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Author: Michael Drummond

Course coordinator: Yihan Xing

Supervisor(s): Charlotte Obhrai

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Feasibility Analysis of Floating Offshore Wind in Svalbard

Master Thesis

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Michael Drummond

Front photo taken by author during stay in Svalbard

Preface and Acknowledgements

This Master’s thesis was written as part of the Master of Science in Marine and Offshore Technology at the University of Stavanger. This thesis was conducted during the Spring semester of 2022.

This study was inspired by courses taken in Arctic Offshore Engineering held at UNIS Research Centre in Svalbard. I became quite interested in exploring renewable energy alternatives in Svalbard as a result of the planned coal mine closure in Longyearbyen. This interest was furthered sparked by the discussions during my courses at UNIS. The purpose of this report is to then research the engineering feasibility of floating offshore wind turbines in Svalbard.

I am very thankful for all the knowledge and insight that has been shared with me during my studies. I would like to thank Shoreline for granting access to their simulation tools. I am especially thankful to my supervisor, Associate Professor Charlotte Obhrai for trusting me with this project and for her guidance.

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Michael Drummond

Abstract

Svalbard is a Norwegian island archipelago located far north in the Arctic with Longyearbyen its largest settlement. Fossil fuel in the form of diesel generators or coal power plants is still the primary energy source in all the settlements of Svalbard. In 2018, The Ministry of Petroleum and Energy (MPE) commissioned a study on the future energy supply options for Svalbard. This study did not explore offshore wind, and considered onshore turbines to have lower cost, with similar environmental consequences. Recently, policy has restricted the future development of onshore wind turbines as a result of local opposition and concern over sensitive bird populations. Floating offshore wind (FOW) could be considered as an alternative and the feasibility of such a project should be investigated further. As such, the purpose of this study is to investigate the feasibility of FOW in Svalbard. This was done through a case study, which is limited to the installation and operational feasibility of a semi-submersible FOW concept layout of six 12MW WINDMOOR units positioned 60km offshore from the entrance at Isfjorden. Reference literature on the subject is scarce, so typical arctic offshore engineering challenges are explored to aid the analysis.

Typical and extreme site conditions and challenges encountered with arctic offshore installations is of great interest to the case study. Of these challenges, sea ice was identified as a critical environmental condition for the installation and operation of offshore structures in the arctic. At the selected site however, due to the warmer and more favourable climate conditions on the west coast of Svalbard, sea ice is expected to be small and in low concentrations. The concept was then tested for the expected extreme ice conditions at the site using the Simulator for Arctic Marine Structures (SAMS) program. The results from the SAMS simulation that replicated adverse sea ice conditions on the FOW concept showed that sea ice would likely be a minor issue and not impact on the stability of the semi-submersible structure. This provides greater confidence that one of the major challenges in the arctic would not be a significant issue at the selected site. The threat from icebergs was also considered, which would need to be monitored and managed should the project progress.

A high-level installation downtime assessment was conducted using Shoreline, a simulation tool for the programming and optimisation of offshore wind construction projects. From the results of the simulation, weather conditions during summer are favourable for the delivery of the project and downtime due to waiting on weather would be limited. From a constructability perspective, the project is possible. The study showed that the FOW concept would be able to meet the energy needs of Longyearbyen. However, while FOW is feasible in Svalbard from an engineering perspective, a business case analysis should be conducted for the selection of the alternative energy system. It is likely that this project may be too costly for any funding to be secured in the immediate future. The cost is projected to decrease which could make this a more attractive option within the decade. The onshore assembly of FOW units combined with long distance towing operations has been achieved before in Norway for a similar scale project. The concept would also be dependent on the future environmental policy as well as conflicts with stakeholders in tourism, fishing, and shipping. More research is required to progress the FOW concept to development. The most critical information required would be a detailed cost estimate enabling a business case analysis to be conducted. A preliminary cost assessment however indicates that electricity costs from FOW would be competitive against other forms of energy. This would ultimately decide the fate of the project. Stakeholder engagement and an environmental impact assessment would also need to be conducted for the project.

