cables can be carried out by local companies and still be competitive on cost and efficiency.

Base on the information above, the international market share for Norwegian companies within subsea export cables is assumed to be low. The market share for the equivalent land-based export cables is considered to be unaffected.

OPERATION AND MAINTENANCE

When it comes to operation and maintenance, it is assumed that the market share for Norwegian companies will be high for the developments located on the Norwegian continental shelf. It is safe to assume that there will be some level of involvement from the international turbine suppliers. Still, as seen in similar cases from the oil industry, these suppliers usually rely on local suppliers for their operation and maintenance activities. Several companies in the western region in Norway are well established within marine operations and supply ship activities. These companies will have natural advantages when it comes to reorganizing their operations to satisfy the needs seen in floating offshore wind projects. Based on these factors, it is assumed that the local market share of operation and maintenance work will be high.

2.2 INSTALLATION SCENARIOS

This chapter will explore the various installation scenarios that are seen as realistic from 2021 and until 2050. When predicting scenarios this far into the future, there are always uncertainties regarding the actual outcomes, factors that can influence the actual outcomes are technological developments, political changes, social-economic changes, and various other unknowns. To account for these uncertainties, the estimates are often split into three different scenarios when predicting the installed capacity in the future: low (pessimistic), basis (neutral), and high (optimistic).

2.2.1 INSTALLED CAPACITY IN EUROPE

As investment costs and LCOE start to drop, Europe is expected to see a drastic increase in realized offshore wind projects. Although the bottom fixed wind will continue to be the preferred option in most European countries, floating offshore wind will also experience a significant increase in developments. WindEurope predicts that the offshore wind market will reach 450 GW installed capacity by the year 2050. WindEurope further estimates in their 2020 report that 100-150 GW of these gigawatts will be accounted for by floating wind energy[21]. There are, however, significant variations in the 2050-estimates published by various experts; a short overview of some of the expert estimates for installed capacity by 2050 is given in Table 2.1.

Table 2.1 - An overview of the various expert estimates on installed FOW capacity by 2050

Organization	Estimates on FOW capacity	Within year	*Source*
WindEurope	100-150 GW	2050	*[21]*
Carbon Trust	11-45 GW*	**2040**	*[22]*
DNV-GL	39 GW	2050	*[11]*

**Carbon Trust have only published estimates for 2040*

The considerable variation in these numbers confirms that there is high uncertainty in the future development of floating offshore wind in Europe. The uncertainty is not whether the technology is feasible or not, but rather the pace of development and the market share between bottom fixed and floating offshore wind. It is challenging to determine which of these predictions are more likely to be correct, but after extrapolating Carbon Trust's estimates until 2050 and taking the average estimate, we end up with roughly 75 GW by 2050, which seems like a reasonable number considering these sources as credible.

The 450 GW mentioned will, according to WindEurope, be divided between four main areas; these are listed in Table 2.2.

Table 2.2 - How the future 450 GW is likely to be divided between the European seas

450 GW installed offshore wind capacity (fixed and floating)			
North Sea	**Atlantic Ocean**	**Baltic Sea**	**Southern European Waters**
212 GW	85 GW	83 GW	70 GW

This means that the northern seas (North Sea, Atlantic Ocean, and the Baltic Sea), which are easily accessible from Norway, would account for 380 GW out of the total 450 GW of installed capacity in 2050. This helps strengthen the assumptions that Norway has a good opportunity of taking a leading role in project development. As mentioned previously in this chapter, this report estimates that roughly 75 GW out of the total 450 GW will be covered by floating offshore wind. Considering the water depths and wind conditions in the North Sea, it can be assumed that a larger share of the installed floating wind projects will be located here.

2.2.2 INSTALLED CAPACITY IN NORWAY

Due to significant uncertainties and a high level of inconsistency in estimates seen from the various sources, the forecast for installed capacity in Norway will be split into two separate scenarios: low and high.

LOW SCENARIO

The previous chapter revealed that trends and prognosis estimate a fair chance of seeing 75 GW installed floating offshore wind power in Europe by 2050. There is a broad consensus in the available sources that approximately 7 GW will be installed on the Norwegian Continental Shelf. Similar to previous estimates, this coincides with estimates done by DNV-GL[23]. The author reviewed and discussed these numbers together with NorSea Group; the results from these meetings suggest that the 7 GW estimate is significantly lower than the realistic potential for installed capacity in Norway by 2050. Based on this information, the forecast on installed capacity in Norway will be divided into a low and a high scenario, where 7 GW of installed capacity by 2050 represents the low scenario.

Table 2.3 presents the low scenario and suggests a gradual installation curve showing the number of gigawatts that could be installed each decade until 2050. The table also illustrates how the turbine capacity affects the number of turbines and wind farms needed.

Table 2.3 – Low scenario, an overview of future installed FOW capacity in Norway and number of wind farms needed based on WTG capacity

Norway							
Year	Installed capacity [GW]	Number of turbines based on capacity			Number of wind farms depending on WTG capacity		
		12 MW	15 MW	20 MW	12 MW	15 MW	20 MW
2020	**0**	0	0	0	0	0	0
2030	**0,5**	42	33	25	1*	1*	1*
2040	**3**	250	200	150	3*	2*	2*
2050	**7**	583	467	350	6*	5*	4*

**the number of wind farms is based on that each wind farm contains 100 floating wind turbines; this would mean an installed capacity of 1200 MW, 1500 MW, or 2000 MW, depending on the chosen turbine.*

HIGH SCENARIO

The high scenario, which has been developed as an optimistic response to the low scenario, is primarily based on information gathered from NorSea Group. NorSea Group has been an excellent collaborator during the study and has offered valuable data, independent views, and knowledge through discussions and email correspondence. The company is the main driver behind WindWorks Jelsa, a project which has been central for this thesis and will be further elaborated on in the coming chapters. The high scenario for installed capacity is based on the optimistic installation rates that WindWorks Jelsa wants to achieve eventually, which is to install about 1,2 GW worth of floating wind turbines each year. These rates can't be reached before one or more onshore bases of significant size are operational. It is also heavily dependent on the optimism and willingness to invest in the technology, thus classified as the optimistic scenario.

The high scenario, reproduced in Table 2.4, predicts an accumulated installed capacity of 19 GW within the year 2050. This is based on installation rates of 100 MW per year from 2020 to 2030, 600 MW per year from 2030 to 2040, and then the desired rate of 1.2 GW per year from 2040 until 2050.

Table 2.4 - High Scenario Showing an Overview of future installed FOW capacity in Norway and number of wind farms needed based on WTG capacity

Norway							
Year	Installed capacity [GW]	Number of turbines based on capacity			Number of wind farms depending on WTG capacity		
		12 MW	15 MW	20 MW	12 MW	15 MW	20 MW
2020	**0**	0	0	0	0	0	0
2030	**1**	83	67	50	1*	1*	1*
2040	**7**	583	467	350	6*	5*	4*
2050	**19**	1583	1267	950	16*	13*	10*

**the number of wind farms is based on that each wind farm contains 100 floating wind turbines; this would mean an installed capacity of 1200 MW, 1500 MW, or 2000 MW, depending on the chosen turbine.*

Both scenarios presented above include both 12 MW, 15 MW, and 20 MW turbines. Realistically it is not expected that any of the turbines installed before 2030 will have a larger capacity than 12 MW. The more realistic scenario, and the scenario that will be simulated, is to assume that the highest-rated turbine capacity between 2020 and 2030 is 12 MW; the capacity will then gradually increase with the following decades; this is seen in Table 2.5.

Table 2.5 - How the turbine capacity is likely to increase with time

Year	**Turbine capacity**
2020 – 2030	12 MW
2030 – 2040	15 MW
2040 – 2050	20 MW

2.3 CONSENTING RATES AND EXCLUSION ZONES

Keeping up with the installation scenario described in chapters 2.2.1 and 2.2.2 would require that the Norwegian, and other European governments, continue to allocate and open new areas approved for floating offshore wind developments. The rate at which new sites were approved in 2020 would need to be significantly improved to meet the future demand over the following decades.

Due to various exclusion zones, it's not currently possible to build offshore wind farms in at least 60% of the North Seas[21]. The exclusion zones exist for various reasons; a great share of these zones is protected due to environmental reasons and to protect threatened species and habitats. Others have been made exclusive for fishing activities, shipping, or military operations. The future consenting rates are directly dependent on the exclusion zones; the allocation of new sites approved for floating offshore wind will depend crucially on the status of these zones as they control such large areas of the North Sea. However, the problem does not regard having enough space for all the installed capacity; it's the issue of driving the costs down so that the technology becomes profitable.

2.3.1 THE CORRELATION BETWEEN EXCLUSION ZONES AND COST

The exclusion zones are most dense in the areas closest to the shore, and these are typically excluded to avoid developments in near-shore areas visible from the coast. This will be specifically challenging for the German and Swedish connection to the Baltic Sea, where it's hard to avoid wind developments being visible from the shore. In addition to this, there are also many exclusions due to shipping routes, pipelines, and fishing activities relatively close to the shore.

Now, the levelized cost of energy (LCOE) of floating wind developments will decrease as the proximity to shore also decrease; this has a lot to do with reduced cost during installation, pipeline services, and maintenance. The outcome of this is that areas with the lowest LCOE are made unavailable due to these exclusions, while the allocated FOW areas are placed in areas with higher LCOE. Cost reduction is, as discussed, a critical factor in floating offshore wind becoming a feasible solution. It becomes clear that to achieve this faster, there will need to be made changes in the exclusion zones found in the northern seas.

2.4 MULTIPURPOSE ASSEMBLY SITE BENEFITS

This chapter will explore the various benefits one could achieve by choosing an assembly procedure solely based on onshore operations. The most important factors to consider are whether implications, efficiency, and cost control.

2.4.1 WEATHER IMPLICATIONS

As discussed in previous chapters, the concrete casting and assembly of SPAR buoys can require water depths up to and over 100 meters. Due to this, previous wind farm developments in Europe which use SPAR buoys have relied on floating cranes and several different locations to fully assemble the floating wind turbines.

When conducting operations out on open waters, especially floating lifting operations, weather plays a critical role because of the operational limits that apply for the cranes and equipment in use. Every lifting operation has to be carefully scheduled with the coming weather forecast in mind. In addition to the wind, both waves and currents could affect a lifting operation have to be taken into consideration.

By moving these lifting operations onshore, one can almost eliminate the effects of waves and current while also lowering the wind exposure. This will ultimately lead to more freedom and flexibility regarding the lifting operations that will have to take place in the assembly process. Moving as many processes as possible onshore will also positively decrease the amount of downtime related to waiting on weather (WOW), which will have a substantial impact on both cost and efficiency.

2.4.2 INCREASED EFFICIENCY

By establishing a multipurpose location that can be used from start to finish of the assembly process and deployment, the need for several different locations is eliminated. For Hywind Tampen, the next big FOW development carried out by Equinor; the assembly process takes place at three different locations scattered out across the Norwegian west coast. As mentioned in chapter 6.1.2, it's seen that after construction start, the Hywind Tampen substructures are towed a total of 220 kilometers at sea before the rest of the tower is installed.

By eliminating these transport intervals, the efficiency would see a drastic improvement. Not only are these transport stages lengthy and time-consuming, but they are also dependent on weather and therefore risk being affected by delays due to WOW.

It's not only within transportation there are potentials of increasing the efficiency; the use of floating offshore cranes could also be a time-consuming operation. When using floating cranes like the Saipem S7000, the number of parts that can be placed in immediate reach of the crane is reduced. An onshore crane is usually installed on tracks and can move freely in 360 degrees; this makes an onshore crane able to easily pick parts up from a storage location and lift them into the place where the structure is being assembled. An onshore crane's reaction time and all-over speed would also be much quicker as it is electrical and not fossil fuel dependent.

2.4.3 COST CONTROL

Cost is essential when planning projects; if a project is considered to not be economically beneficial for the company in charge, it's likely that it won't become a reality at all. All improvements made that can make a project more cost-effective without significantly increasing the risk will therefore be of interest to the developers.

In comparison to weather and efficiency, the matter of cost also improved long term when considering the use of onshore cranes instead of floating ones. The highest cost concerning floating offshore cranes is seen in the day rate, with cranes like the Saipem S7000 costing up to 6 000 000 NOK/per day[24]. With rates like this, avoiding downtime becomes crucial as the costs involved could turn a project from profitable to non-profitable if margins are small. Transitioning to the use of onshore cranes would involve a very high entry cost, as the market for these cranes is very new, and only a few have yet to be manufactured. But looking at long-term cost and the amount of future floating wind projects planned in the North Sea, the author of this report deems it profitable to invest in establishing an onshore multipurpose location.

2.5 INDUSTRIALIZATION

The industrialization of floating offshore wind technology will be crucial in lowering the LCOE and reaching the installed capacity needed to satisfy the climate goals set. This could potentially be the factor that decides if this technology becomes a success or not, since new investors and companies will hesitate to get involved if the costs (LCOE) do not significantly decrease over the following decades.

The industrialization of FOW primarily concerns mass production and how this can be facilitated. Various floating offshore wind turbine designs have been presented in this thesis but considering the early phase that the technology is in, none of these are yet seen as dominant. Finding the cheapest and most reliable solution that is also the easiest to construct for large-scale deployment is a time-consuming and challenging process, seeing that all designs show different strengths depending on conditions on the seabed, water depths, and the supply chain[25]. Seen from a longer perspective, it's expected that the designs that win tenders will start to standardize. The subsequent standardization and industrialization of the supply chain will open up significant cost reductions[25]. This is something that is being investigated by the Federation of Norwegian Industries, through the project "Delivery models for offshore wind"[5].

There is a direct link between bottom fixed offshore wind and floating offshore wind, and it is, therefore, natural to compare the two. Based on several recent global and European estimates, it was shown that the LCOE of bottom fixed offshore wind fell up to 50% in the time from 2014 until 2019, an amount far more significant than what was predicted prior to 2014[26]. This significant decrease in LCOE was, amongst other things, a result of competition, industrialization, low steel prices, and larger turbines, all factors that are also essential in FOW. The increased competition can be explained as the driver behind the increase in developments and decrease in cost, while industrialization is seen as the reliever or the factor that makes it possible. The supply chain regards all activities connected to the floating offshore wind market, from manufacturing parts to installing subsea cables; there is a lot of potential for local vendors in Norway to participate in this supply chain. As the supply chain increases in local presence and gets more standardized, it will help drive the prices down. When this happens, an increase in industrialization will also be observed.

An important aspect to consider that has a direct link to industrialization is the learning curve. The general concept of a learning curve points out how the selling price of a product will decrease as a function of the total amount of the product being produced[27]. In other words, the more floating wind turbines produced, the lower the unit price becomes. As an example, a 15% learning curve means that every time the production quantity is doubled, the unit price is reduced by 15%. Through standardization and separation of fabrication and installation, onshore steel wind turbine towers have become a truly industrialized supply chain. Floating offshore wind is now in a unique position to take advantage of this supply chain. In simple terms, the only difference between floating offshore wind and onshore wind is the floating structure. This means that by utilizing the same steel tower sections for FOW, the industry can take advantage of an industrialization and reduction in cost that has been ongoing for several decades. However, the floating structures themselves will not experience industrialization before the production volume and investments are significantly increased. To summarize, three of the critical aspects of industrializing floating offshore wind is:

- Factory manufacturing as many parts as possible, which is cheaper and more controllable
- Assemble all components quayside at an installation hub
- Turbine mounted to substructure in the harbor and towed to site, no offshore lifting vessels

The continuous increase in turbine capacity is expected to significantly impact the levelized cost of energy. If industrialization is achieved along with an increase in turbine size, the floating technology can be competitive with bottom fixed offshore wind from 50 meters depth[28].

3 THEORY

This chapter aims to provide a theoretical introduction to the topics that are important to cover to answer the problem to be addressed. This includes but is not limited to; different structures and turbines, the software that has been used, geographical locations, future developments, technology, and data.

3.1 FLOATING SUBSTRUCTURES

When discussing floating offshore wind, the type of substructure is of utmost importance. The wind turbine itself is almost no different from the ones used onshore; it is the substructure that gives the floating offshore wind turbine its unique characteristics. The cost, construction time, and compatibility will vary greatly depending on which type of substructure is chosen. A successful floating wind development heavily depends on a reliable floating foundation; the following section will yield some insight into three of the main floating structures that can be used for future floating offshore wind projects. There are other concepts as well, but the ones discussed here have been deemed most suitable for the large-scale operations and capacity discussed in this report.

3.1.1 STRUCTURE 1: SEMI-SUBMERSIBLE

The semi-submersible structure has been tried and tested in the oil industry and is considered a reliable design. These structures rely on buoyancy and ballasting systems to maintain level and compensate for external environmental forces[29]. The planned wind farm developments are long-term investments, meaning that the wind turbines need to maintain their geographical position for many years without moving. To maintain secure over a longer period of time, the semi-submersible structures will have to be anchored to the seabed via mooring lines typically fastened to pre-installed suction anchors.

The most common semi-submersible structures found on the floating wind market are based on a triangular-shaped frame equipped with three separate hollow cylinders to keep its balance. The wind turbine will be installed directly on top of one of the three cylinders; thus, there will be a significant unbalance in the weight distribution on top of the semi-sub. This unbalance is handled by the integrated ballasting system, increasing the weight in the two opposite cylinders[29]. Strengths and weaknesses seen with semi-submersible structures are seen in Table 3.1.

Table 3.1 - Strengths and Weaknesses with semi-submersible floaters

Strengths	Challenges
Can be assembled and operate in shallow waters (low draft)	Complex steel structure with many welded joints
Low vessel requirements (only basic tugboats)	Costly active ballasting systems
Onshore WTG assembly (dry dock)	High structural mass needed to maintain stability
Suitable for mass fabrication	Complex mooring and stability control
Inherently stable for towing	

Several companies have tried and tested the basic semi-submersible structure using three or four columns, bracing, and catenary mooring. It can be seen in the Fukushima FORWARD FOW project in Japan (by Mitsu Engineering and Shipbuilding) and both the WindFloat Atlantic and WindFloat Kincardine projects.

The Norwegian-based company Dr. Techn. Olav Olsen has long been developing a floating offshore wind turbine concept based on a semi-submersible structure. The design has now been patented using the name OO-Star offshore wind floater[30]. Their concept is illustrated in Figure 3.1.

Figure 3.1 - Dr. Techn. Olav Olsens OO-Star Offshore Wind Floater[30]

3.1.2 STRUCTURE 2: BARGE

Similar to the semi-submersible structure, the barge is also a very reliable and stable structure. Barges are most commonly used to transport equipment and goods and have remained a popular choice of transport due to their low cost combined with excellent load capabilities. These load capabilities have made barges an interesting option as a floating base for offshore wind turbines.

The large waterplane area combined with the relatively shallow draft makes the barge a very stable option, but it also makes the barge susceptible to large wave motions. This is concurred by using bilge keels and heave compensation systems. Barges depend on buoyancy to maintain stability. Strengths and weaknesses with barge-type floaters are listed in Table 3.2.

There exist a few FOW projects which have chosen barge as the floating substructure, where the demonstration project by Floatgen (developed by the French Ideol) and the Hibiki project in Japan stand out as the most promising to date, these concepts use a concrete ring-shaped barge structure, where the patented damping pool is utilized as a motion damping system. The design process and final concept can be further studied in BW Ideol's design publications which has been used in this thesis research[31]. An illustration of the concept developed by BW Ideol is seen in Figure 3.2.

Table 3.2 - Strengths and Weaknesses with barge floaters

Strengths	**Challenges**
Inexpensive hull	Susceptible to larger hydrodynamic forces
Easy to assemble and install (assembled onshore)	Large forces on the mooring line system
It can be assembled and operated in shallow waters	
Deck area which can be used under operation and maintenance	

Figure 3.2 - BW Ideol's patented damping pool technology in use on a floating wind turbine[31]

3.1.3 STRUCTURE 3: SPAR

Unlike the other structures presented above, the SPAR-buoy is a deep draft structure with a relatively small waterplane area. The structure relies on a ballasting system to keep stable in shifting waves and winds. Like the two other options above, it requires a mooring system to maintain its geographical position[32].

The buoy itself is a large watertight cylindrical hollow structure, which can support the tall wind turbine due to the vast amount of weight that can be achieved in the hollow structure, hereby making the center of gravity (COG) very low. Due to the large draft combined with a small waterplane area, the SPAR is very good at resisting heave motions. Other strengths and weaknesses are listed in Table 3.3.