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Nomenclature

AEP	Annual Exceedance Probability
AUV	Autonomous Underwater Vehicles
ARI	Average Recurrence Interval
CAPEX	Capital Expenditures, investment costs
CCS	Carbon Capture and Storage
FOW	Floating Offshore Wind
GW	Gigawatt
HAWT	Horizontal Axis Wind Turbine
HVDC	High Voltage Direct Current
IRENA	International Renewable Energy Agency
LNG	Liquefied Natural Gas
MPE	Ministry of Petroleum and Energy
MW	Megawatt
NTS	Not to Scale
OPEX	Operating Expenses, operational costs
O&M	Operations and Maintenance
ROV	Remotely Operated Vehicle
SAMS	Simulator for Arctic Marine Structures
SIA	Sea Ice Area
SIC	Sea Ice Concentration
SIE	Sea Ice Extent
SPAR	Single Point Anchor Reservoir
VAWT	Vertical Axis Wind Turbine
VIV	Vortex-Induced Vibrations
WOW	Waiting on Weather

1 Introduction

1.1 Background and Historical Overview

Svalbard is a Norwegian island archipelago located far north in the Arctic. There are five main settlements all located on Spitsbergen Island. Longyearbyen, a Norwegian settlement, is the largest settlement in Svalbard accommodating over 2100 inhabitants (Tennbakk et al., 2018). There are also two Russian mining settlements, namely Barentsburg and Pyramiden, which accommodates around 450 people and 10 people respectively. In addition, there is a smaller Norwegian settlement in Ny-Ålesund, accommodating around 35 people (VisitSvalbard, 2021), and a Polish settlement accommodating around 10 people in Hornsund which serve as bases for research (Hornsund, 2022). The current and historic main mining settlements are located by Isfjorden, the widest and second longest fjord in Svalbard (Barr, 2020). A location map is provided in Figure 1-1.

Figure 1-1 Location map of the islands of Svalbard n.t.s. (Kartverket, 2021)

The settlements in Svalbard have traditionally been linked to mining activities (Barr, 2022). Longyearbyen started as a coal mining town in the early 20th century and has since developed to be a central location for tourism and research in the arctic. Fossil fuel in the form of diesel generators and coal power plants remains the primary energy source in all the settlements of Svalbard (Buseth & Lindberg, 2020). Since the 1930's, only Norway and Russia (or Soviet Union) have undertaken coal mining activities (Barr, 2022). Today, coal mine operations are limited to Longyearbyen and Barentsburg, and with recent increases in tourism the focus has shifted away from mining to more profitable activities in Svalbard.

Throughout the history of Svalbard, many countries have been involved in whaling, fur hunting and mining, and the question of sovereignty appeared on the international agenda. The Svalbard Treaty of 1920 (implemented in 1925) granted Norway sovereignty over the islands, whilst giving all 46 signatory countries equal rights to economic activity in the region. The treaty is the foundation of the environmental governance structure, assigning Norway with full rights and responsibility to conservation and rehabilitation of flora and fauna (Kaltenborn et al., 2020). As such, Norway has a responsibility to preserve the environment and ensure a sustainable future for the settlements of Svalbard.

In 2016, the Foreign Affairs and Defence Committee of Norway asked the Government to explore proposals for funding a study on renewable solutions for Svalbard (Stortinget, 2016). In 2018, The Ministry of Petroleum and Energy (MPE) commissioned Thema Consulting Group to conduct a study of future energy supply options for Svalbard (Tennbakk et al., 2018). This study explored alternatives such as combined heat and power based on liquefied natural gas (LNG) and biofuels with carbon capture and storage (CCS), onshore wind and solar with battery and hydrogen storage and a power cable from the mainland. Whilst assessing multiple combinations of these alternative energy options, the study concluded that the most attractive alternative option was the use of LNG power with CCS and wind solutions were among the least attractive. This study did not explore offshore wind, and considered onshore turbines to have lower cost, with similar environmental consequences. Wind would also need to be combined with storage capacity and it would be beneficial to combine with solar power to utilise the midnight sun during the lower wind speed periods of summer.