There exist a few full-scale spar developments and many concept developments. The spar technology has been successfully used in Equinor's Hywind Scotland project and will also be used for the upcoming Hywind Tampen project. The Hywind concept developed by Equinor is what they will continue to rely on, at least for their Norwegian-based developments. The technology requires a very deep draft, which will only get deeper as larger turbines with higher capacity are put to use. The main challenge with this concept will become finding waterways and ports which are deep enough to transport these wind turbines. An illustration of the Hywind concept is seen in Figure 3.3, the structure be further studied in Equinor's Hywind Tampen publications[33].

Table 3.3 - Strengths and Weaknesses with spar floaters

Strengths	**Challenges**
Inexpensive hull geometry	Need deep water for assembly and operation
Small waterline area (small wave forces)	Offshore turbine assembly is very complex and demanding
Low-cost mooring system	Deep draft limits the ability of towing structure in and out of port, both for installation and repair
No active ballasting system required	Material usage
Inherently stable	
Suitable for mass fabrication	

Figure 3.3 - Equinor's Hywind structure which utilizes SPAR buoy[33]

3.2 UTSIRA NORTH AND SØRLIGE NORDSJØ II

As mentioned in the introduction, Utsira North and Sørlige Nordsjø II were recently approved and regulated for renewable offshore developments. In practice, this means that any company that wants can submit a license application for offshore wind developments in these areas. This regulation is seen as an excellent achievement for the Norwegian floating wind industry. If the expert prognosis is correct, it will be the first of many areas to be approved in the coming decades. The following chapters will give an informative insight into both of these areas.

3.2.1 UTSIRA NORTH

The field is located approximately 18km west of Haugesund, just outside Utsira municipal[6]. The water depths at Utsira North are ranging from 220 to 280 meters, making it suitable for floating wind farms[34]. The area is relatively large, measuring roughly 1000 square kilometers and its proximity to shore makes it one of the most accessible potential wind farm locations in Norway[6]. The exact location of the allocated area can be seen using coordinates in Figure 3.4.

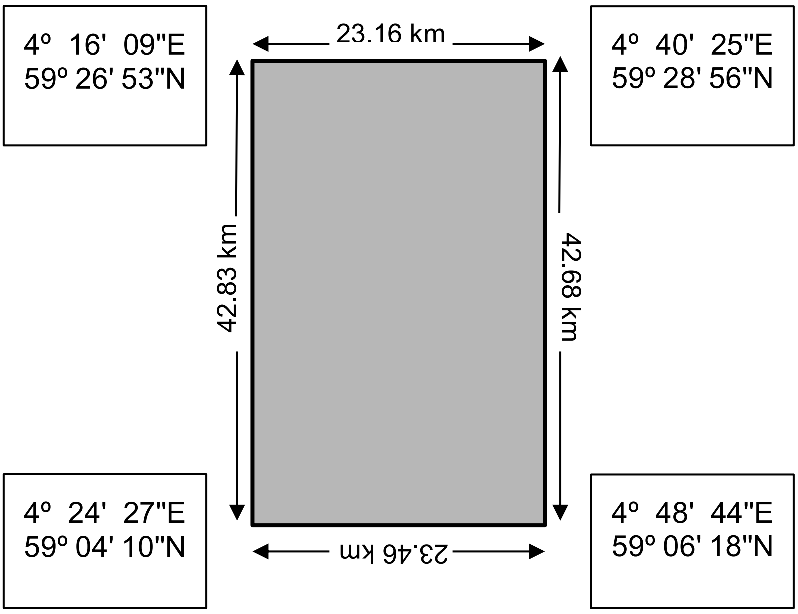


Figure 3.4 – Illustration showing the exact location of Utsira North on the NCS using coordinates

The area described above has been approved for a production cap of between 500-1500MW[35]. With this production cap, the developments at Utsira North have the potential of setting a new industry standard for how large these floating wind farms can be.

3.2.2 SØRLIGE NORDSJØ II

Together with Utsira North, Sørlige Nordsjø II was also opened for offshore wind developments by the Norwegian government. The area is located roughly 140 km off the Norwegian coast and is located on the border between Norway and Denmark: the area measures 2591 square kilometers making it considerably larger than Utsira North. The area has been approved for installed capacity up to 3000 MW[34]. The exact location of the allocated area is illustrated using coordinates in Figure 3.5.

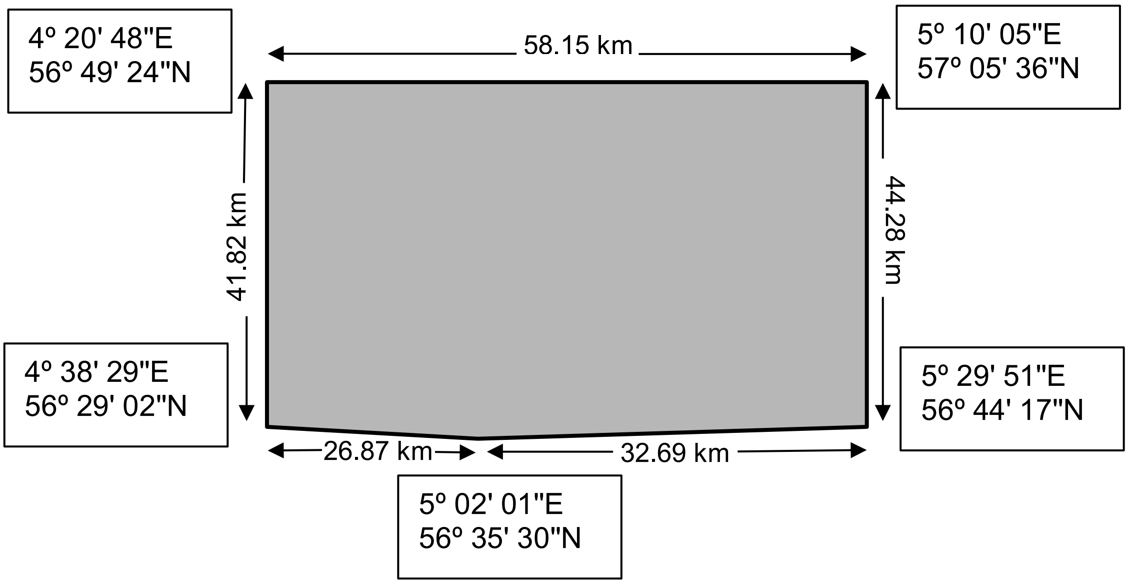


Figure 3.5 - Illustration showing the exact location and size of Sørlige Nordsjø II on the NCS using coordinates

The area has water depths ranging from 40 to 70 meters; unlike Utsira North, this area is, therefore, feasible for both bottom fixed and floating offshore wind. It is assumed that FOW developments in this area will depend heavily on positive changes in LCOE, making the technology more competitive.

3.3 WIND TURBINES

A wind turbine converts wind energy to electric energy by harvesting the aerodynamic forces that are acting on the rotor blades, which can resemble the blades found on a helicopter. Simply put, wind flow forces the rotor blades to rotate, making the generator spin, which generates power.

There are two common types of wind turbines available on the modern market: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The horizontal axis wind turbine is the most common of the two, and to this date, the most efficient solution. The modern horizontal axis turbines are usually equipped with three rotating blades. After numerous tests and concept studies, the three-bladed turbines have been deemed most efficient[36].

Floating offshore wind turbines are used in areas too deep for regular bottom fixed wind turbines, like Utsira North. When water depths exceed 60 meters, bottom fixed turbines will no longer be a cost-efficient solution and the LCOE of floating wind turbines will be lower.

As Figure 3.6 shows, these types of structures mainly consist of the following main components, tower, rotor, nacelle, and rotor blades[37]. The nacelle works as a housing for the more delicate components, hereunder the generator, gearbox, transformer, etc. The platform illustrated on top of the nacelle is special for offshore wind turbines and is used to drop off service personnel and equipment used for maintenance and service.

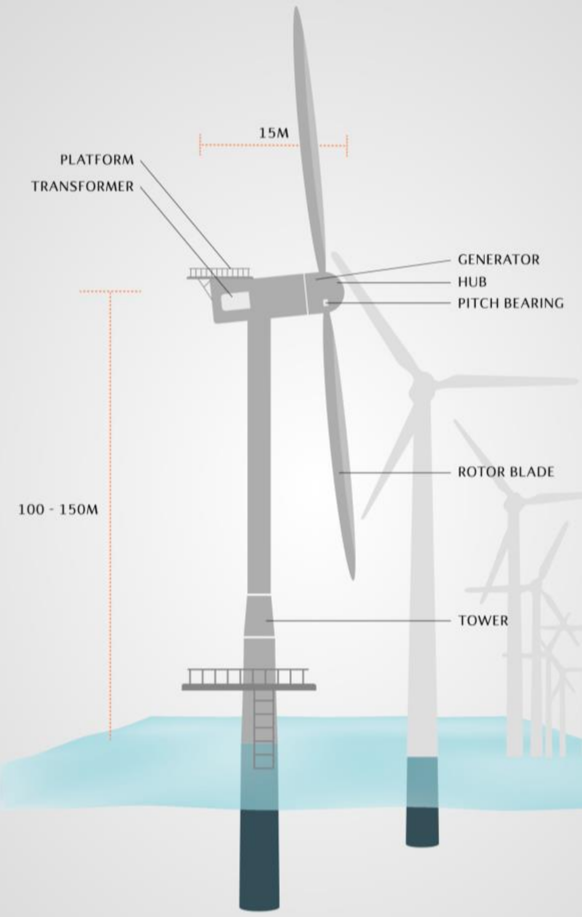


Figure 3.6 - Floating Wind Turbine, illustrating the main components and dimensions[36]

Like all other technical assets, wind turbines rely on regular service and will have to be repaired in case of defects. Due to the ambient conditions which are often unusually though and prone to high dynamic loading, maintenance of wind turbines are of special significance. Although these factors are carefully considered in the design and material selection, the conventional components still require maintenance. The most common failure seen with wind turbines is breakdown of components, other common failures include control system failure, excessive wind loads, waves and lightning strikes[38].

3.3.1 OFFSHORE TURBINES

A wind turbine is considered offshore if the main load-bearing structure is subjected to hydrodynamic forces[39]. Offshore and onshore wind turbines are very similar in terms of the technology that is being used and the functionality of the components. Both onshore and offshore turbines need all the components discussed in the previous sub-chapter, meaning that the towers are of very similar construction. The big structural differences are seen when looking beneath the water surface, where an offshore turbine depends on a much stronger and longer foundation or a floatation concept.

In new offshore developments, there is a substantial difference in the size of the structures, which makes the potential power output of the offshore WTGs much larger. The reasoning behind this is that there are higher mean wind speeds offshore than onshore; in addition to this, there are fewer regulations concerning the maximum allowable size of a turbine.

3.3.2 FLOATING SPAR STRUCTURE

There are many different concepts when it comes to floating wind turbine structures; the main differences are found in the type of floating structure that is chosen. One of the most widely used, and the one that this report will focus on, is a structure type called spar. A spar structure has a very deep draft and relies on a traditional mooring system, where it's secured to the seabed via mooring lines and anchors in order to maintain its plane position[40].

This type of structure is already successfully used on oil platforms on the Norwegian continental shelf; thus, there is a lot of valuable knowledge that can be transferred to the renewable sector in order to put this technology in use for floating wind turbines. This type of floating structure is also the one planned for the Hywind Tampen development. The experience

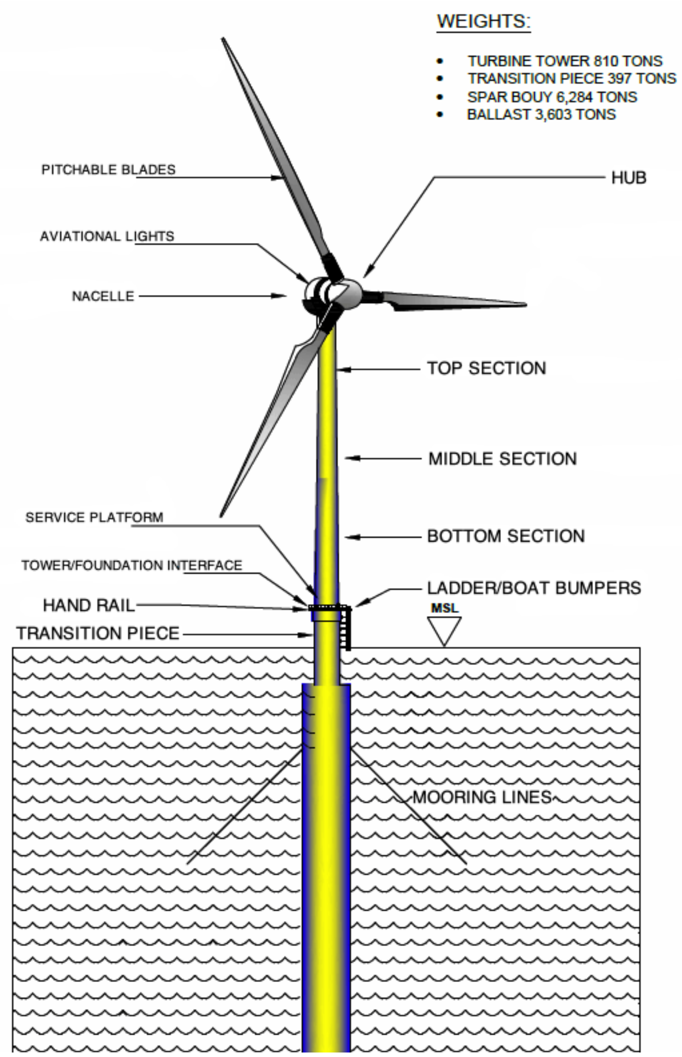


Figure 3.7 – Floating turbine on SPAR Buoy showing components and weight [40]

gained from the spar structures used in the oil industry and the Hywind Scotland project has shown that this type of structure is well equipped to handle the harsh and unpredictable environmental conditions that are found in the North Sea, which is the main reason why this structure was used in the reference case simulations in this study. Compared with barges and semi-submersibles, the spar structure requires significant water depth during the assembly phase; it would therefore be interesting to study the other substructures in greater detail to explore how these advantages could impact the assembly procedure; this will be included in future work due to limited scope on this project.

Figure 3.7 showcases some of the main components needed on a floating wind turbine rated at 10-20MW[41]. The weight section listed in the top right corner of the figure is a proposed estimate carried out by Paul Dvorak[41] in order to understand the weight distribution.

A big advantage with these floating SPAR structures is that they can be fully assembled and commissioned at the fabrication/assembly yard onshore and then be towed out to their final site without requiring any further assembly work other than the mooring line connection[42]. The structure itself is not very complicated; the limited waterline area combined with the deep draft helps minimize the heave effects. The ballasting system is located at the bottom of the buoy. This ensures that the center of gravity is located as low as possible. The low COG makes the structure very stable and more resistant to pitch and roll motions[41].

3.4 WIND TURBINE POWER CURVE

As wind turbine technology evolves, the potential energy output will increase. The most widely used tool for illustrating a turbine's power characteristic is the power curve. Since this study has used the IEA 15-MW turbine for a lot of the simulations, this turbine will be used as an example in this chapter[43]. This turbine is not yet in production, but the concept is planned and developed in cooperation between the National Renewable Energy Laboratory (NREL), Denmark Technical University (DTU), and the University of Maine. In the referenced study there has been developed specific design features which are reproduced in Table 3.4. Figure 3.8 shows the respective power curve used for the IEA 15-MW turbine. As mentioned in section 6.1.1, the author does not see it necessary to change the reference wind speed from 119m to 150m, which is the IEA 15MW WTG hub height.

Table 3.4 – IEA 15MW WTG design summary[43]

Parameter	**Value**
Power rating	15 MW
Specific rating	332 W/m^2
Rotor orientation & Configuration	Upwind, 3 blades
Rotor & Hub diameter	240m & 7.94m
Hub height	150 m
Cut-in wind speed	3 m/s
Rated wind speed	10.59 m/s
Cut-out wind speed	25 m/s

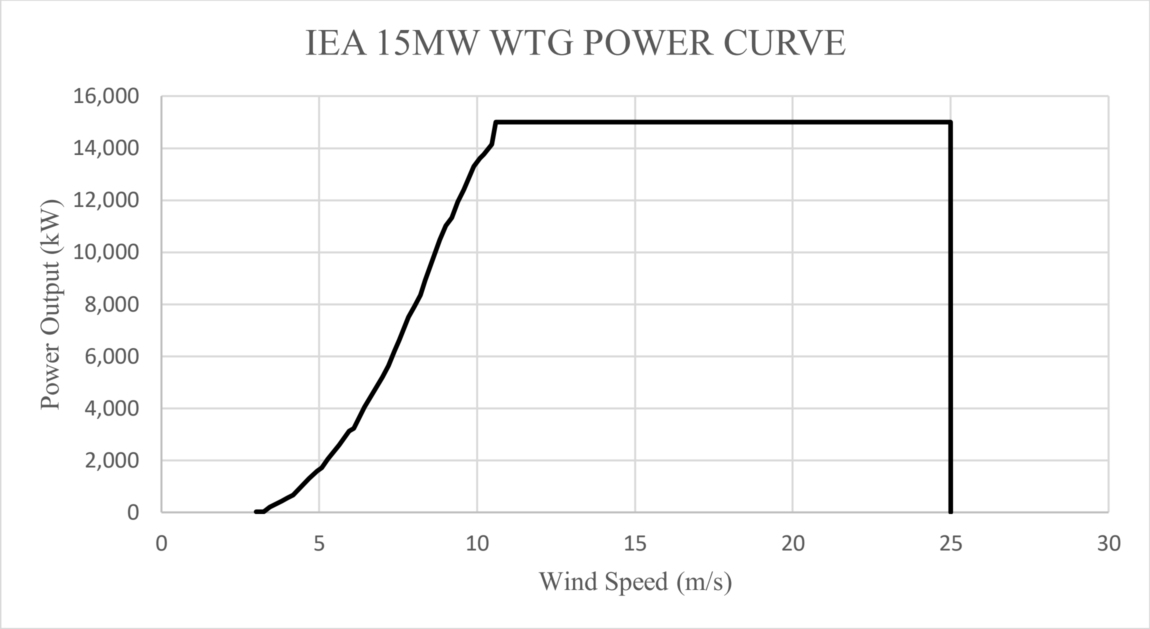


Figure 3.8 – IEA 15MW WTG Power Curve[43]

4 METHODS AND METHODOLOGY

The methods cover the various research methods and types of analysis needed to collect data for a survey or report. The methodology seeks to justify the use of multiple methods. The selection of correct methods becomes essential for the outcome of data collection. It is important to use research methods that make it possible to gather all the necessary information needed to answer the thesis' research question[44].

This chapter aims to address and provide a better understanding of how the knowledge used to answer the research question and related sub-questions have been gained. The chapter will describe the chosen method, how different data and information have been collected, and evaluate the method used.

4.1 PRIMARY VERSUS SECONDARY DATA SOURCES

When discussing how data is collected, one differentiates between the two main categories of primary and secondary data sources. Primary data is gathered through field research and is collected to provide answers to a clearly defined and current issue; this can be done through interviews, discussions, or field research. The primary data originates directly from the source and is collected for the first time by the researcher/author. On the other hand, secondary data is data that already exists and has been obtained by others. This is typically information that is found in articles, reports, newspapers, or public records. In a research paper, one can choose to use just one of these methods or both. This will depend on the issue at focus and the ramifications of the research paper[45].

4.2 QUALITATIVE VERSUS QUANTITATIVE ANALYSIS

There are two main methods to use when collecting primary data: qualitative and quantitative analysis[44][46]. The most suitable method of analysis depends on the research question and the overall purpose of the study. The following subchapters will give a better understanding of the main differences between the two methods.

4.2.1 QUALITATIVE ANALYSIS

A qualitative research program relies on data collected from other people's experiences, knowledge, and opinions which cannot be quantified or measured. The method is often aimed at groups or individuals that, prior to the survey, are considered to be relevant sources. This strategic selection of sources is made to facilitate experience-based argumentation/discussion within the relevant topic[44], [47]. When adopting a qualitative analysis, the collection of data is often done through personal interviews or discussions with a selection of relevant interviewees who answer questions pertinent to the issue at hand.

Qualitative analysis is favorable to use if the researcher has limited prior knowledge of the relevant topic. This is because it is easy to follow up and adapt to new information that emerges and change the research question/issue as needed. However, the method will be more time-consuming than a quantitative analysis but, in most cases, give a more extensive result as it allows interpretation of both body language and personal statements.

4.2.2 QUANTITATIVE ANALYSIS

The quantitative analysis method is called a measurable method and can be used to quantify data. Unlike qualitative analysis, which relies on personal interviews and discussions on a large scale, this method uses mathematical and statistical modeling, measurement, and research to gather data[48]. This method allows the researcher to test different hypotheses by using statistical analysis. The process of finding the average energy output from all floating wind farms is, as an example, a quantitative analysis.

4.3 COMPARATIVE CASE STUDY

A case study was necessary to analyze different procedures and the effect of changing variables in the assembly and installation process. The comparative case study approach was deemed most suitable as this method focuses on *how much can be achieved through comparison[49]*. The approach differentiates from regular case studies by engaging two logics of comparison; it utilizes both the common *compare and contrast* in addition to what's called *tracing across* sites or scales. These properties make this method ideal for a case study where the object is to analyze the similarities, patterns, and differences across several cases that share the same goal, which resonates well with this study's objective of comparing several methods of assembling and installing offshore floating wind turbines[50].

The comparative case study proved paramount in answering the thesis research question; the study is structured as a thesis and is found in chapter 6.

4.4 SIMULATION SOFTWARE – SHORELINE

New simulation tools and digital solutions have pointed the wind energy industry in a direction where trial and error are far less of a concern. The modeling and simulation software available on the market has made investments significantly less of a risk. Shoreline is an excellent example of this and has been the preferred software for this study.

Shoreline was established in 2014 by Ole-Erik Vestøl Endrerud, a former Ph.D. student at The University of Stavanger[51]. The company offers a simulation tool that allows for detailed design of the critical aspects within renewable asset management, especially wind, at all phases of the asset lifecycle. Excellent benefits combined with simple yet effective user interphase has quickly sent Shoreline well on its way to becoming an industry standard[8].

4.4.1 INPUT DATA

The user input that Shoreline allows for can be highly specified and customized to fit each specific scenario that is to be simulated. For the simulations executed in this study, each floating wind turbine was programmed into Shoreline by coordinate positions. This allows for a precise wind farm configuration that is easy to troubleshoot. Shoreline has an extensive list of inputs that can be customized, ranging from wind turbine capacity and design to maintenance vessels, assembly base locations, and various costs. By allowing such detailed inputs, Shoreline can generate very detailed outputs through simulation and statistical models. Results include project duration, detailed timelines, vessel and asset cycles, costs, and more.

WEATHER DATA

The software allowed for the use of very precise wind and wave simulations; this is made possible by using a bivariate Markov Chain Monte Carlo weather model. The model uses historical weather data gathered from meteorological stations in the vicinity of the wind farms to predict the weather. This weather data was incorporated into the simulations to evaluate the downtime caused by external factors.

VESSEL DATA

There is a very high level of confidentiality in the service and supply industry; a result is that it is hard to obtain specific information on the vessels needed to construct and operate the wind farms, especially the cost of these vessels is hard to pinpoint. Therefore, the vessels used in this study are generic, thus not representing any specific vessels on the market. For the construction simulations (including assembly, deployment, and installation), four different vessels were used: anchor handling vessel, mooring line handling vessel, onshore crane, and towing vessel. Shoreline allows for various vessel characteristics to be assigned; the simulation in this study uses significant wave height criteria (H_s) and wind speed (U_w) as criteria to limit the weather conditions in which they can operate.

TURBINE AND LOCATION DATA

A vital input factor to consider when setting up Shoreline is the respective wind turbine's power curve. The power curve yields essential information about how much electrical power a WT can generate under various wind speeds. These numbers will vary depending on the turbine capacity and manufacturer; the turbine's location in the wind farm can also affect the maximum power generation. Three terms essential to mention when discussing a WT power curve are cut-in, rated, and cut-out; these terms refer to specific wind speeds that will be important to consider for each different wind turbine model. The cut-in wind speed ($U_{cut\text{-}in}$) refers to the wind speed at which the wind turbine can generate electricity; these values usually lie around 3-5 $^{m}/_{s}$. The rated wind speed (U_{rated}) refers to the wind speed at which the wind turbine generated the optimum amount of electricity; this wind speed is not a fixed value but rather all wind speeds between rated and cut-out; rated wind speed is often found at around 10-13$^{m}/_{s}$. Lastly, at cut-out wind speed ($U_{cut\text{-}out}$), it is no longer safe to produce electricity due to structural limitations; thus, the rotating rotor is stopped by pitching the blades to feather position to reduce the lift force to a minimum. The cut-out wind speed is often set to 25$^{m}/_{s}$. Since the power curve varies with the specific wind turbine model and manufacturer, it is essential to input the correct data for each WTG in Shoreline.

After a successful simulation, Shoreline automatically generates a highly detailed report which includes all the information listed above; this report is Excel compatible and can be directly downloaded from the online simulation website. By analyzing this report, the user can discover the strengths and weaknesses in the planned project, which can be improved on in the next simulation.

For this study, the Shoreline Con Design™ feature was used to simulate all phases during the assembly, deployment, and installation of a floating offshore wind project. The use of simulations has been critical for this study. The exact and detailed results make it possible to fine-tune small margins that eventually make up several days in project duration[52].

4.5 DESK RESEARCH

Desk research is conducted to review previous research findings and theories, and it is carried out to gain a broader understanding of the field[53]. The data found through desk research is called secondary data and is often found in existing sources like scientific articles, reports, books, and web pages. Desk research is critical to understanding the topic better and will yield a better outcome if done prior to qualitative or quantitative analysis.

4.6 CHOICE OF RESEARCH DESIGN

This study has relied on a pragmatic approach to research, also known as mixed methods[54]. The qualitative analysis was chosen as the main method for primary data collection. To acquire sufficient knowledge of what is needed for Norway to take on a leading role in the floating offshore wind industry and how to optimize the installation procedures, it was decided that a qualitative method could contribute to gaining a deeper understanding of the topic. Qualitative discussions with central individuals from the industry have been carried out through Microsoft Teams. Through these discussions, the interviewees could produce nuanced descriptions of their situations and opinions. Thus, the method provides a basis for gaining knowledge about the objects' views and experiences[44]. It was essential for the outcome of this thesis to get in contact with experienced individuals who work with the technology and have realistic visions of how the industry is going to evolve.

Quantitative analysis has also been done in the form of data simulations; these have been carried out by using a software called Shoreline. There is a minimal number of actual projects completed within floating offshore wind, and therefore a lack of experience and knowledge on which solutions work best. Consequently, it has been crucial to simulate different cases to determine how changing a few variables impacts the downtime and overall project duration.

The thesis has been very dependent on proper desk research to gather secondary data and detailed simulations to gather knowledge about the installation phase. The desk research formed the foundation for all theory-based information used in this thesis. Linking the research question to relevant secondary data will contribute to helping strengthen the reliability of the outcomes from both the discussions and the simulation results. Choosing a research design consisting of both primary and secondary data opened for the development of an appropriate discussion and subsequent conclusion to answer the main research question and its sub-questions.

4.7 DATA COLLECTION

The central thesis project extends over a six-month period, starting in January and ending in June 2021. The thesis builds on a project that began in September 2020, also written by the undersigned author. The objective was to research installation procedures for floating wind and investigate the effect of changing and centralizing the assembly and installation location for future floating offshore wind projects. The six months have actively been used to continuously gather new and relevant information that can help answer the thesis' research question. The floating offshore wind technology is flourishing, and further information and discussions surrounding significant investments and developments in the technology are emerging daily. It has therefore been necessary and crucial to constantly stay updated with the developments. The data collection has mainly been carried out through (1) qualitative analysis through discussions, (2) quantitative analysis by running simulations, and (3) desk research.

4.8 CONDUCTING DIGITAL DISCUSSION MEETINGS

The quantitative analysis has been carried out throughout the six-month period in which the thesis has been written. The has been carried out several discussion meetings with various businesses and individuals where the contact with one of the companies, NorSea Group, developed into a more permanent collaboration. It would be favorable to meet all the contributors face-to-face for discussion. Still, due to the circumstances surrounding the Covid-19 pandemic, all meetings and conferences have been done using Microsoft Teams' communication platform.

It was essential to reach out to several different companies within the industry; this ensures a broader specter of answers and a holistic picture of the various points of view. Different companies in the same industry don't necessarily think alike.

4.9 IMPLEMENTATION OF SECONDARY ANALYSIS

Desk research has been carried out continuously through the whole process of writing this thesis. This method of analysis has been utilized to acquire knowledge within:

1. The floating offshore wind technology and market
2. EU's future commitment to the technology
3. Potential Norwegian onshore base locations

The secondary analysis of already existing data has many advantages. It is highly efficient, and one can take advantage of it when preparing for discussions since the research is not dependent on other respondents. The primary sources of information have been official reports, annual statements, professional articles, and online news articles, all from sources that are seen as trusted and professional. There has been a focus on selecting sources that can be trusted with accurate and unbiased data and statistics; the majority of data, therefore, originate from sources like DNV, WindEurope, IEA Wind TCP, GWEC, EERA, and the Norwegian ministry of petroleum and energy.

Floating offshore wind is seen as a new technology globally; it is rare and has not been tested to the same extent as bottom fixed and land-based wind turbines. The technology is, therefore, naturally met with skepticism and low expectations. This has led to significant variations and disagreements between the sources used; large uncertainties characterize estimates for installed capacity and cost trajectory.

4.10 SOURCE CRITICISM

For a survey to achieve the best possible result, it is of utmost importance to ensure accurate and appropriate data collection. Thus, it has been essential to set requirements for the quality of data to maintain the integrity and validity of the research, which are central concepts when assessing the quality of a study[55]. Quality assurance and quality control are two approaches that have been proved helpful in preserving data integrity and ensuring the scientific validity of the research results[56].

4.10.1 QUALITY ASSURANCE

The main focus of quality assurance is prevention (i.e., forestalling issues concerning the data collection) since it precedes data collection. In any type of research for an important publication, prevention will be the most cost-effective (figuratively speaking) activity ensuring validity since it is far more challenging to go back and change details after publication.

Part of the quality assurance process has been maintained by constantly checking sources thoroughly prior to using them. This involves background checking the publisher, checking if the published document could be biased, and investigating if the document is based on primary or secondary sources. It is also essential to check if the cited references have been correctly understood and retold. The purpose of quality assurance is to check the legitimacy of the data and check to what extent the data is valid and relevant to use in the study; this is called validity.

4.10.2 QUALITY CONTROL

The activities involving quality control occur during and after the data collection; the primary purpose of this activity is to confirm the reliability of the data/source[56]. It has been challenging to maintain proper quality control on the data used in this thesis; this has a lot to do with the wide range of sources with very different answers to the same questions. This is especially seen when researching future trends and estimations for floating offshore wind technology development, where there is a constant shift in goals and optimism.

A significant amount of the quality control done in this thesis has been through a comparison of the different data sets. A lot of the organizations in floating offshore wind get their information from the same sources; it has therefore been interesting to observe how that information is processed and adjusted before publication. A factor that has made it challenging to compare is that many sources use various scenarios (high, medium, and low) to describe their predictions. It can therefore be hard to interpret what data the estimates are based on. Good quality control will be able to explain how the data collection has taken place and uncover potential sources of error in the data; this is a good measure of reliability[44].

5 LOCATION STUDY

The research question that this study seeks to answer regards how the construction phase of floating offshore wind can be optimized, and by doing so, lead Norway into a central role within the FOW market. Geography is an essential part of this question and will be vital in the success or failure of optimizing the processes and thus have a significant impact on Norway's future role within FOW. Finding suitable areas for onshore production, storage, and assembly will be crucial in ensuring that cost, efficiency, and downtime are held at satisfactory levels.

The first out of three hypotheses that were established to help answer the research question regards the geographical aspect of success within FOW. The hypothesis states that the downtime and installation process (i.e., the construction phase) has large potentials for improvement that could be realized by centralizing the construction to one location onshore. As described in Chapter 1.2, the current floating wind developments in Norway rely on a lot of seaway transportation along the west coast to assemble the floating WTG's. Finding possible locations for the construction of floating wind will therefore be an essential part of the analysis to find out whether Norway has the opportunity to invest in floating offshore wind.

This chapter will explore some of the locations that have the potential of being used as a complete onshore assembly site, where the main goal is to assemble the entire WTG using only onshore cranes and equipment before the towing operation out to the final site will commence. By doing all of these operations on land and in one location, a lot of the offshore weather uncertainties can be eliminated, as can the cost of using offshore lifting vessels.

5.1 ALTERNATIVE LOCATION STUDY

There are various prerequisites that a location needs to satisfy to handle the construction and assembly of these wind turbines. These are needs related to accessibility, infrastructure potentials, size, proximity to Utsira North, cost of development, and more.

One of the most important factors to consider when planning a SPAR-buoy development is the water depth that can be reached from the quay. As explained in previous chapters, this assembly method requires the SPAR-buoys to be slip-form cast vertically down into seawater until the required length is obtained. When considering 150 m tall wind turbines, it's estimated that the buoy's draft can be upwards of 120m, meaning that a satisfactory location needs a quay that can obtain these depths[57]. The five sites assessed and their location relative to Utsira North are seen in Figure 5.1.

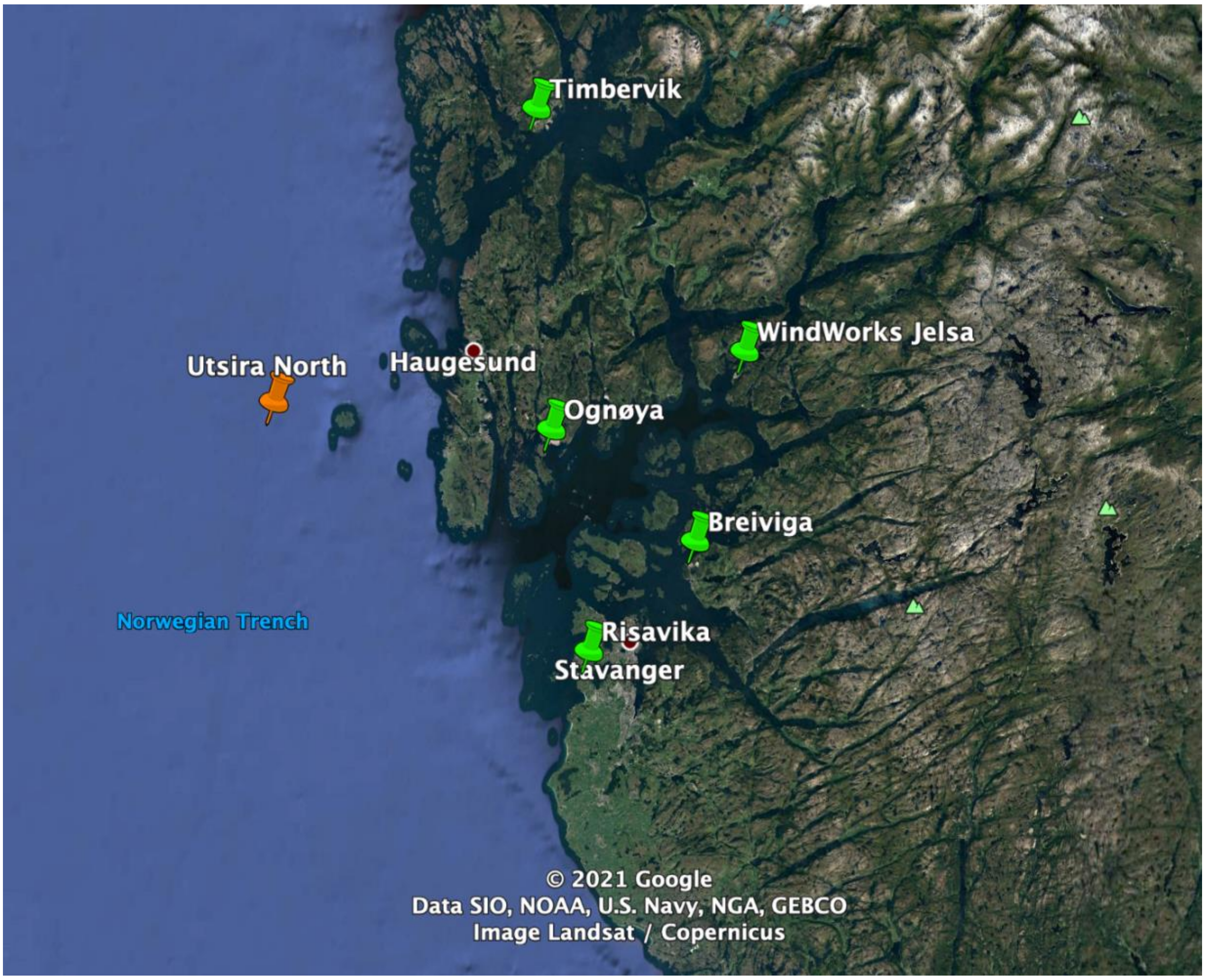


Figure 5.1 - An overview of the five different locations that will be assessed in the alternative location study. Source: [58]

OGNØYA – ROGALAND

Ognøya is located approximately 20km south of Haugesund and is a small island of only 5.5 square kilometers. Despite the island's small size, it's connected to the European route E39 by a series of bridges.

The interest for this exact location comes mainly due to its proximity to Equinor's Kårstø processing plant, which is located right next to Ognøya. This, combined with the fact that Utsira North is located relatively close (40-45km west in air distance), seemingly makes Ognøya a good potential base location.

The island's proximity to Equinor's Kårstø plant means that the location is very accessible for extensive equipment and heavy shipments. The nearby processing plant contains a lot of heavy equipment and relies on a quay with significant depth; this indicates that it would be possible to establish a similar quay on the neighboring island.

Table 5.1 illustrates the general preliminary location study for Ognøya; these four factors all need to be balanced in order to move on with the study.

Table 5.1 – Ognøya location study

OGNØYA			
Accessibility	**Proximity to Utsira North**	**Cost of establishing base**	**Water depth**
Good	40-45km	Very high	30-50m

The obvious and biggest challenge with this location is that the land is entirely undeveloped as of today. This means that there will need to be comprehensive costs allocated to the planning, development, and execution of establishing a new assembly base at this location. The island has a small population and is only inhabited by a farming family who also owns most of the land. In the event of going further with development at this location, it will be crucial to negotiate an agreement with the farmers. This will include acquiring a sufficient amount of land from the farmer and compensation for any inconveniences that may be caused.

Figure 5.2 – Ognøya location study showing nearby water depths

When investigating the surrounding water depths, it quickly becomes clear that the depths around Ognøya are not deep enough. This would mean that the operation would depend on a second location to completely assemble the wind turbines.

RISAVIKA, TANANGER – ROGALAND

Risavika is the main port area of the industrial area of Tananger, which lies just outside Stavanger. This location is an already well-established port that is used for offshore base operations[59].

Risavika is already a supplier for Northern Europe's largest oil and gas cluster, making this location an intriguing case. This experience can be precious when looking for a site that can be used to construct and assemble large-scale wind turbines. As there has been a decrease in the activity surrounding supply transport for the offshore fields over the past years, there is reason to assume that there is excess space available at Risavika that can be used for wind turbine assembly.

As seen in Table 5.2, the proximity to Utsira North is also relatively short; a distance of 65 km means that it would take a towing vessel upwards to 9 hours to tow a wind turbine from start to finish, assuming that the average speed is four knots per hour. This relatively short distance, especially compared to using the Skipavik Gulen base, means that it will be significantly easier to predict the weather along the towing route, resulting in less downtime and higher precision.

Table 5.2 – Risavika location study

RISAVIKA			
Accessibility	**Proximity to Utsira North**	**Cost of establishing base**	**Water depth**
Good	65-70km	Acceptable	30-50m

The cost of establishing an assembly base at Risavika is assumed to be acceptable, mainly due to the already existing supply base located there. This means that the quays are dimensioned to handle heavy crane operations and good accessibility for heavy equipment.