In 2021, Master's students at UNIS Svalbard conducted a study on the operational and logistic challenges of a theoretical offshore wind farm at the entrance of Isfjorden (Klis et al., 2021) and (Drummond et al., 2021). Whilst this study focused on the operations of autonomous underwater vehicles (AUV) and remotely operated vehicles (ROV) tested in the region during course fieldwork, some installation scenarios for the theoretical wind farm were considered. Some of the challenges identified included the presence of ice and the remoteness of the location to establish a working compound. The installation would be a logistical challenge due the remoteness of the site and the lack of safe harbour between the mainland of Norway and Svalbard.

Continuing from this previous work dedicated to investigating alternative energy solutions for Svalbard, this study will investigate in more detail the feasibility of floating offshore wind (FOW) as a renewable option that Longyearbyen can adopt as it transitions away from fossil fuels. FOW technology has developed substantially over the past decade, and many member states of the European Union (EU) are looking to utilise this technology to meet their 2050 climate neutral targets (EU, 2020). Norway in particular is well placed to deliver FOW solutions due to its history in the oil and gas industry (Skår, 2021). An MPE commissioned report on the delivery models for FOW has identified Norway's international competitive advantage and market potential to deliver these renewable projects (Bjerknes et al., 2021). Norway is able to optimise the delivery process from assembly, deployment and installation with its vast selection of deep ports and construction yard space (Sveen et al., 2020).

1.2 Purpose of Study and Motivation

The governor's office in Longyearbyen is eager to see the town move to a less environmentally damaging power source, and hopes the coal plant will be able to close within two to five years (Nilsen, 2021). With the Longyearbyen community developing its research and tourism infrastructure, an alternative source of energy will need to be established to meet the increasing power demands. Arctic regions are particularly vulnerable to the impacts of climate change, so reducing greenhouse gas emissions by replacing the fossil fuel energy systems with a renewable system is not only highly relevant, but desirable and should be thoroughly investigated. A renewable option that has not been given significant consideration to date is FOW, which could meet the growing energy demands whilst minimising the impact on the environment.

Transitioning Longyearbyen towards renewables is challenging as the community is small and won't benefit from economies of scale. The environment is harsh and challenging, and such a project would be exposed to remote location risks, insecurity of energy supply, reliability challenges and difficult logistics for maintenance (Buseth & Lindberg, 2020). During the cold and long winters, there is a substantial energy demand for heating, and the community's survival is dependent on secure and reliable energy sources. The renewable energy sources available is practically limited to solar and wind, however solar energy is limited only to the summer months in the arctic circle. Harsh environmental conditions place large technical requirements on the robustness of the construction.

While FOW has been disregarded as an unviable alternative in the past, rapid improvements to this technology and optimisation of its delivery could increase its feasibility in an arctic application. This study seeks to explore some of the challenges that can be anticipated in developing a FOW farm in the arctic. The purpose of this study is to explore some of the technological develops that could make FOW a feasible option for powering Svalbard. With the technology developments of today, barriers that prevented such a project in the arctic in the past may have disappeared.

It is anticipated that such a solution to the energy problem in Svalbard would be well received by the community due its minimised impact on the environment. While it is expected that the costs involved in developing this project today may possibly exceed all other alternatives, with future optimisation of FOW construction perhaps this option may become more attractive in the near future. Even with a higher expected cost, alternative options may be limited if the objective to minimise harm to the environment is prioritised.

1.3 Research Question

Based on the challenges transitioning Svalbard to renewable energy reliance, the following research question has been proposed:

Is FOW a feasibility renewable option for Longyearbyen and what are some of the critical challenges that will be encountered during construction, installation, commissioning and operations?