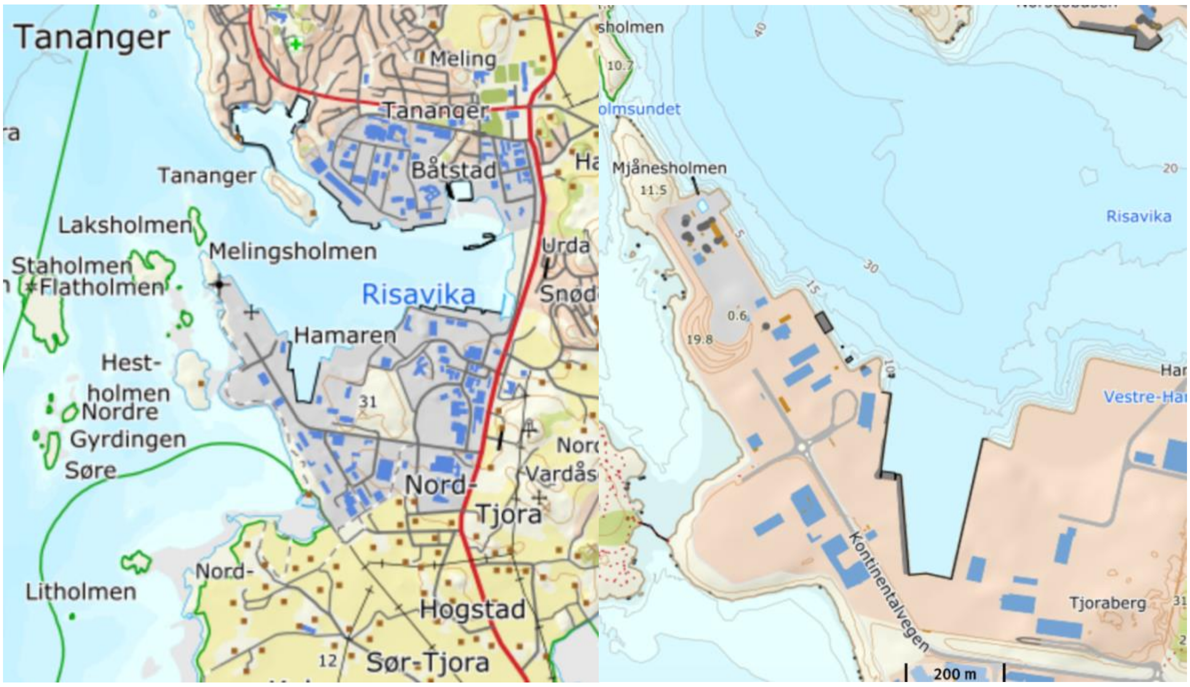


Figure 5.3 – Risavika location study showing nearby water depths

Similar to Ognøya, the location of Risavika also comes up short when assessing the necessary water depths. As mentioned previously, it's estimated that depths upwards of 120m will be required to assemble the floating wind turbines fully.

BREIVIGA, TAU – ROGALAND

Breiviga is located at the end of Fognafjorden, 10km north-west of Stavanger. The proposed location is currently being used and operated by Norsk Stein, who produces sand used in asphalt and concrete[60]. The location already has a large deep-water port that's being used to load high-capacity vessels.

The geography of this exact location makes it very intriguing; the proximity to a big city like Stavanger means that there is a lot of valuable knowledge and competency in the local community that can be put to good use when establishing a new deep-water offshore base. Stavanger is also home to many big energy corporations' headquarters, meaning that whoever ends up developing Utsira North probably already has an established business unit in or near Stavanger.

Table 5.3 – Breiviga location study

BREIVIGA			
Accessibility	**Proximity to Utsira North**	**Cost of establishing base**	**Water depth**
Good	75-80km	High	85-120+

As seen in Table 5.3 above, Breiviga scores well on all criteria except the cost, which the report has deemed high. The high cost comes mainly because the port will need a significant increase in size to handle the operations described in this report. The length of the quay itself is sufficient, but there will have to be improvements as to how far out into the water the dock stretches. This is to reach deeper water, which will be required when concrete casting the SPAR-buoys for the floating WTG's.

Figure 5.4 – Breiviga location study showing nearby water depths

The proximity to the Utsira North field is quite similar for this location as well; although it is 75-80km from the final location, it will take a towing vessel roughly 10 hours to tow the wind turbines from start to finish. This is a conservative estimate and is therefore deemed acceptable by the author of this report.

TIMBERVIK – STORD

Situated between the cities of Bergen and Haugesund lies Stord, a small municipality that has played an essential role in the western Norwegian shipping scene. Stord is home to a large shipyard owned by Kværner, which has been used to construct a significant number of some of the largest and most successful oil rigs on the NCS.

Just west of the large Kværner shipyard, there is a partly developed plot of land along the ocean; the location is called Timbervik. The fact that Timbervik lies right next to the big Kværner port means that it is very accessible, and that the area is used to the coming and going of significantly large equipment and structures. The location has been cleared of trees and flattened out and can be seen as partly developed, and there is also an already established quay that has been used to load out timber.

This location is made extra intriguing because the Bergen-based company called UNITECH Energy Group has already started investigating the possibilities of establishing a deep-water assembly port in this exact location. The concept study carried out by UNITECH will be capable of assembling and deploying a large variety of floating structures and configurations due to the available space and deep waters. With this, the location can be a central hub for lots of different future FOW projects.

Table 5.4 - Timbervik location study

TIMBERVIK

Accessibility	Proximity to Utsira North	Cost of establishing base	Water depth
Good	65-70km	Acceptable	140m+

As illustrated in Table 5.4, Timbervik is the first out of the five selected locations that score well on all factors in the location study. The accessibility is good, and the area has a long history of towing large oil rigs out to the North Sea. The onshore is also very well connected and has proximity to large cities with valuable knowledge and experience. The Utsira North development is also in fair reach from Timbervik at about 65km; it is well within the acceptance criteria. The location is cleared of trees and relatively flat due to previous lumber activities. A lot of cost is saved by having a relatively flat and cleared area, so the establishment of a new assembly base is not likely to present a lot of unforeseen cost. Although existing infrastructure apart from access roads and basic ports are missing, the location has been given an acceptable mark for the cost of a new establishment.

Figure 5.5 - Timbervik location study showing nearby water depths

As this report focuses mainly on using floating wind turbines based on the SPAR type buoy, the quay used is required to have an immediate water depth of over 120 meters. Now, many of the locations discussed will not be able to provide this; in fact, not many quays have this feature. The solution is to build a floating structure pointing outwards to where deeper waters are found; these floating quays can be dimensioned to support the weight of both equipment and several docking stations for SPAR buoys under construction. This concept is shown in UNITECH's illustration of their concept study below[61].

Figure 5.6 - UNITECH's concept of an onshore assembly base in Timbervik, Stord[61]

WINDWORKS – JELSA

Jelsa is located approximately 50km north-east of Stavanger, making it very competitive as an export location for floating wind turbines. The specific area proposed as a potential wind turbine hub has long been an active quarry site. This ensures an ideal place where several ports are already established and in reach for large transportation vessels. The proximity to both Stavanger and Haugesund makes the accessibility very good, especially by sea.

Just recently, a new company called WindWorks Jelsa was established; the company has been made possible by NorSea Group, Suldal county, and Ryfylke IKS through cooperation with Norsk Stein and New Kaupang. Part of the old quarry at Jelsa is no longer in use, and since it's already excavated, it makes an ideal wet dock. The newly established company's vision is to produce and assemble the WTG's onshore and then lift them directly into the water-filled quarry, ready to be towed to their respective wind farm location. WindWorks Jelsa's procedure has a lot of resemblance to the methods proposed in this study and is therefore seen as an ideal location.

The existing quarry is around 40 meters deep and will not be suitable for today's spar buoys. However, NorSea Group is currently investigating the possibility of assembling SPAR buoys outside the quarry so that the concrete structure can be cast in the quarry. At the same time, the assembly and towing, which requires deeper waters, can be finished outside of the quarry. It is essential to address that WindWorks Jelsa is looking to start up serial production of floating wind turbine generators that can be exported globally and will therefore not limit their production to only WTGs based on spar floaters. The location is very suitable for floating substructures like semi-submersibles and barges. The sizeable available area allows for storage both on land and in the wet dock.

Seen in Table 5.5 is the summary of the location study for Jelsa; based on this summary, it is safe to assume that the location fulfills all the requirements set in this study which is needed to work as a central exportation hub for coming floating wind projects in Europe, especially the North Sea.

Table 5.5 - Jelsa location study

WINDWORKS - JELSA

Accessibility	Proximity to Utsira North	Cost of establishing base	Water depth
Good	80-90km	Acceptable	40-100m

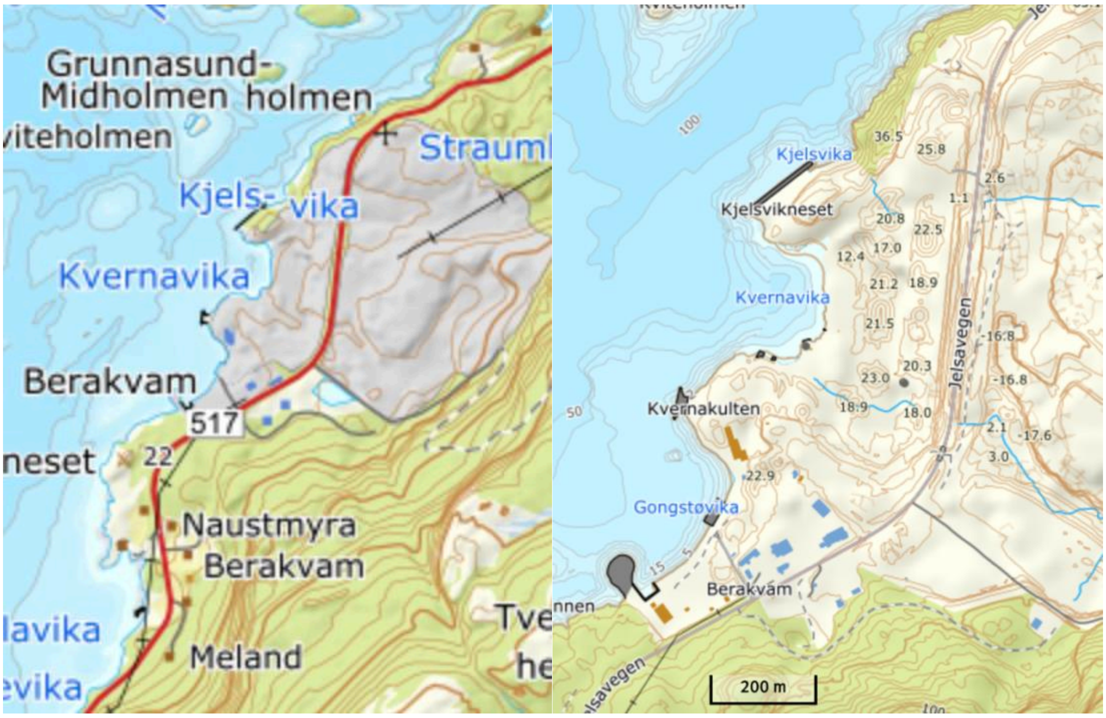


Figure 5.7 - Jelsa location study showing nearby water depths

Figure 5.7 shows the already existing quarry and the coastal area surrounding it. The proposed plans suggest excavating a canal into the quarry that is no longer active so that it fills up and essentially works as a wet dock shielded, which will also be naturally shielded from harsh weather due to the surrounding geography.

The sketch in Figure 5.8 is used as a mock-up by WindWorks Jelsa to illustrate how the site development could look if the plans are realized. The sketch shows a dry dock where the floating elements are constructed and stored, and also the wet dock where the buoyant elements are launched and fitted with turbines[62].

Figure 5.8 - WindWorks Jelsa illustration showing the potential development at site[62]

6 CASE STUDY

Optimizing the procedures in floating offshore wind is a process that will take time and involve a lot of different aspects of the installation process. This comparative case study will investigate how location choice and change in procedure affect the project outcome in project duration and effectiveness. The optimization will have an increasingly important role in the growth and cost trajectory of floating offshore wind and will help enable a green energy transition.

6.1 CASE STUDY METHODS

This chapter aims to introduce and understand the base case, the data that it's based on, and what it seeks to answer. Further methodology on the software that has been used is found in chapter 4.4. For simplicity, the various cases that will be compared and discussed have been assigned abbreviated names. An overview of these names is given in the below list:

Case A	The base case uses WindWorks Jelsa as a multipurpose assembly hub and has one crane used for assembly.
Case B	A case where Skipavik Gulen is used as a multipurpose assembly hub
Case C	The Hywind Tampen procedure uses Stord, Dommersnes, and Skipavik Gulen for the assembly and Skipavik Gulen as deployment base
Case D	An optimized base case which is the same as Case A but has two cranes for the assembly process

As explained in the list above, Case C uses three different locations in the assembly and construction process. At the same time, cases A, B, and D rely on a single multipurpose hub for all operations related to storage, assembly, and deployment. This means there is room for a significant reduction in the number of transport intervals in some of the cases that will be simulated. To put the distances into perspective, all simulated locations and their location relative to Utsira North can be seen in Figure 6.1.

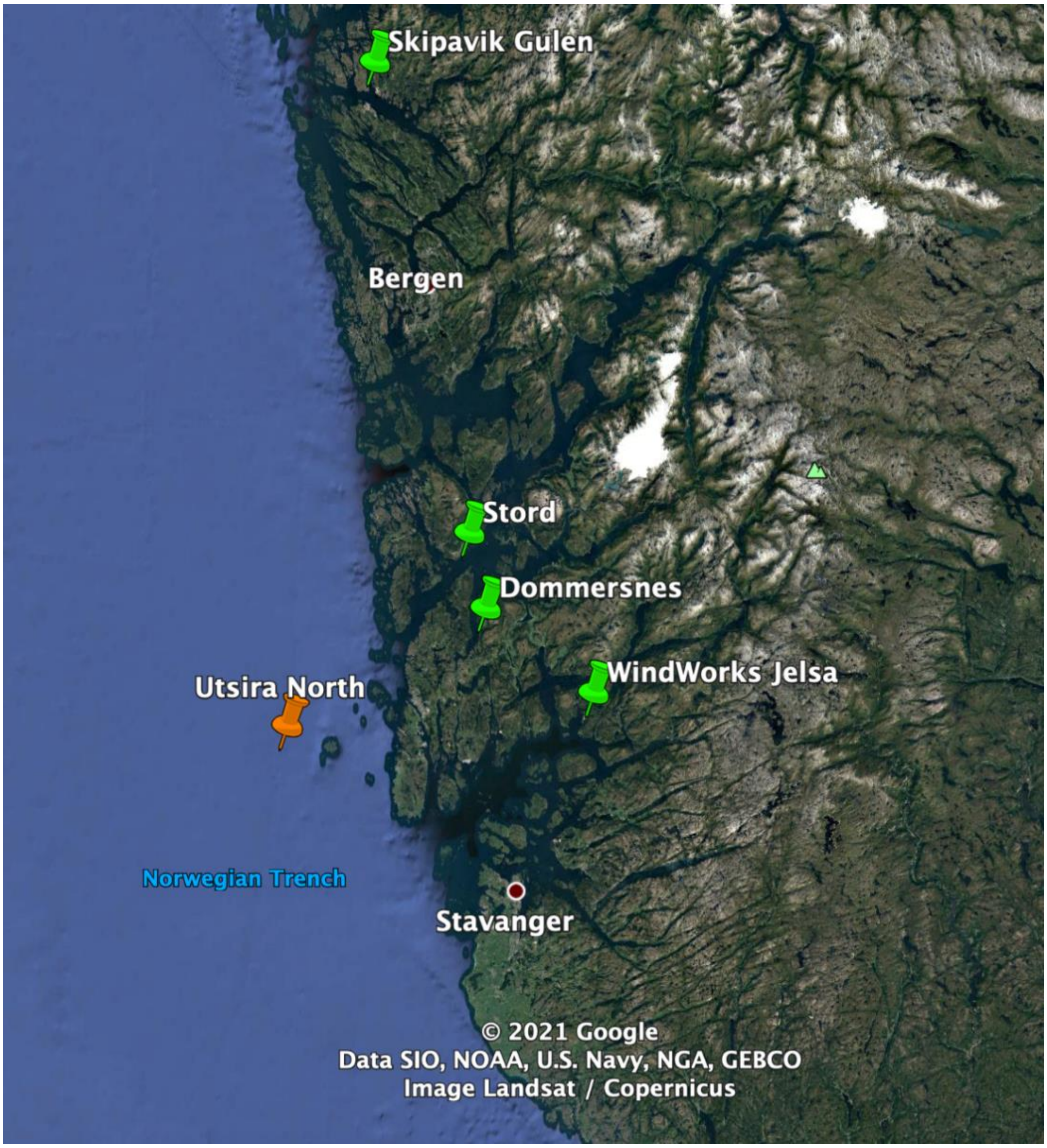


Figure 6.1 - An overview of the various locations used in the case study simulations [63]

6.1.1 BASE CASE DESCRIPTION

All simulations carried out for this comparative case study are based on a hypothetical floating wind farm development at Utsira North, consisting of 20 individual IEA 15-MW floating wind turbine generators. Each turbine is using a SPAR foundation and has a respective hub height of 150m. A floating wind farm consisting of 20 turbines would amount to an installed capacity of 300 MW, which in the future be considered small. But, as this case focuses on how location and procedure affect project duration and effectiveness, it was not essential to simulate the construction of a larger wind farm since the result will be somewhat linear and scalable.

The location chosen for this base case scenario is based on the results from the location study performed in chapter 5, which deemed WindWorks Jelsa as the most suitable site for onshore assembly. Considering the location study, the simulations in this base case will assume that the wind turbines are assembled at Jelsa and then towed out to Utsira North when ready, a distance of 80-90 kilometers.

LOGISTICS

The logistics of a floating offshore wind farm project are extensive and important in each phase of the project, especially during the assembly and installation campaign. The delivery of components is a crucial factor in logistics planning, and the way this is handled plays an essential role in the installation phase[64]. In this case, it's assumed that every needed component is already delivered and stored at the respective site, which is part of the vision for a multipurpose assembly site like WindWorks Jelsa. Internal on-site logistics ensures that the components will be available and in reach of the crane in charge of assembly.

There is one onshore crane configured for this base case scenario, this crane is used for all lifting activities required in the assembly campaign, and the availability of this crane is thus vital. There are strict operational limits concerning wind for safety reasons, and the regular availability is configured to be between 07:00 and 20:00. Further detailed configurations can be seen in the appendix.

MET-OCEAN DATA

Within the Shoreline software, there is access to eleven years of weather data from Utsira North, Skipavik Gulen, Stord, and Dommersnes gathered from January 2009 until December 2019. The weather data was obtained from ERA5, which provides global, hourly estimates of atmospheric variables[65, p. 5]. ERA5 has a regular latitude-longitude resolution of 0.25°*0.25°; thus, the weather data for Utsira North, Skipavik Gulen, Stord, and Dommersnes was obtained from the nearest possible point. The following table (Table 6.1) gives exact information on which coordinates were used for the collected weather data in relation to the coordinates for the respective locations.

Table 6.1 – Simulated locations compared to the respective ERA5 locations with available atmospheric data

Location	Latitude (N)	Longitude (E)
Utsira North (Mid-point)	59.13250	4.60972
Utsira North (ERA5)	59.25000	4.50000
Sørlige Nordsjø II	56.80000	4.90000
Sørlige Nordsjø II (ERA5)	56.75000	5.00000
Skipavik Gulen Port	60.85551	5.03450
Skipavik Gulen Port (ERA5)	60.75000	5.00000
Stord Port	59.75964	5.49351
Stord Port (ERA5)	59.75000	5.50000
Dommersnes Port	59.593627	5.575394
Dommersnes Port (ERA5)	59.500000	5.500000
WindWorks Jelsa Port	59.375629	6.050517
WindWorks Jelsa Port (ERA5)	59.75000	5.50000

As seen in Table 6.1, due to the resolution, the ERA5 coordinates do not accurately match the researched locations. This results in some limitations regarding the accuracy of the weather data used in the case study. For Skipavik Gulen, Dommersnes, and WindWorks Jelsa, the topography of the exact ERA5 data coordinate differs from the actual location, thus leading to a potential variation between the simulated weather and the actual weather at the respective site.

Included in the ERA5 atmospheric measurements are both wind and wave data. This information allows for conduct predictions of significant wave height, mean wind speed, and wind directions at different altitudes above sea level in the respective areas. The measurements have resulted in accurate models that can be used to decide on the most efficient placement of the floating wind turbines and the wind turbine assembly locations. The data is specifically vital to explore how the project duration of more sheltered onshore areas varies compared to those more frequently exposed to harsh weather [66].

There is a limited amount of available weather data from the exact location at Jelsa, which is being studied. In addition to this, some of the hypothetical wind farm locations in the large-scale simulation also lack precise weather data. Because of this, some necessary limitations have been made regarding the case study. The restriction regarding meteorology is that the weather data used for Jelsa use the same ERA5 data as Stord, located 50 kilometers north-west of Jelsa. This decision was made considering the proximity of the two locations, the similarity in surrounding topography, and the fact that there is a lot of available weather data for Stord. The weather data for Utsira North and Sørlige Nordsjø II have been used for the hypothetical wind farms, depending on the closest location with ERA5 weather data.

The simulations are conducted using an integrated Shoreline function for weather data called *Historical* weather simulation. This means that the weather time series is used directly and will start from year one, with the earliest matching date. The weather data used for these simulations are gathered from 2009-2019, meaning that if a simulation strategy has the 1st of April 2022 as its starting month, the Historical weather simulation will use the weather from 1st of April 2009 as its starting point.

WIND FARM LAYOUT

Due to the limited size of the wind farm simulated in this case study, and since the case study will focus on the onshore installation hub, it was decided to opt for a very simple wind farm layout. The main object with the layout for this case was that it should be practical and easy to install using tug vessels. The correct spacing of eight diameters is taken into concern, but the layout in respect to wind direction was not. A screenshot of the respective layout of the 20 turbines is provided in Figure 6.2.

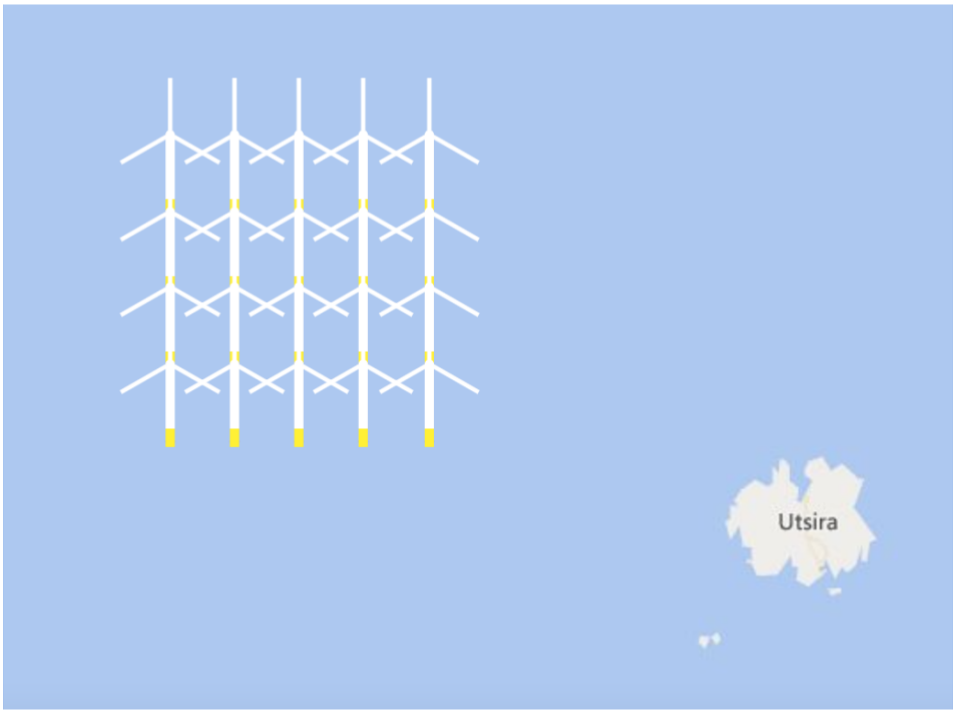


Figure 6.2 - Wind farm layout of the 20 individual 15 MW WTGs at Utsira North for the Case Study

6.1.2 HYWIND TAMPEN COMPARISON – CASE C

Hywind Tampen is a planned and approved floating wind farm developed by Equinor. In writing time, the project is in its turbine construction phase. When the wind park opens, which is planned to be in 2022, it will be the world's largest floating wind farm development. Hywind Tampen's purpose is to partly supply the oil fields Snorre and Gullfaks with electricity. When comparing this project to a potential Utsira North development, it's easier to understand the magnitude and potential upside; Hywind Tampen is located 140km off the coast and has a planned capacity of 88 MW divided on 11 floating WTG's [33]. The Utsira North is, as mentioned, located only 18km from the shore, and combined with Sørlige Nordsjø II, the two areas allow for the development of 4500 MW of wind power. These numbers reflect the substantial upscaling the industry would need to fully take advantage of the granted capacity.

The installation process of Hywind Tampen is split into several sections and is dependent on several locations, each of which is used to perform a respective task in the installation process. First, the bottom sections of the SPAR-buoy elements are cast in concrete using slip-form; this happens at a shipyard in Stord. The bottom sections are then towed 20km to Dommersnes, where a deeper quay allows for the concrete casting of the rest of the buoy length. After the buoy sections are finished, they are towed roughly 200km to the Skipavik Gulen yard, where the tower section, hub, and blades are installed piece by piece on top of the floating SPAR-buoy. To summarize, to assemble these floating wind turbines, they will have to be towed 220 km along the west coast of Norway before they are fully assembled and can start their 140 km tow out to the Tampen field. The long towing distance results in difficult weather predictions and an increased risk of downtime due to weather, which was part of the motivation behind exploring new site opportunities.

6.1.3 LARGE SCALE INSTALLATION SCENARIO USING CASE A

The case study will be divided into two main parts: a comparison case between the specified Base Case scenario and the Hywind Tampen procedure, as presented in the previous sections. Part two will use the results and experience gathered from the comparison simulations and apply this to a large-scale operation.

Various installation scenarios for Norway and Europe were reviewed and presented in Section 2.2. These scenarios included a low and a high scenario for the expected installed capacity on the Norwegian Continental Shelf (NCS) by 2050. This next part of the case study will continue using the Base Case scenario as a multipurpose onshore base and simulate the installation of all wind turbines needed to reach the estimated installed capacity presented in the low scenario and the high scenario from Section 2.2.2. The low scenario, which was developed based on various sources, predicts that floating offshore wind on the NCS will have reached an installed capacity of 7 GW within 2050. In the high scenario, the accumulated installed capacity is predicted to be 19 GW.

Both scenarios have been configured with only one crane available for the assembly process for the first phase; this was decided upon after recommendations from NorSea Group. This configuration reflects their visions for the WindWorks Jelsa assembly hub, where the current plan is to use one single crane for assembly operations until an expansion happens. This expansion will most likely occur sometime in the 2030s; thus, Phase 1 in the simulated scenario uses one crane. It is assumed that the expansion has happened prior to the remaining phases, which then use two cranes for assembly.

LOW SCENARIO

The low scenario predicts an installed capacity of 7 GW FOW by 2050. The simulation assumes that the two newly opened areas of Utsira North and Sørlige Nordsjø II are developed first and fully utilized with 4500 MW, which is the maximum allowed combined capacity of the two areas[34]. The remaining 2500 MW will be installed in a hypothetical wind farm located south-west of Stavanger. The layout and location of these farms can be further studied in the appendix. Considering the size of the development, the project has been split into three different phases, these are summarized below:

Phase 1: 125 floating wind turbines of 12 MW each, located at Utsira North. Combined capacity of 1500 MW, which is the maximum allowed capacity for the area[35].

- 1 Crane available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines and mooring anchors

Phase 2: 250 floating wind turbines of 12 MW each, located at Sørlige Nordsjø II. Combined capacity of 3000 MW, which is the max allowed capacity for Sørlige Nordsjø II[34].

- 2 Cranes available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines
- 1 handling vessel for mooring anchors

Phase 3: 167 floating wind turbines of 15 MW each, located at a hypothetical wind farm location south-west of Stavanger. Combined capacity of 2505 MW.

- 2 Cranes available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines
- 1 handling vessel for mooring anchors

At the end of these three phases, the total capacity will have accumulated to 7.005 GW, which coincides with the original low scenario.

HIGH SCENARIO

Based on input from NorSea Group and an optimistic approach to the potentials of floating offshore wind power, the high scenario predicts an installed capacity of 19 GW within 2050. This involves installing 1,2 GW of floating offshore wind power per year after 2040, which is in line with NorSea Group's vision. Similar to the low scenario, this also had to be split up into several different phases. This was mainly done in order to make the simulation more realistic, but it also had to be done due to limitations within the software used. The two first phases are the same as for the low scenario; a summary is presented below:

Phase 1: Same as for the Low Scenario

Phase 2: Same as for the Low Scenario

Phase 3: 200 floating wind turbines of 15 MW each, located at a hypothetical wind farm location south-west of Stavanger. Combined capacity of 3000 MW.

- 2 Cranes available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines
- 1 handling vessel for mooring anchors

Phase 4: 400 floating wind turbines of 15 MW each, divided on two parks located north of Utsira. Combined capacity of 6000 MW.

- 2 Cranes available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines
- 1 handling vessel for mooring anchors

Phase 5: 370 floating wind turbines of 15 MW each, divided on two parks located west of Utsira North. Combined capacity of 5550 MW.

- 2 Cranes available for assembly
- 2 towing vessels
- 1 handling vessel for mooring lines
- 1 handling vessel for mooring anchors

At the end of these five phases, the total capacity will have accumulated to 19.05 GW, which coincides with the high scenario.

6.2 CASE STUDY RESULTS AND DISCUSSION

Shoreline had a significant influence on how this thesis has developed during the span of the underlying project. In this study, the built-in simulation tool called Con Design™ was used to simulate the complete construction phase, from assembly start to commissioning on site. The results gathered from the software are intended to be used as a strengthening factor, backing up the assumptions made, and the results gathered from the alternative location section.

For this study, the results on *asset weather downtime*, *schedule,* and overall *installation time* are the most interesting, as these are the results that see the heaviest influence from a change in assembly location and procedure. The simulations carried out are based on the information provided in chapter 6.1.1 (base case description), including the subchapters, which elaborate on the subjects of wind data and power curves.

6.2.1 WEATHER DOWNTIME STUDY

To correctly interpret the simulation outcomes, the study is dependent on having a clear perception of the realistic effects of weather. A short weather downtime sensitivity study is therefore conducted to gather data on the impact of weather [67]. This is done by comparing two base case scenarios; one isolated case where the weather data is ignored will be compared with the normal base case where weather data is included. The case where the weather data is left out will yield a project duration with zero downtime due to weather.

SHORELINE RESULTS – CASE A - WEATHER DOWNTIME SENSITIVITY

This study is carried out to give the reader a better understanding of the effect that external factors have on the project duration. The differences between the base case and the alternative onshore location can be better understood. Table 6.2 shows the results from the weather downtime sensitivity study. There were completed 12 individual simulations for both of the cases, each representing a different starting month. This was done to understand better what starting month would provide the least amount of downtime and confirm the importance of incorporating the effect of weather in construction scheduling[68].

Table 6.2 – Case A - Start month and weather downtime sensitivity study

Start Month	Project Duration of Case A Unaffected by Weather	Project Duration of Case A Using Weather Data	Downtime due to Weather	Increase in Project Duration due to WOW (%)
January	82.07 Days	114.72 Days	32.7 Days	40 %
February	82.07 Days	103.52 Days	21.5 Days	26 %
March	82.07 Days	97.79 Days	15.7 Days	19 %
April	82.07 Days	91.52 Days	9.5 Days	12 %
May	82.07 Days	92.46 Days	10.4 Days	13 %
June	82.07 Days	93.18 Days	11.1 Days	14 %
July	82.07 Days	87.88 Days	5.8 Days	7 %
August	82.07 Days	100.81 Days	18.7 Days	23 %
September	82.07 Days	116.96 Days	34.9 Days	43 %
October	82.07 Days	111.59 Days	29.5 Days	36 %
November	82.07 Days	102.52 Days	20.5 Days	25 %
December	82.07 Days	95.69 Days	13.6 Days	17 %
Average	**82.07 Days**	**100.72 Days**	**19 Days**	**23 %**

There is broad consensus among project planners that offshore projects should not be commenced in the winter season when the weather is statistically more challenging. However, this preliminary study was carried out to visualize the effect on this exact project. The most important information to gather from Table 6.2 is the increase in project duration due to waiting on weather (WOW); it's seen that the overall increase in project duration varies from 7% to 43%. The significant variation can be explained by the relatively short project duration that's seen if the weather is not considered, meaning that if the project is started in a month where there are statistically low chances of strong winds and waves, like April to June, the project can be finished in about three months if everything runs as simulated.

The least amount of downtime is seen when the project starts in July, where there are 5.8 days of downtime due to WOW. As discussed above, this is most likely because there are statistically fewer strong winds and waves in July and the following months where the project is carried out. On the other side of the specter, if the operation were to start in September, there would be an estimated 34.9 days of total downtime, which is surprising because the two months that resulted in maximum and minimum downtime are relatively close to each other. This observation proves that it is the following months after the project start that counts the most.

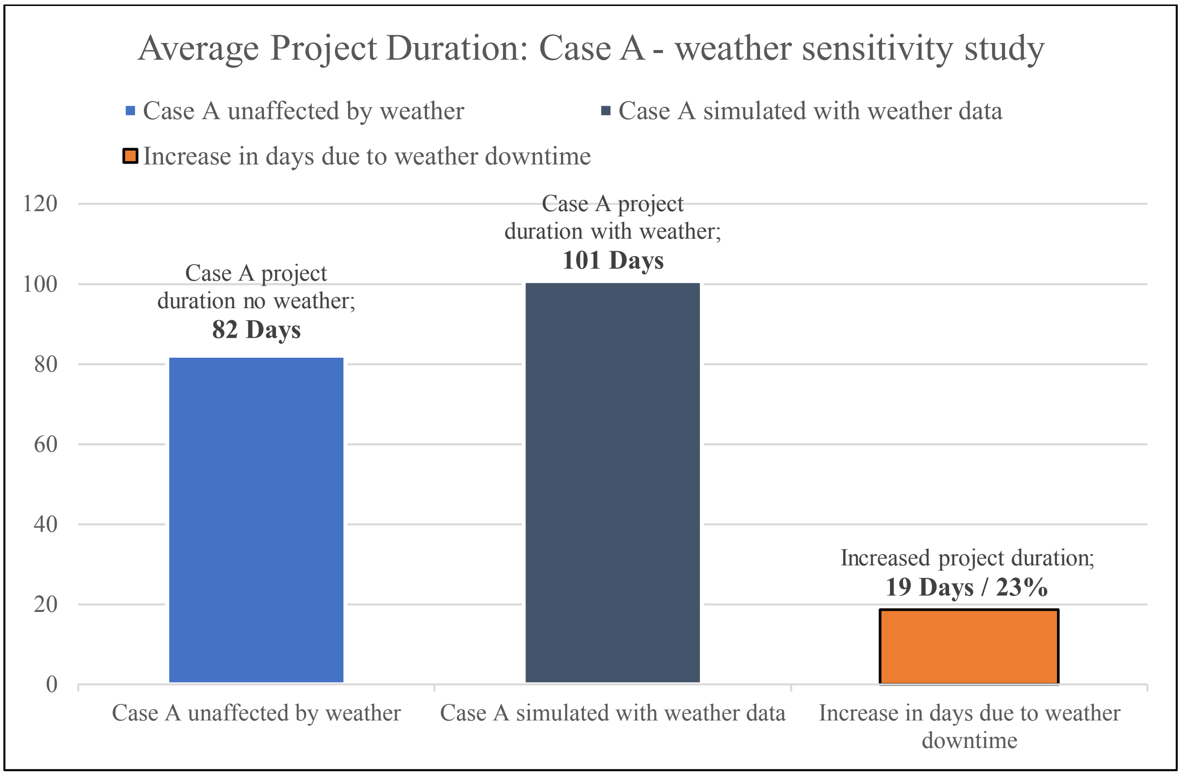


Figure 6.3 - Case A - Average project duration, weather sensitivity study

Figure 6.3 illustrates the average project duration with and without the weather data included in the simulations. The figure also highlights how much the overall duration increase on average when the weather is accounted for.

6.2.2 SIMULATION RESULTS FROM THE CASE COMPARISONS

Chapter 5 was dedicated to a location study, used to decide which of the alternative locations were most compatible with the demands that the future FOW projects will have; it was decided that WindWorks Jelsa had qualities that resulted in the highest probability of success between the five different options.

The first subchapter will use the results from Table 6.2 to compare with the simulated project duration achieved when using Skipavik Gulen as a multipurpose onshore base for assembly and deployment. Skipavik Gulen is the port used for the final assembly of the turbines for Hywind Tampen and is therefore seen as today's equivalent to what WindWorks Jelsa could be. The big difference is that Skipavik Gulen, as of today, does not work as a multipurpose assembly and installation site, and the distance from the installation hub to the final site is much longer. Similar to the previous chapter, the results in Table 6.3 were gathered through Shoreline simulations. The study expects that the simulations based on the new location will result in a shorter project duration due to better wind conditions and shorter transportation time.

SHORELINE RESULTS – CASE A VS. CASE B

Table 6.3 - Downtime Saved by Changing Location from Gulen to WindWorks Jelsa

Start Month	Project Duration Using Case B	Project Duration Using Case A	Duration Saved by Changing Location
January	134.19 Days	114.72 Days	19.5 Days
February	117.96 Days	103.52 Days	14.4 Days
March	120.02 Days	97.79 Days	22.2 Days
April	108.19 Days	91.52 Days	16.7 Days
May	104.19 Days	92.46 Days	11.7 Days
June	103.35 Days	93.18 Days	10.2 Days
July	131.58 Days	87.88 Days	43.7 Days
August	139.96 Days	100.81 Days	39.2 Days
September	131.54 Days	116.96 Days	14.6 Days
October	124.44 Days	111.59 Days	12.9 Days
November	105.19 Days	102.52 Days	2.7 Days
December	93.69 Days	95.69 Days	-2.0 Days
Average	**117.86 Days**	**100.72 Days**	**17 Days**

As seen in Table 6.3, the results from Shoreline show that the expectations towards the new multipurpose location are met. The collected data shows that just by changing location from Case C to Case A, there is potential to save up to 43.7 days of project duration, with an average of 17 days saved, depending on which starting month is chosen. This translated to an average decrease in project duration of 15% due to weather downtime and travel distance.

An abnormality is observed in the results from November and December in Table 6.3, where the overall project duration for Case B is peculiarly low when considering the seasonal average. After further examination of the applied ERA5 weather time series for Skipavik Gulen, it was proven that the abnormality was caused due to an unusually calm weather period between December of 2009 and March of 2010. This period of calm weather caused the average wind speed and wave height to be lower in the winter season of 2009/2010 than in the summer season of 2009, which lead to significantly lower downtime due to weather. The event affected the results in this case study due to the use of *historical* weather data simulation (as explained in section 6.1.1) in Shoreline. It could be avoided if the study used *increment start year* as an alternative method. The average wind speeds and significant wave heights for Skipavik Gulen and the cause of the abnormality can be observed in Figure 6.4.