In addressing this question, extensive research and testing is required, some which relating to financing lies beyond the scope of this research thesis. The following hypotheses have been developed to be confirmed or disproved during the course of this research, and aid in answering the research question:

Hypothesis 1*: A FOW farm is a feasible solution to meet the energy needs of Longyearbyen*

Hypothesis 2: *While a FOW farm is technically feasible, financing barriers will prevent this solution*

Hypothesis 3: *Future optimisation of FOW solutions will improve the project's feasibility*

1.4 Scope of Research

This research topic has many areas that can be explored to assess the feasibility of FOW in an arctic environment such as Svalbard. A challenge in this study is defining the scope of the research so that the topic is adequately explored, and the research question sufficiently answered. As such, the scope of the study is defined into the following areas of focus as below in Table 1-1. It is intended that these focus areas will assist in addressing the research question defined in Section 1.3.

Table 1-1 Scope of Research

Focus Area	Brief Description
Renewable Solutions in Svalbard	Exploring the existing renewable infrastructure in Svalbard and the conditions that may favour an energy alternative over another.
Arctic Offshore Engineering Challenges	Identifying some of the critical challenges in similar arctic engineering projects that would impact the success of a FOW project in Svalbard.
Svalbard Site Conditions	Defining the current and projected environmental conditions of Svalbard which would influence construction and operations.
FOW Industry Development	Reviewing the current context of FOW developments, including the immerging technologies, current projects and construction methods.
Concept Case Study	Analysing in detail a possible FOW concept that could be used in Svalbard and assessing the feasibility of its use.

1.5 Limitations

As the scope of this research is broad, limitations have been defined so that the study is more concisely addressing the question outlined in Section 1.3. The study will mainly focus on FOW technology over other renewables and the development of offshore infrastructure in challenging arctic and cold environments. Considering the vast scope of alternative energy solutions, the study will be limited to FOW and site conditions unique to the west coast of Svalbard near Isfjorden. As the region is sparsely populated, with a challenging climate, reference literature on the subject is scarce and several assumptions will be made and outlined in the case study. Additionally, due to time and funding limitations, early contractor, supplier, and stakeholder engagement has not been conducted. As a result of this limitation, it is difficult to understand the contractual and funding structures that will that have a large influence on the overall feasibility of a FOW project in the arctic. Without understanding the full cost implications of the project, it will be difficult to fully assess the feasibility of this solution.

Aside from a high-level installation study and ice loading simulation, no additional simulations will be conducted. An established FOW concept will be assessed, and no design calculations will be performed in this analysis. This study is intended for discussion purposes only and is not definitive or prescriptive. The information should be used for information only, and additional analysis performed for any further development of this concept.

1.6 Structure of the Report

A brief literature review will be conducted in Section 2 exploring the current state of research and the typical conditions in Svalbard that would form a Basis of Design. In Section 3, FOW theory is to be explored, providing context for the array of renewable options that can be selected for the Svalbard case. Following this, an example FOW case study will be conducted in Section 4. In this case study, a concept FOW development will be explored in more detail to provide insights into the installation methodology and feasibility of the project. A discussion of the findings from the case study will be presented in Section 5 followed by a concluding summary in Section 6.

2 Literature Review

To comprehensively analyse the potential of offshore wind in Svalbard, an understanding of the current technological developments and theory of arctic offshore infrastructure is necessary. This literature review has been conducted to develop an understanding of the current state of research around arctic offshore infrastructure and renewable solutions. In addition, an investigation of advancement of FOW turbines will be explored. The literature review also offers an opportunity to understand the environmental conditions at the site which will form a basis of design for a future FOW facility.

2.1 Svalbard's FOW Potential

In the context of Europe, the plans for offshore wind park developments in the future is formidable (Barstad et al., 2012), with several projects already completed and many more in development. Currently, electricity supply in remote arctic areas is heavily dependent on coal and diesel sources, which impose an economic and social burden on the local populations from greenhouse gas emissions, black carbon and oil spills (Boute, 2016). While there are many energy alternatives to coal and diesel, there is a global push for renewable options to be considered to replace the environmentally harmful energy sources.