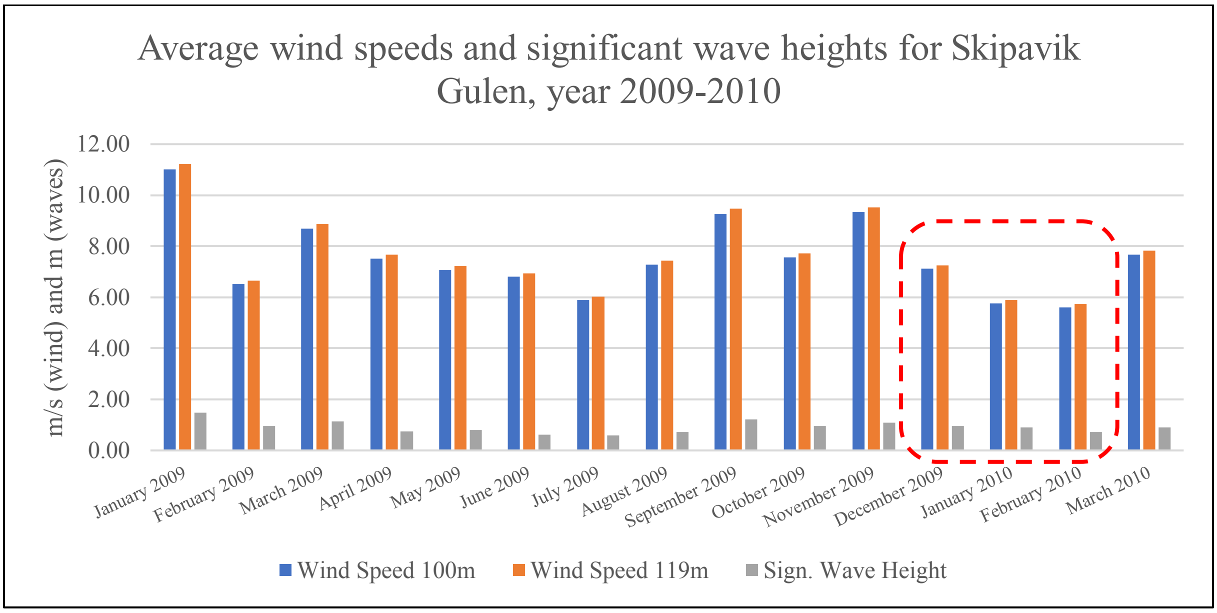


Figure 6.4 - Average wind speeds and significant wave heights for Skipavik Gulen in 2009-2019, showing the cause of the abnormality observed in the comparison of Case A and B

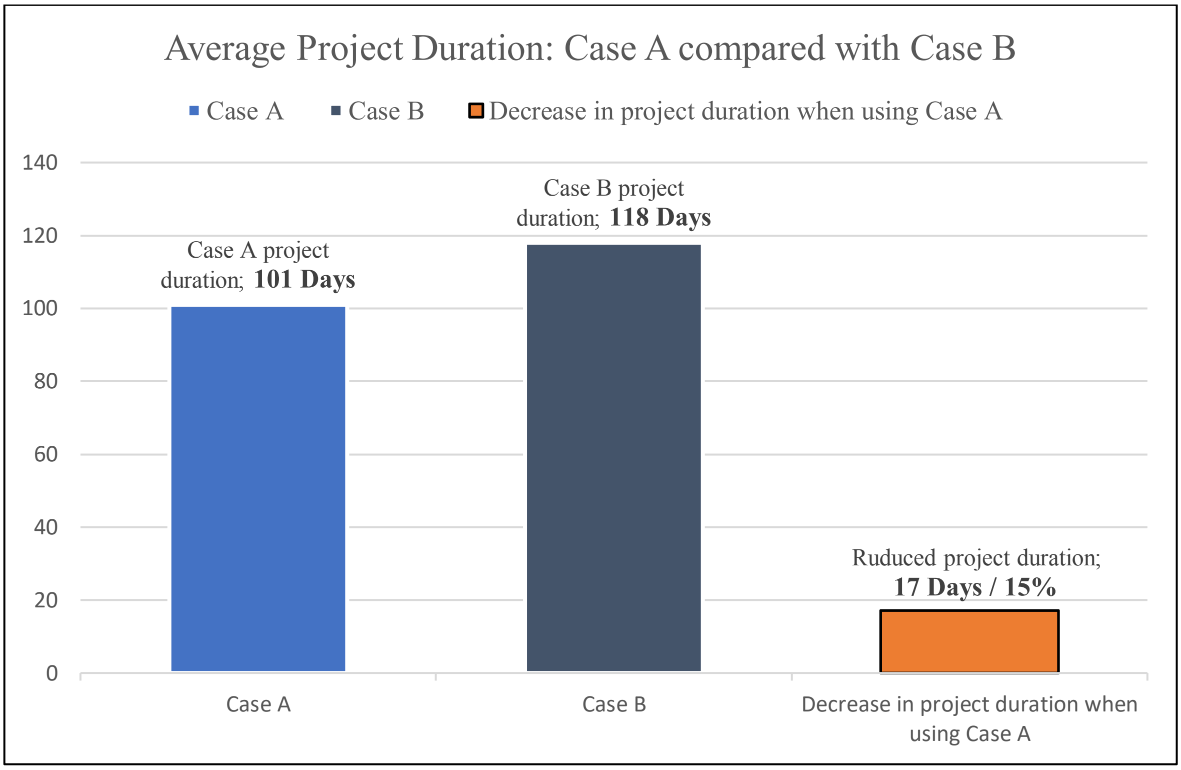


Figure 6.5 - Case A compared with Case B, average project duration

Figure 6.5 illustrates the average project duration of both Case A and Case B; the average reduction in project duration is shown in orange. Since these two cases have the same procedure and vessel configuration, the only factors separating them are the geographical location and local weather. Thus, it was expected that Case A, which is closer to Utsira North, would yield the best results in this simulation.

SHORELINE RESULTS – CASE C VS. CASE A

To better understand the potential savings of establishing a new multipurpose onshore assembly base, the study will use the new proposed assembly base of WindWorks Jelsa and compare it with the multi-location assembly procedure that Hywind Tampen makes use of, which will be referred to as Case C. Table 6.4 uses the project duration values gathered in Table 6.3 for Jelsa and compares it with the simulation results collected from Case C, which is adapted to fit a potential Utsira North development.

Table 6.4 - Downtime Saved by Changing Assembly Procedure and Location

Start Month	Project Duration Using Case C	Project Duration Using the Case A	Duration Saved by Changing Location and Procedure
January	142.11 Days	114.72 Days	27.4 Days
February	125.27 Days	103.52 Days	21.8 Days
March	121.79 Days	97.79 Days	24.0 Days
April	117.17 Days	91.52 Days	25.7 Days
May	117.33 Days	92.46 Days	24.9 Days
June	119.1 Days	93.18 Days	25.9 Days
July	119.35 Days	87.88 Days	31.5 Days
August	130.28 Days	100.81 Days	29.5 Days
September	131.1 Days	116.96 Days	14.1 Days
October	127.1 Days	111.59 Days	15.5 Days
November	121.56 Days	102.52 Days	19.0 Days
December	117.17 Days	95.69 Days	21.5 Days
Average	**124.11 Days**	**100.72 Days**	**23 Days**

The simulation results that compare Case C with Case A show that the multipurpose assembly site (Case A) is more effective in twelve out of twelve cases. The base case performs with an average 19% increase in efficiency, varying from 14-31% depending on the starting month. However, the results gathered from the simulations were to some degree unexpected, as the amount of downtime saved is not as dramatic as first expected. The number of long transport distances and exposure to weather seen in Case C was expected to have a more significant impact on the project duration than what is seen in Table 6.4.

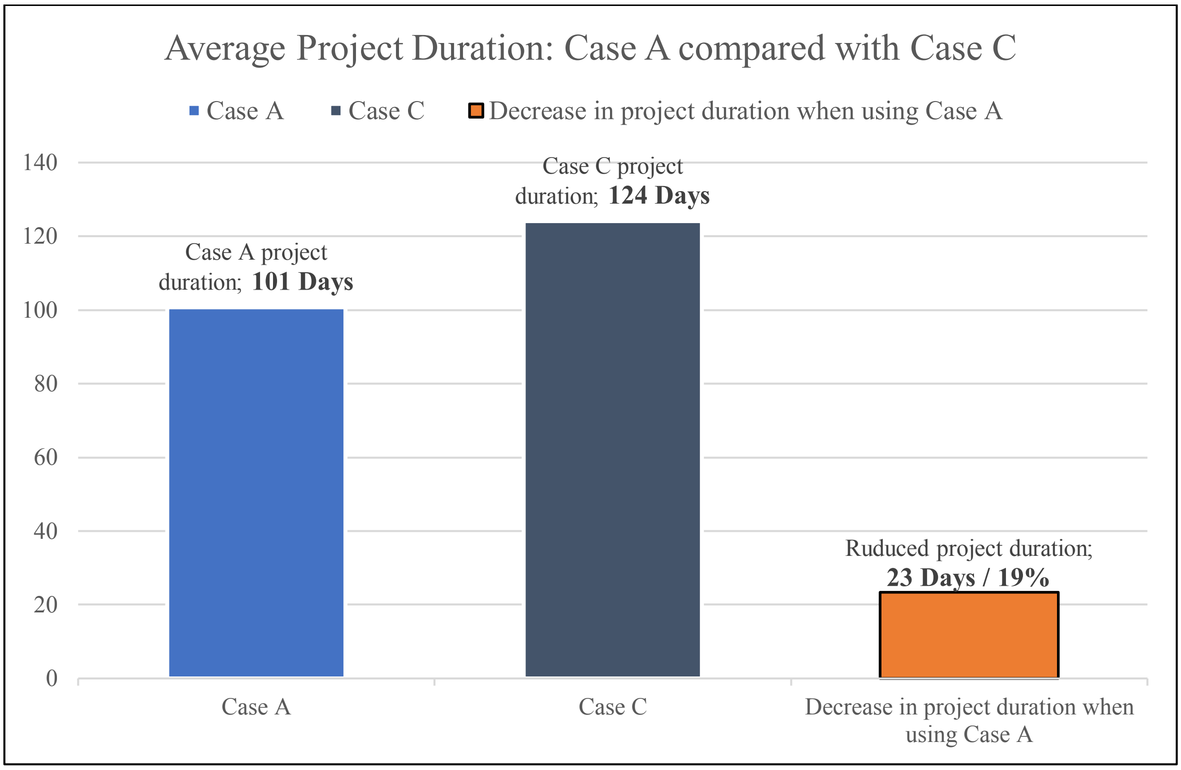


Figure 6.6 - Case A compared with Case C, average project duration

Considering Case A's proximity to Utsira North and the reduction in transport intervals and operations compared to Case C, it was expected, and likely, that Case A would outperform Case C significantly. The average project duration of each case is illustrated in Figure 6.6, the orange bar in the chart presents the average reduction in project duration that is achieved when choosing Case A over Case C. Even though an average increase in efficiency of 19% is substantial, one cannot assume that it makes changing location and establishing a new base a feasible option in terms of cost.

CASE D - OPTIMIZING THE BASE CASE SCENARIO

Based on the findings from the previous chapter and the results shown in Table 6.4, it was concluded that the procedure that the base case simulations were based on could be further improved. To maintain the study's validity, the adjustments that were made needed to be done so realistically and in line with WindWorks Jelsa's vision. NorSea Group, the main company behind WindWorks Jelsa, has been a good sparring partner through this study and has been a good source of credible data when setting up this base case scenario.

NorSea Group envisions that WindWorks Jelsa will be developed through multiple phases as more quarry area becomes available and the technology becomes more attractive to investors. The first phase of development is in line with the current base case described in this section, while the highest priority for the next expansion is adding an extra onshore crane for wind turbine assembly. Moving on with this case study, the base case scenario will be configured with one additional onshore crane used in the assembly process. Now that the study already has a good foundation of results using one crane, one can measure the positive/negative effect of duration and downtime when adding one more.

SHORELINE RESULTS – EFFECT OF ONE EXTRA CRANE IN BASE CASE

Based on the information presented above, the case study will now investigate the effects of optimizing the procedure by adding one more crane for assembly. The optimized case A scenario will be referred to as Case D. All other vessel configurations will remain the same as for the previous simulations; this is done to isolate the results of just changing the number of cranes, which is the effect that NorSea Group will have most use of. The first simulation will compare the original base case scenario with the new and optimized case. The result of this simulation is seen in Table 6.5.

Table 6.5 – Case A compared with Case D, effect of adding one extra crane for assembly

Start Month	Project Duration Using Case A (Original)	Project Duration Using Case D (One extra crane)	Duration Saved by Adding One Crane
January	114.72 Days	74.34 Days	40.4 Days
February	103.52 Days	70.37 Days	33.2 Days
March	97.79 Days	56.63 Days	41.2 Days
April	91.52 Days	47.8 Days	43.7 Days
May	92.46 Days	46.91 Days	45.6 Days
June	93.18 Days	48.42 Days	44.8 Days
July	87.88 Days	43.42 Days	44.5 Days
August	100.81 Days	48.84 Days	52.0 Days
September	116.96 Days	71.65 Days	45.3 Days
October	111.59 Days	86.05 Days	25.5 Days
November	102.52 Days	70.34 Days	32.2 Days
December	95.69 Days	56.4 Days	39.3 Days
Average	**100.72 Days**	**60.10 Days**	**41 Days**

The results in Table 6.5 confirm the assumption that the project duration can be significantly improved by adding an extra crane in the assembly process. In the most extreme cases, it was shown that the project duration could be more than halved. This illustrates how time-consuming the assembly process is and how significant the potential for optimization is. The highest impact is seen in the summer months when the weather is statistically more stable and less prone to strong winds and unpredictable changes. During the winter months, especially when the project start is set to October, the margin is lower but still significant, with a saved downtime of 25.5 days.

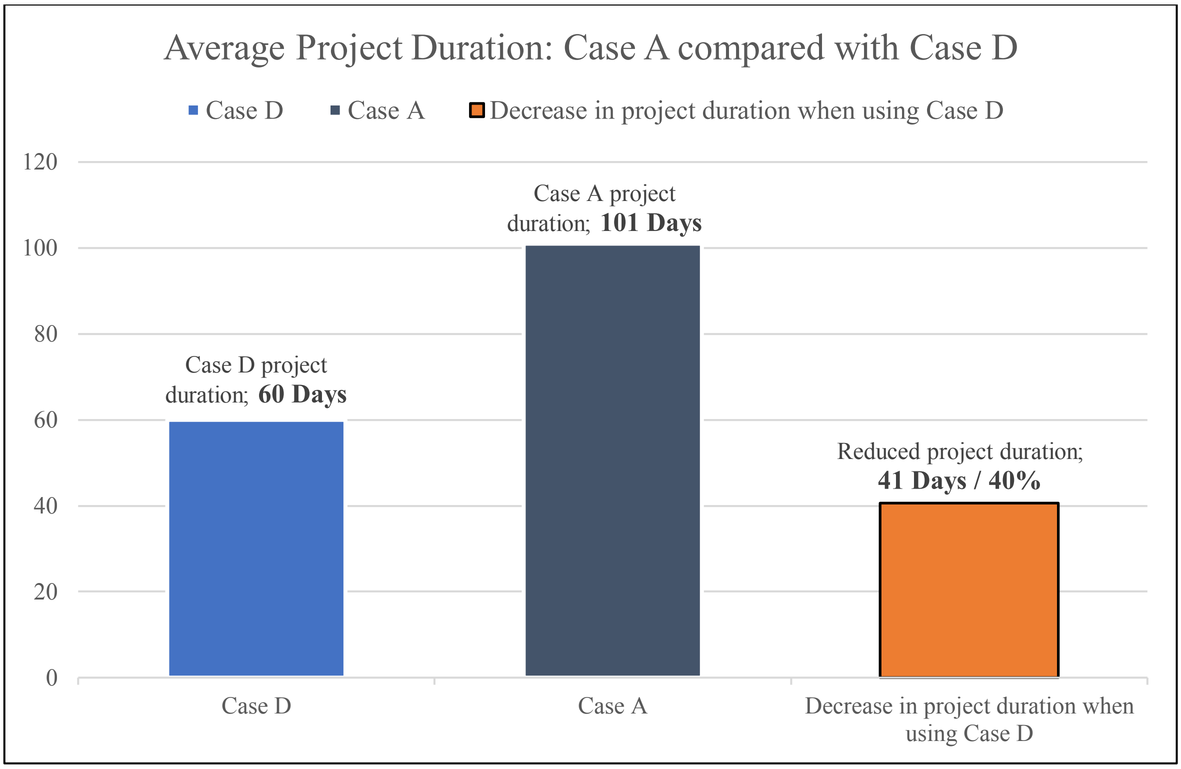


Figure 6.7 - Case A compared with Case D, average project duration

The illustration seen in Figure 6.7 provides a chart showing how the average project duration gets reduced when installing an extra crane in the assembly procedure. In this case, the decision should be based on a comparison between the cost of adding another crane and the cost of extending the project duration. For projects of longer duration, as will be investigated in the large-scale installation scenario, it is expected that the downtime will vary less depending on the respective starting month.

SHORELINE RESULTS – CASE D VS. CASE C

After changing the case A assembly and installation procedure features by adding one more crane, the updated project duration will be compared with today's solution, the Hywind Tampen procedure (Case C). The outcome of this final simulation comparison is considered the first section of the case study's final result. They will showcase how much time can be saved by switching location and procedure.

Table 6.6 – Case C compared with Case D; downtime saved when comparing the Hywind Tampen procedure with an optimized WindWorks Jelsa Base Case

Start Month	Project Duration Using Case C	Project Duration Using Case D	Time Saved by Changing Location and Procedure
January	142.11 Days	74.34 Days	67.8 Days
February	125.27 Days	70.37 Days	54.9 Days
March	121.79 Days	56.63 Days	65.2 Days
April	117.17 Days	47.8 Days	69.4 Days
May	117.33 Days	46.91 Days	70.4 Days
June	119.1 Days	48.42 Days	70.7 Days
July	119.35 Days	43.42 Days	75.9 Days
August	130.28 Days	48.84 Days	81.4 Days
September	131.1 Days	71.65 Days	59.5 Days
October	127.1 Days	86.05 Days	41.1 Days
November	121.56 Days	70.34 Days	51.2 Days
December	117.17 Days	56.4 Days	60.8 Days
Average	**124.11 Days**	**60.10 Days**	**64 Days**

It's seen in Table 6.6 that when optimizing the base case procedure by adding an extra crane to share the assembly workload, the combination of location and procedure provides a significant decrease in the overall project duration. The expected result was that the most significant margin of saved time would be found in the periods where the weather along the coast of Norway is at its roughest; this was proven wrong by the simulations. In fact, the months where the weather is most stable are also where the most considerable differences in project duration are seen. This proves that having fewer operations that depend on weather will cause a positive effect through every season, not only the winter months.

Table 6.7 also presents the results from the simulation that compared the present Case C procedure with Case D; in this table, the reduced project duration is shown in percent.

Table 6.7 - Reduced Project Duration Shown in Percent, Comparing the Hywind Tampen Procedure with an optimized WindWorks Jelsa Base Case

Start Month	Project Duration Using Case C	Project Duration Using Case D	Reduced Project Duration
January	142.11 Days	74.34 Days	48 %
February	125.27 Days	70.37 Days	44 %
March	121.79 Days	56.63 Days	54 %
April	117.17 Days	47.8 Days	59 %
May	117.33 Days	46.91 Days	60 %
June	119.1 Days	48.42 Days	59 %
July	119.35 Days	43.42 Days	64 %
August	130.28 Days	48.84 Days	63 %
September	131.1 Days	71.65 Days	45 %
October	127.1 Days	86.05 Days	32 %
November	121.56 Days	70.34 Days	42 %
December	117.17 Days	56.4 Days	52 %
Average	**124.11 Days**	**60.10 Days**	**52 %**

Listing the reduced project duration in percent instead of the accumulated number of hours gives the reader a better understanding of the impact that changing location and procedure can have on the total project duration. This final case study simulation showed that it was possible to reduce the project duration by up to 64% by changing location and procedure.

An interesting observation obtained from the final Shoreline results was the increased difference between the maximum and minimum project duration depending on the respective starting month. When assessing the project duration using Case C, the minimum duration was 117.17 days (April and December). The maximum was observed to be 142.11 days (January), resulting in a deviation of 21% depending on the starting month. On the other hand, the results from the optimized base case scenario found the shortest project duration to be 43.42 days (July), while the longest was estimated to 86.05 days (October), resulting in a potential deviation of 98%. This increase in variation is explained by the effect of centralizing the entire procedure: when using Case C, the various operations are spread out at three different locations which are all operating simultaneously, so if one location is experiencing downtime due to weather the other locations can still operate if the weather allows it. This allows the procedure to even out the differences in project duration from month to month. In Case D, however, all operations are centralized and essentially taking place in one location. A negative effect of this, which has been discovered by running these simulations, is that downtime due to weather at this location will affect both the cranes and vessels and essentially halt the entire process. This effect explains why the project duration can deviate more in the base case scenario than the compared solutions.

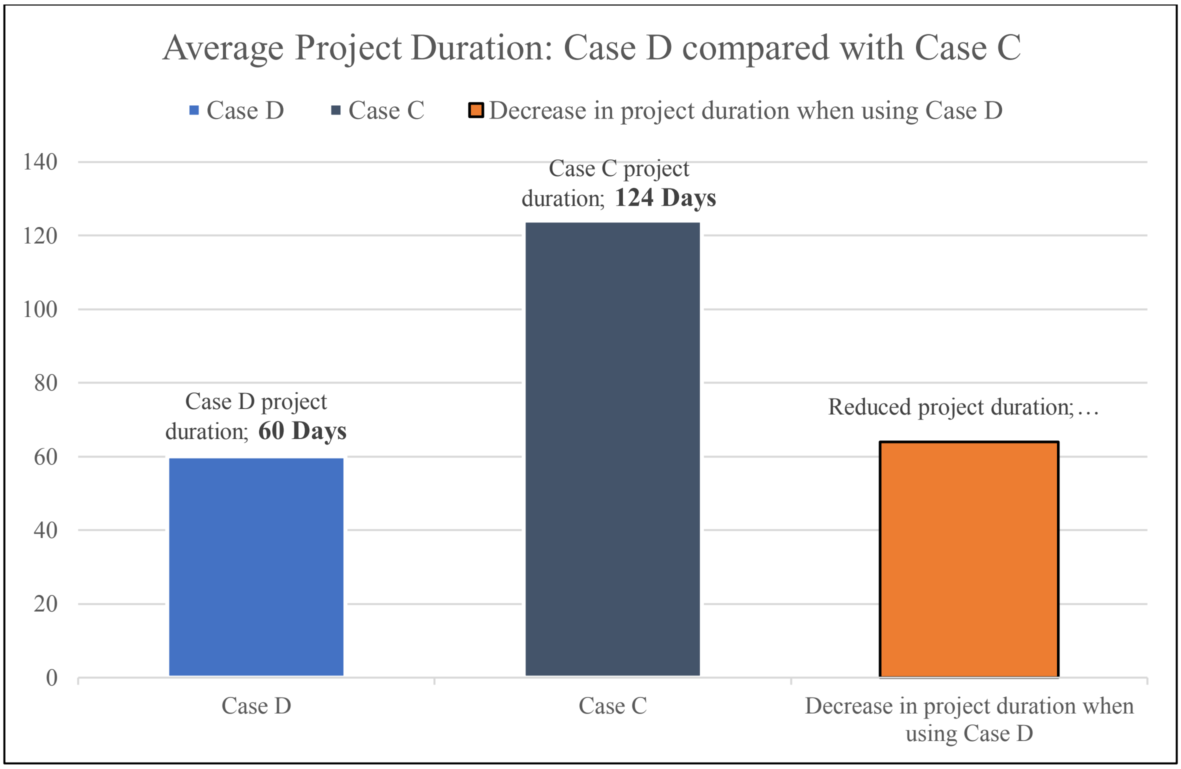


Figure 6.8 - Case D compared with Case C, average project duration

Figure 6.8 summarizes what has been discussed and illustrates the average project duration of Case C and D, the average reduction in duration was 52% when each starting month was accounted for. An actual development like the one simulated would involve careful planning in regard to the optimal starting month, meaning the potentials for reduction in project duration is greater than the average percentage shown in orange in the above figure.

6.2.3 LARGE SCALE SIMULATION SCENARIO

As explained in Section 6.1.3, the large-scale installation scenario will simulate the construction phase of the low and high scenarios presented in the literature review section. The results discussed in the previous section showed large deviations in the project duration depending on which starting month was chosen. The following section will provide better insight as to how this change when the project duration is longer, often lasting several years. A map showing each scenario and the installed capacities are provided in Appendix A.2 and Appendix A.3.

LOW SCENARIO

The following results show the low scenario, which simulated the construction and installation phase of 7 GW FOW power using WindWorks Jelsa as an installation hub. For further description of the simulated scenario, see Section 6.1.3.

Table 6.8 – Low Scenario, project duration of the three phases needed to complete the low scenario

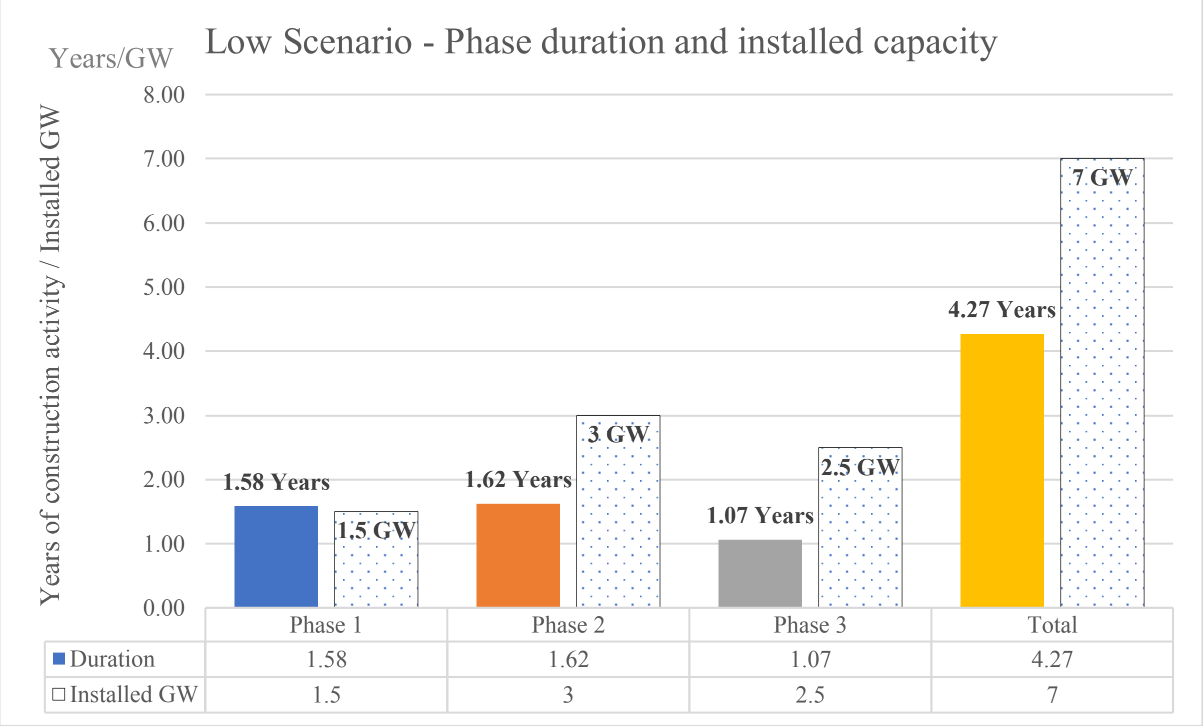
Start Month	Project Duration of Phase 1 Low Scenario	Project Duration of Phase 2 Low Scenario	Project Duration of Phase 3 Low Scenario
January	591.57 Days	593 Days	415,16 Days
February	581.57 Days	583 Days	408,41 Days
March	573.78 Days	586,4 Days	399,58 Days
April	582.33 Days	591,63 Days	389,8 Days
May	572.74 Days	578,66 Days	386,81 Days
June	576.63 Days	580,84 Days	386,81 Days
July	573.48 Days	606,95 Days	381,81 Days
August	590.32 Days	620,16 Days	383,81 Days
September	585.41 Days	609,08 Days	384,64 Days
October	579.57 Days	606,02 Days	378,81 Days
November	570.76 Days	592,51 Days	379,1 Days
December	560.91 Days	571 Days	376,14 Days

In Phase 1 of the low scenario, it's assumed that Case A is used (i.e., the installation hub is operating with one crane), but for the remaining phases, there are two cranes involved in the assembly process (i.e., Case D is being assumed). The reasoning for this is further described in section 6.1.3.

Table 6.9 – Low Scenario, average duration and total elapsed time for the entire low scenario

	Project Duration of Phase 1 Low Scenario	**Project Duration of Phase 2 Low Scenario**	**Project Duration of Phase 3 Low Scenario**
Average time	578 Days	593 Days	389 Days
Total elapsed time		**1561 Days / 4.3 Years**	

The results show that the overall project duration of Phases 1, 2, and 3 can deviate with 31 days, 49 days, and 39 days respectively. Resulting in a maximum deviation of 5%, 9%, and 10%, which is significantly lower than the potential deviations seen in the shorter duration projects. This confirms the expectation that longer-lasting projects are not sensitive to starting month deviations.



	Phase 1	Phase 2	Phase 3	Total
■ Duration	1.58	1.62	1.07	4.27
□ Installed GW	1.5	3	2.5	7

Figure 6.9 - Low Scenario, average duration of each phase and overview of installed capacity

The above figure (Figure 6.9) shows the average duration of each phase in the low scenario and how many gigawatts of installed capacity each phase include. The figure provides good visualization of the actual effect of upgrading from one single crane to two cranes in the assembly stage. It's seen in the figure that Phase 1 and 2 have very similar durations. However, Phase 2 has double the amount of installed capacity, which is a direct result of adding one extra crane in Phase 2 of the scenario. This strengthens the result seen in Figure 6.7, where it was shown that one additional crane in the assembly process reduced the average project duration by 40%.

HIGH SCENARIO

The high scenario involved simulating the construction and installation phase of 19 GW FOW capacity; similar to the low scenario; this was done in several phases. Phases 1 and 2 are the same as for the low scenario and are found in Table 6.8. Descriptive details regarding each phase included in the high scenario can be read in section 6.1.3.

Table 6.10 - Project Duration of The Five Phases Needed to Complete the High Scenario

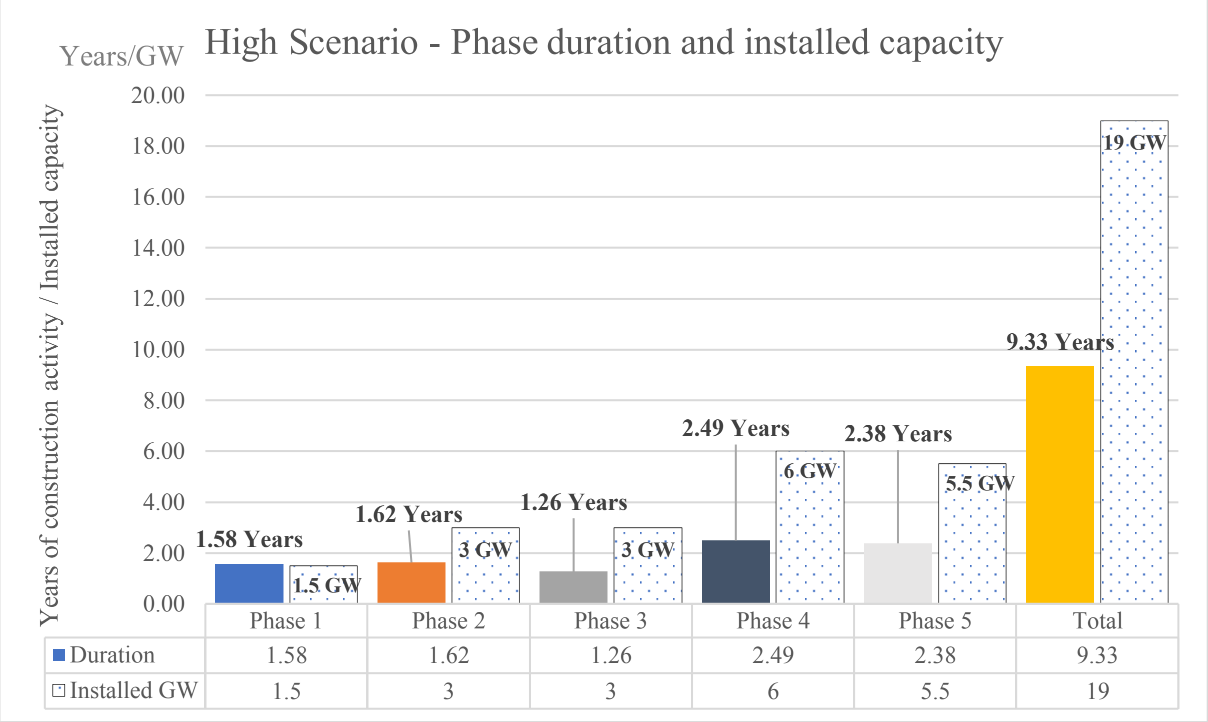
Start Month	**Project Duration of Phase 3 High Scenario**	**Project Duration of Phase 4 High Scenario**	**Project Duration of Phase 5 High Scenario**
January	483.72 Days	947.75 Days	877.39 Days
February	472.72 Days	920.75 Days	861.76 Days
March	465.88 Days	916.76 Days	854.29 Days
April	457.08 Days	908.72 Days	840.76 Days
May	455.68 Days	915.35 Days	838.76 Days
June	452.72 Days	901.75 Days	838.59 Days
July	448.3 Days	895.75 Days	848.92 Days
August	465.91 Days	904.26 Days	870.43 Days
September	467.12 Days	902.39 Days	910.5 Days
October	459.03 Days	895.75 Days	903.39 Days
November	447.55 Days	890.72 Days	890.08 Days
December	454.71 Days	886.2 Days	873.58 Days

The results seen in the above table (Table 6.10), show that the more prominent developments, which have several hundred turbines, have a more predictable duration as the project time increase relatively linear with the increase in the number of turbines. Table 6.11 presents the average duration of each phase in the high scenario, together with the total elapsed time for the entire construction and installation phase.

Table 6.11 - Average Duration and Total Elapsed Time for the Entire High Scenario

	Project Duration Phase 1	**Project Duration Phase 2**	**Project Duration Phase 3**	**Project Duration Phase 4**	**Project Duration Phase 5**
Average time	578 Days	593 Days	461 Days	907 Days	867 Days
Total elapsed time	**3407 Days / 9.3 Years**				

Similar to the low scenario, the observed deviation in project duration is much smaller in the longer-lasting phases, with 8%, 7%, and 9%, respectively, for phases 3, 4, and 5.



	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Total
■ Duration	1.58	1.62	1.26	2.49	2.38	9.33
☐ Installed GW	1.5	3	3	6	5.5	19

Figure 6.10 - High Scenario, average project duration and overview of installed capacity

Figure 6.10 displays an overview of the five different phases needed to finish the high scenario, consisting of 19 gigawatts of installed FOW power by 2050. The figure show both the duration of each phase and the amount of installed capacity included in the respective phase. It is important to note that the accumulated time shown in the figure is the number of years with constant construction activity on site. This means that the timeframe of 9.3 years to install 19 gigawatts of power on the NCS does not include organizing, planning, waiting time between projects, etc.

7 DISCUSSION

The most important findings and results from the preliminary chapters, location study, and case study will be discussed and evaluated through the course of this chapter. The discussion will focus on showing how the various results relate to the literature review and research question. All results and other findings have been made by utilizing in-depth discussions, literature study and computer simulations. The subtitle of the intermediate sections will indicate what will be discussed and the discoveries made.

7.1 CASE STUDY

The case study clearly demonstrates a correlation between the choice of location (and configuration) and the overall effectiveness or project duration of a floating offshore wind park construction phase. The results succeeded in illustrating the effect of weather and procedure on project duration. They showed that the proposed new location and procedure was, in fact, more effective than the solutions that are being used today. Although the results showed promising potential, it's important to emphasize the limitations made in the case study, as these could potentially alter the results. As briefly discussed in section 6.1.1, the Metocean data used for simulations were obtained from ERA5, which has a latitude-longitude resolution of 0.25°*0.25°. In practice, this means that the weather data used does not precisely correlate with the actual weather at the investigated areas, as it can deviate by up to 30 km in distance[69]. However, the thesis deems it *not likely* that the distance between the obtained weather data and the actual weather can result in changes so significant that the results end up favoring Case B or Case C.

Another limitation concerning a critical logistical aspect that was not considered in the simulations is the storage of fully assembled wind turbines waiting to be towed offshore. The Shoreline Con Design™ simulation tool is configured to assume that the wind turbines are continuously towed out to the site as they are completed, while the current plan for future developments is to move the finished floating wind turbines to a designated storage area where they are anchored until towing can commence. This procedure will lead to longer durations than what has been simulated. It will also require an area of significant size, considering the large dimensions and space needed between each turbine. However, if this detail were to be included in the simulation, it would affect every case in the same manner, resulting in a similar increase in project duration for every case while maintaining the same percentage of difference between the cases.

The case study was initiated to help answer parts of the research question as well as the first hypothesis, which stated that *the downtime and installation process would drastically improve if the assembly and installation process was centralized and moved entirely onshore.* In line with the hypothesis, the results have shown that the downtime was reduced by changing location and centralizing the operation. The overall project duration has shown potential of being lowered by 52% on average. The possibility of halving the duration of the construction phase is seen as a drastic improvement, and the first hypothesis is considered confirmed.

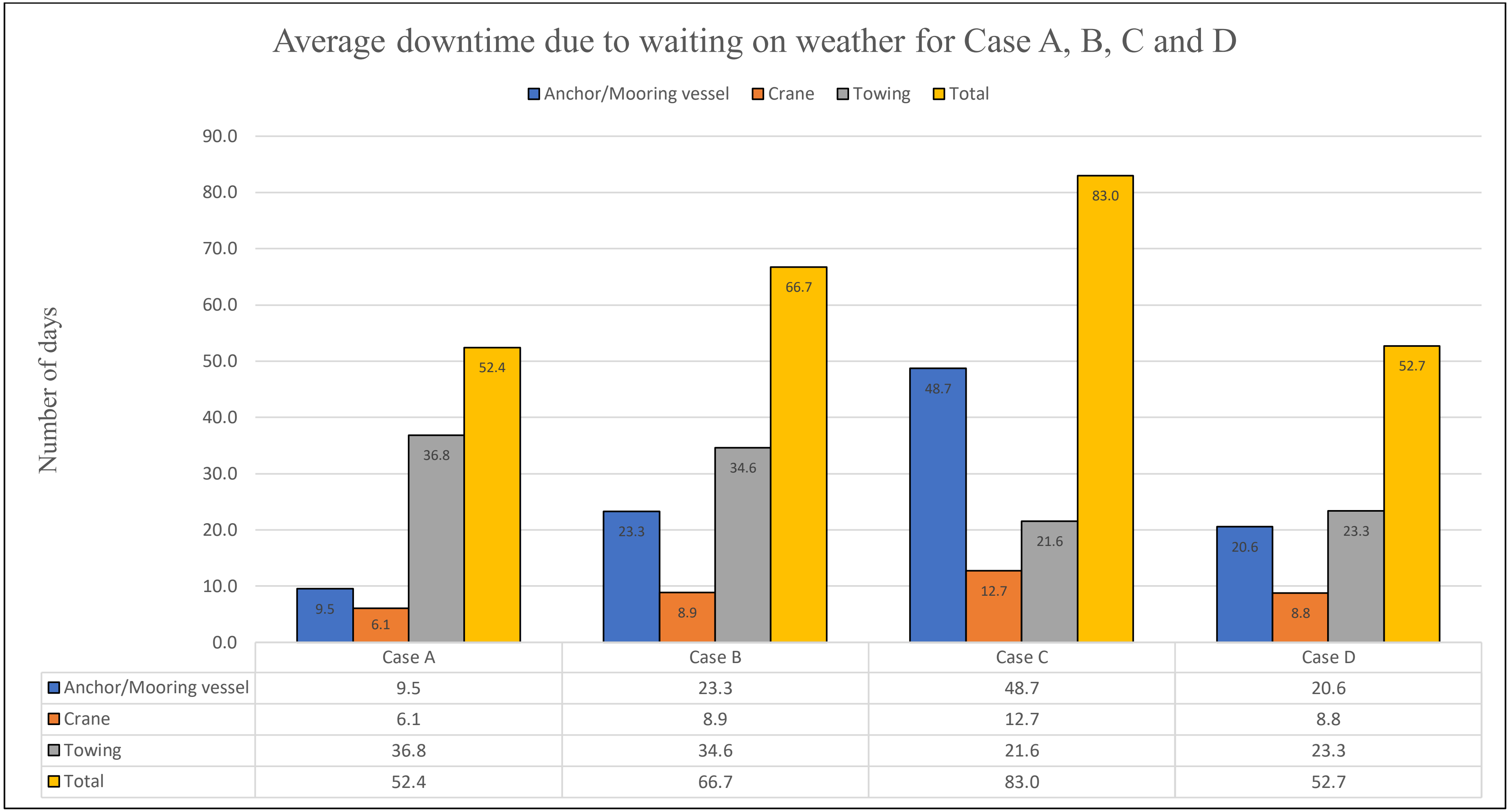
7.1.1 LARGE SCALE SIMULATION SCENARIO

The large-scale simulations found in section 6.2.3 were carried out as a stress test to investigate the effects of using the proposed location and procedure to assemble and install all FOW capacity predicted installed in Norway until 2050. These simulations were essential in allowing the thesis to follow up and investigate the subjects discussed in the literature review section. It was also done as a feasibility study to check the yearly installation capacity of an onshore assembly base with WindWorks Jelsa's configuration. The results show that if the same location were to be used for all floating offshore wind activity, it would require 1561 days (4,3 years) of continuous activity on-site to install the 7 GW of capacity included in the low scenario. This duration results in an average installed capacity per year of 1.6 GW, which is higher than what NorSea Group envisions for the WindWorks Jelsa assembly hub. However, it is important to note that the project duration presented here does not consider the time it would take to initiate, plan, and organize these developments, which would significantly increase the overall duration, thus bringing the yearly installed capacity down. But, when considering the result, which suggests an overall construction duration of 4,3 years, it is believed that it could be feasible to use the proposed assembly base at WindWorks Jelsa to install the 7 GW of FOW capacity by 2050.

The high scenario investigated how long it would take to install 19 GW of floating offshore wind capacity by 2050. In this scenario, the first two phases were identical to the first two phases in the low scenario; this was decided since Utsira North (Phase 1) and Sørlige Nordsjø II (Phase 2) are the only fields on the NCS that in writing time have been opened for floating wind developments. In this scenario, the average total project duration ended up being 9.3 years, with an average installed capacity per year of just over 2 GW. Like the low scenario, this timeframe does not include any other project activities than the construction and installation. An actual development of this size would consist of a lot of legal applications, planning, organizing, and waiting time between phases. Based on this information, the thesis considers it *not likely* that a single installation hub like WindWorks Jelsa could manage that amount of work on its own before 2050. However, if several installation hubs similar to WindWorks Jelsa were to be established in Norway, the competition would most likely result in cost reductions and increased installation capacity.

7.2 DOWNTIME DUE TO WEATHER

It's already established and agreed upon that starting short duration (less than six months) offshore projects in the winter months cannot be justified due to the negative effects of weather. However, by running separate simulations for each starting month, the simulations successfully gave a better insight into the actual consequence of choosing the correct starting period for shorter projects, where it's observed that the project duration can deviate by up to 98% (Table 6.7)—knowing which vessels or which part of the operation that is most sensitive to variation in weather is valuable information for future project planning and optimization. By investigating the effects of centralizing the construction/assembly procedure for FOW through a case study, the thesis acquired good insight on the impact of weather on project duration depending on the chosen location. In Figure 7.1 the average downtime due to waiting on weather has been isolated for each simulated scenario; the data clearly demonstrates a correlation between centralizing the construction/assembly process and reducing the amount of downtime due to WOW. The results clearly indicate that the offshore-based operations are most affected by fluctuations in weather, supporting the hypothesis that the downtime will be significantly improved by moving more of the processes onshore. This is reflected in the fact that the anchor handling vessel/mooring line handling vessel and the towing vessel account for most of the downtime due to weather. As expected, the downtime values were by a large margin higher for Case C, explained mainly by the number of transport intervals and distance from Utsira North compared to the other cases.



	Case A	Case B	Case C	Case D
🟦 Anchor/Mooring vessel	9.5	23.3	48.7	20.6
🟧 Crane	6.1	8.9	12.7	8.8
⬜ Towing	36.8	34.6	21.6	23.3
🟨 Total	52.4	66.7	83.0	52.7

Figure 7.1 - Case comparison, overview showing the downtime for each vessel during an average project duration for each case

On the other hand, while this research has focused on centralizing the entire process, the results have demonstrated unforeseen advantages of choosing the existing procedure, which is represented in Case C. By diversifying the location dependency of the operation, Case C manages to even out the impact of downtime due to weather since a lot of the processes are carried out simultaneously at the different sites. In practice, this means that if the operation at one location is haltered due to WOW, it doesn't necessarily impact the operations ongoing at the other site. This differs from the centralized cases seeing that downtime due to weather would put the entire assembly operation (especially lifting operations) on pause if only one location is used.

As briefly discussed in the case study methodology (section 6.1), there were some limitations regarding the weather data used for simulations. For weather simulation, Shoreline offers three different modeling methods; *Historical*, *Increment start year,* and *Markov*, where the first one mentioned was applied in this thesis. When using the Historical weather simulation, it's only the first available year in the measured time series that is being used, as experienced in the comparison results for Case A and B; this can lead to some misleading results if there were abnormalities in the weather at that specific year. Deviations like this would be less likely and could potentially be avoided if the thesis used *increment start year (ISY)* as a weather modeling method instead. The ISY method provides a better average result, as every simulation run is started one year incremented from the previous. Thus, for future studies, it would be beneficial to use an *Increment Start Year* approach to the weather data simulation instead of the *Historical* weather simulation tool used for this case study.

7.3 INDUSTRIALIZATION

Through writing and doing research for the literature review, location study, and case study, it has become clear that the industrialization of floating offshore wind technology in Norway will be a crucial success factor that needs to be met to reach the predicted goals for installed capacity. It is important to note that the simulations performed in the case study have outcomes that would not be realistic unless industrialization is achieved. The high volume of installed turbines requires a continuous supply of the parts needed to assemble and fully commission the turbines. A supply like this would require a separate manufacturing and assembly process, meaning that parts have to be produced in factories and delivered to the installation hub for storage and assembly; this construction method reduces costs and maintains volume.

The third hypothesis found in section 0 presents a theory stating that the goals related to installed capacity in Norway and Europe will not be reached unless the industrialization of floating offshore wind happens over the course of the coming decades. In the result section from the two large-scale simulation cases, it was stated that the 7 GW installation scenario, which lasted 4.3 years, seemed plausible using the suggested WindWorks Jelsa installation hub. However, as discussed in this section, this simulation assumed constant availability and access to the parts and human resources required to assemble and install all 542 individual floating wind turbines included in that scenario. Currently, the world's largest floating offshore wind farm, which is planned to open in 2022 (Hywind Tampen), will consist of 11 floating offshore wind turbines of 8 MW each. Based on this information, it is evident that the development of 542 wind turbines of 15 MW each is not possible with the existing supply chain and infrastructure. But, if the discussion regarded expanding the number of onshore wind turbines by 542 units by 2050, the development would be considered feasible. This points to that by combining the knowledge and expertise on floating structures gained in the oil and gas industry with the industrialization seen in steel tower sections from the onshore wind turbine industry, the industrialization of FOW has a good starting point. The Federation of Norwegian Industry is currently examining how to optimize the Norwegian supply chain for offshore wind solutions through the project "Delivery models for offshore wind", projects like these are very valuable as it allows competitive companies to collaborate on finding the best solutions[5].

8 CONCLUSION

The demand for renewable energy in Europe has seen rapid growth over the last decade and will, according to most trends, continue to rise over the coming years[70][71]. The floating offshore wind market has seen many great leaps in technology. There are many promising future developments in the making – but considering the current infrastructure and procedures, the market will struggle to meet the future energy demands and the ever-accelerating need for reduction in carbon emissions[72]. This research aimed to identify how the construction phase of FOW could be improved, with this securing Norway a leading role in the European floating offshore wind market. Based on quantitative and qualitative analysis on the effects of centralizing the construction and assembly procedure, it can be concluded that utilizing multipurpose installation hubs at strategic locations will improve the overall effectiveness of floating offshore wind developments. The results indicate that targeted investments in infrastructure specific for the installation of floating offshore wind can significantly affect the installation time and hence the cost of a floating wind development. In writing time, there is a few other nations who are operating with centralized installation hubs for bottom fixed offshore wind developments. Still, the methods simulated in the case study where the installation hub is dedicated to onshore construction and assembly of floating offshore wind are yet to be applied by any nation, suggesting that a transition to this model could advance Norway into a leading role in the European FOW market.

Both qualitative and quantitative methods have been applied to answer the thesis research question, where the latter has been emphasized the most. The choice of doing a case study where a quantitative method was used through simulations proved to be a valuable tool for comparative reasons. As a reference point for the simulations that were completed, the study established a base case scenario. The base case was built on a fictive wind farm development at Utsira North, consisting of 20 individual floating wind turbines with a 15 MW capacity. The wind turbines used SPAR-type substructures with a catenary mooring system and were planned assembled at a centralized onshore installation hub at Jelsa. The case study completed seven different comparison simulation scenarios where each case was used to build upon and fine-tune the result. The most significant simulation results are presented in the below bullet list, details on the various cases are found in chapter 6.1.

- A weather downtime sensitivity study of Case A showed that, on average, the effects of weather caused the project duration to increase by 23%. The starting month causing the least downtime was July, while September prolonged the duration the most.
- A comparison simulation between Case A and B confirmed that changing location would result in a shorter project duration. Case A was 15% more effective on average when the geographical location was the only variable.
- By optimizing the assembly procedure for Case A by utilizing an extra crane, the overall project duration was reduced by 40% on average.
- Case C represented the procedure currently being used for FOW developments in Norway; this method was compared with the optimized Case A in the final comparison simulation.

The results showed that by transitioning to a centralized installation hub, like WindWorks Jelsa, the overall duration of the construction and installation phase could be reduced by an average of 52%. As a stress test for the proposed new assembly hub, two realistic installation scenarios for Norway were simulated using results gathered in the comparison cases: A *Low scenario* representing an installed floating wind capacity of 7 GW within 2050 and a *High scenario* of 19 GW. The thesis concludes that the *Low scenario*, which would require 4.3 years of continuous construction activity, is seen as feasible using an installation hub with the configuration of Case D. In contrast, the *High scenario* would need several of these assembly hubs. All of these results clearly illustrate the advantages of centralizing the entire installation process. Still, it also raises questions regarding the cost aspect of establishing a new infrastructure and supply chain for mass production of 15 MW turbines.

Through a location study done prior to the simulations, the thesis concluded that WindWorks Jelsa's location had all the prerequisites needed to work as a multipurpose storage, assembly, and deployment base. It was stated that this location has the potential of serving as a hub for several future FOW developments, both in the North Sea and other European sites. It is believed that by applying the knowledge and experience from the oil and gas industry while using the same steel tower structure parts as onshore wind developments, industrialization of floating offshore wind in Norway is realistic.

8.1 FUTURE WORK

Due to limitations on the scope and available data, various experiments, tests, and adaptations have been allocated to future work. Thus, the following are suggestions for future work, based on the simulations and results found during the work with this master's thesis.

- To better understand the cost aspect of the results presented in this thesis, future studies could include a cost comparison between a centralized model and the multi-location method which is being used today. The cost of establishing the required infrastructure and the cost of both vessels and human resources is a considerable uncertainty and could strengthen the claim that transitioning to a centralized installation hub is a favorable solution.

- This thesis focused on simulating the construction phase of potential FOW developments. Future work could run Shoreline simulations where the operation and maintenance stages are investigated and compared with the solutions in use today.

- Due to limiting factors, it was decided to mainly focus on WTG's based on the SPAR structure. However, it is reasonable to assume that many future FOW developments will rely on semi-submersible or TLP structures. Thus, it would be interesting to assess and simulate these structures' assembly and installation processes from an installation hub like WindWorks Jelsa.

- Floating wind developments will require significant storage space for the turbines that are fully assembled and waiting to be towed out to the site. The simulations included in this study do not account for this step in the installation procedure. The additional time and space this would require are left for future studies.

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A APPENDIX

A.1 CONFIGURATION OF THE SIMULATED CASES FROM SHORELINE

	Case A	
Base	**Assets**	**Vessels**
WindWorks Jelsa Location: 59.375629, 6.050517 Repair slots: 10 Weather data: Stord, ERA5	**Assembly of wind turbine** 20 Assemblies Wind farm: Utsira North Port: WindWorks Jelsa Arrival rate: 2 hours Weather data: Stord, ERA5	**Anchor/Line vessel** 1 Anchor/Line handling vessel Transit speed: 15 kn Towing speed: 5kn
	IEA Wind 15 MW Turbine 20 Wind turbines Wind farm: Utsira North Port: WindWorks Jelsa Turbine type: Floating Max no. techs: 5 Weather data: Utsira, ERA5	**Crane** 1 Crane Port: WindWorks Jelsa Transit speed: 10 kn Shift: 07-20
	Mooring anchor 20 Mooring anchors Wind farm: Utsira North Port: WindWorks Jelsa Weather data: Utsira, ERA5	**Tug** 1 Towing vessel Transit speed: 10 kn Towing speed: 4 kn
	Mooring line 20 Mooring lines Wind farm: Utsira North Port: WindWorks Jelsa Weather data: Utsira, ERA5	

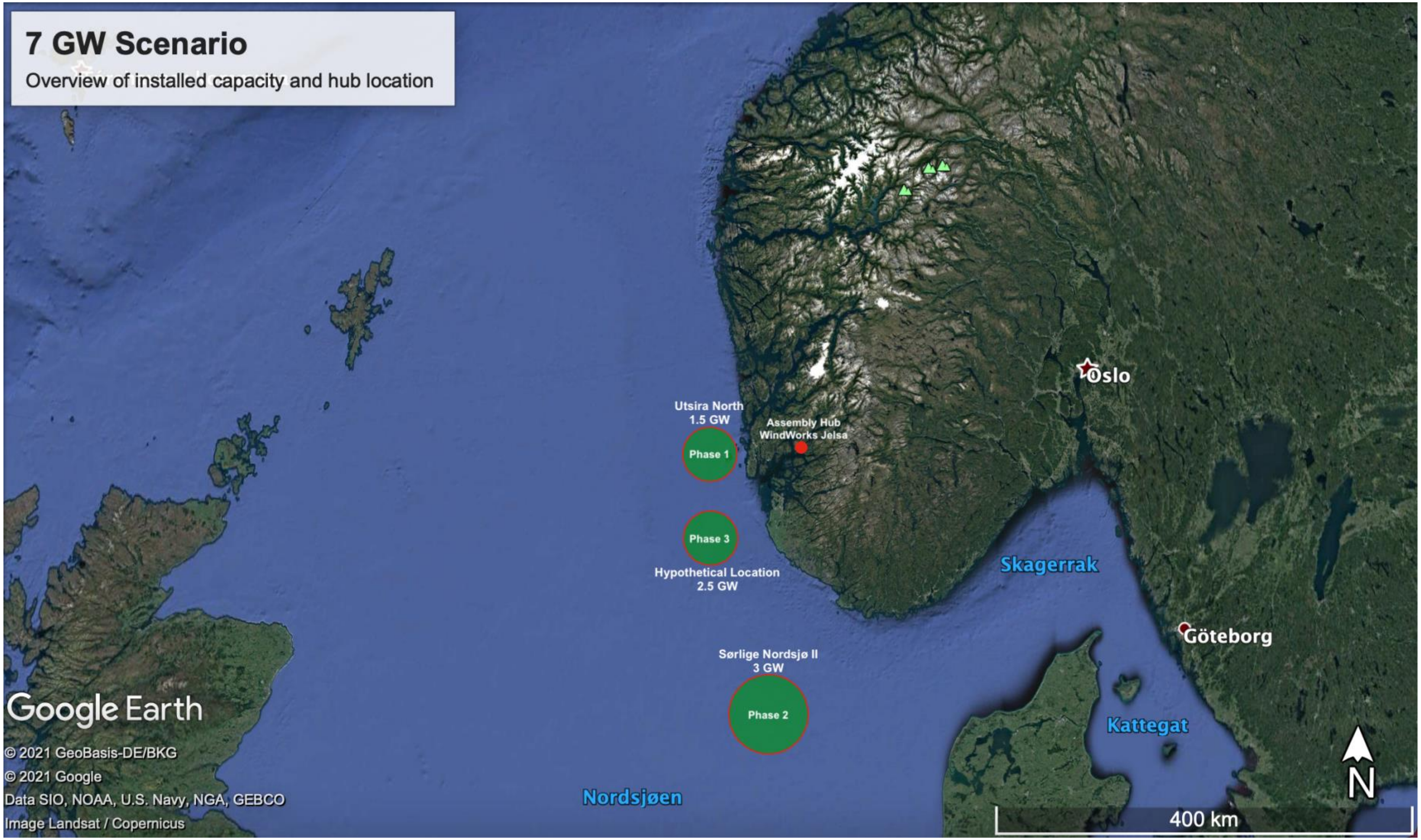
	Case B	
Base	**Assets**	**Vessels**
Skipavik Gulen Location: 60.85551, 5.0344955 Repair slots: 10 Weather data: Gulen, ERA5	**Assembly of wind turbine** 20 Assemblies Wind farm: Utsira North Port: Skipavik Gulen Arrival rate: 2 hours Weather data: Gulen, ERA5	**Anchor/Line vessel** 1 Anchor/Line handling vessel Transit speed: 15 kn Towing speed: 5kn
	IEA Wind 15 MW Turbine 20 Wind turbines Wind farm: Utsira North Port: Skipavik Gulen Turbine type: Floating Max no. techs: 5 Weather data: Gulen, ERA5	**Crane** 1 Crane Port: Skipavik Gulen Transit speed: 10 kn Shift: 07-20
	Mooring anchor 20 Mooring anchors Wind farm: Utsira North Port: Skipavik Gulen Weather data: Gulen, ERA5	**Tug** 1 Towing vessel Transit speed: 10 kn Towing speed: 4 kn
	Mooring line 20 Mooring lines Wind farm: Utsira North Port: Skipavik Gulen Weather data: Gulen, ERA5	

Case C

Bases	Assets	Vessels
Stord Location: 59.75964, 5.4935075 Repair slots: 10 Weather data: Stord, ERA5	**Assembly of wind turbine** 20 Assemblies Wind farm: Utsira North Port: Skipavik Gulen Arrival rate: 2 hours Weather data: Gulen, ERA5	**Anchor/Line vessel** 1 Anchor/Line handling vessel Transit speed: 15 kn Towing speed: 5kn
Dommersnes Location: 59.593627, 5.575394 Repair slots: 10 Weather data: Dommersnes, ERA5	**IEA Wind 15 MW Turbine** 20 Wind turbines Wind farm: Utsira North Port: Skipavik Gulen Turbine type: Floating Max no. techs: 5 Weather data: Gulen, ERA5	**Crane Dommersnes** 1 Crane Port: Dommersnes Transit speed: 10 kn Shift: 07-20
Skipavik Gulen Location: 60.85551, 5.0344955 Repair slots: 10 Weather data: Gulen, ERA5	**Mooring anchor** 20 Mooring anchors Wind farm: Utsira North Port: Skipavik Gulen Weather data: Gulen, ERA5	**Crane Skipavik Gulen** 1 Crane Port: Skipavik Gulen Transit speed: 10 kn Shift: 07-20
	Mooring line 20 Mooring lines Wind farm: Utsira North Port: Skipavik Gulen Weather data: Gulen, ERA5	**Tug (Dommersnes to Gulen)** 1 Towing vessel Towing speed: 5 kn
	Floating foundation 20 Floating substructures Port: Dommersnes Weather Data: Gulen, ERA5	**Tug (Stord to Dommersnes)** 1 Towing vessel Towing speed: 5 kn
	Floating foundation completion 20 Assemblies Port: Dommersnes Arrival rate: 2 hours Weather data: Dommersnes, ERA 5	**Tug (Gulen to Utsira North)** 1 Towing vessel Transit speed: 10 kn Towing speed: 4 kn
	Floating foundation transfer (Stord to Dommersnes) 20 Component transfers Port: Stord Weather data: Stord, ERA5	

	Case D	
Base	**Assets**	**Vessels**
WindWorks Jelsa Location: 59.375629, 6.050517 Repair slots: 10 Weather data: Stord, ERA5	**Assembly of wind turbine** 20 Assemblies Wind farm: Utsira North Port: WindWorks Jelsa Arrival rate: 2 hours Weather data: Stord, ERA5	**Anchor/Line vessel** 1 Anchor/Line handling vessel Transit speed: 15 kn Towing speed: 5kn
	IEA Wind 15 MW Turbine 20 Wind turbines Wind farm: Utsira North Port: WindWorks Jelsa Turbine type: Floating Max no. techs: 5 Weather data: Utsira, ERA5	**Cranes** 2 Cranes Port: WindWorks Jelsa Transit speed: 10 kn Shift: 07-20
	Mooring anchor 20 Mooring anchors Wind farm: Utsira North Port: WindWorks Jelsa Weather data: Utsira, ERA5	**Tug** 1 Towing vessel Transit speed: 10 kn Towing speed: 4 kn
	Mooring line 20 Mooring lines Wind farm: Utsira North Port: WindWorks Jelsa Weather data: Utsira, ERA5	

A.2 7 GW SCENARIO - OVERVIEW OF THE INSTALLED CAPACITY AND LOCATIONS



A.3 19 GW SCENARIO - OVERVIEW OF THE INSTALLED CAPACITY AND LOCATIONS