Longyearbyen houses the only remaining coal-fired power plant in Norway, and there is a large and growing political pressure to reduce emissions from the settlement's primary energy source. The coal-fired power plant is the main source of energy for Longyearbyen, providing around 40GWh electricity and 70GWh heat annually and emitting approximately 60 000 tons of carbon dioxide waste annually (Ringkjøb et al., 2020). Continued coal energy production in Svalbard faces challenges regarding the upkeep of ageing equipment and the near exhausted resources in the nearby mines (Tennbakk et al., 2018). Opening a new mine and refurbishing the aging equipment is not a preferable option for the government or community. In addition to the main coal-fired power plant, there are five diesel generators, a reserve heat-exchanger and six oil-fired boilers to cover peak electricity demand and to serve as reserve generation capacity (Ringkjøb et al., 2020). A stable energy supply, as provided by the current system, is critical for a community in such a harsh arctic environment. There is also a small amount of solar infrastructure installed in the settlement.

Longyearbyen's energy demands are changing, with energy previously required to sustain only resource extraction activities in the past, the community has now shifted to tourism and research industries. The energy needs are increasing rapidly with the growing population associated with the change in industry (Tennbakk et al., 2018). With the pressure to find alternative energy sources, a combination of renewable options may be desirable providing they can meet the growing needs of the settlement. The Norwegian MPE has already started investigating different energy options for Longyearbyen and stresses that the solution must be sustainable and cost-effective, as well as provide adequate security of supply (Magnar Brekke et al., 2018).

Other settlements in Svalbard largely rely on diesel generators, which are compromised by complex logistics, affecting both availability (delivery during navigation season) and affordability (Gritsenko & Salonen, 2021). There are limited renewables currently in use in the smaller settlements. A 20kW turbine was installed in Hornsund in 1989, but was destroyed by a blizzard within two years and a 1kW turbine was implemented in Ny Ålesund as part of a small off-grid hybrid solar-wind energy system (Aalde & Adaramola, 2018). With extensive research dedicated to the development of renewable technology, a modern solution may be more robust to survive these challenging conditions.

2.2 Alternative Renewable Energy Solutions

The MPE report exploring alternative energy solutions considered several cases and options for solving the energy problem in Svalbard. The options included the continuation of coal and diesel with and without carbon capture and storage, the use of liquified natural gas and biofuel, and the transition to a renewable alternative including a combination of onshore wind, solar and hydrogen storage (Tennbakk et al., 2018). Combining wind and solar power in a hybrid renewable energy system can improve the efficiency and reliability of the power output due to the seasonal and complementary characteristics of the resources (Solbakken et al., 2016). With solar energy restricted to only the summer months of sunlight, the focus on wind as the primary energy source should be considered particularly for the winter months. The environmental consequences of a solar installation on Platåberget (the plateau adjacent and to the west of Longyearbyen) has been deemed insignificant (Barstad et al., 2012).

This study focuses on offshore as a renewable alternative energy source for Svalbard, however the MPE report did not consider this as a likely option. As an attractive alternative to offshore wind, the more cost-effective onshore wind developments could be considered. There is however strong public resistance to the installation of turbines on the vulnerable arctic islands, with concern over the impact on the sensitive permafrost as well as endangered bird species. In line with this sentiment, Norway has recently tightened the rules for onshore wind power developments to better protect the environment (Adomaitis, 2020). This then opens the possibility for offshore wind solutions instead, which appears to be generally preferred over the onshore alternative in the new restrictions.

When considering possible offshore wind configurations, a decision needs to be made whether the solution is floating and secured with moorings or fixed to the seabed by a monopile or jacket structure. A bottom fixed offshore wind turbine hasn't previously been considered and would likely not be feasible to construct due to the protection measures required for marine mammals. Isfjorden is abundant with marine life, particularly during the summer months where marine mammals such as whales, seals and walruses actively hunt in these waters. The summer months would also me more ideal for the installation works due to the favourable weather so a bottom fixed solution may be problematic. Driving piles for a bottom fixed monopile would require exclusion zones for marine mammals and extended interruptions and downtime for each sighting (JNCC, 2010). This is due to the loud underwater shock from the pile driving hammer causing injury to these mammals. In comparison, FOW solutions use suction anchor moorings which could have a lower impact on the marine life during installation.

Hydrogen production can also be integrated into a renewable solution in Svalbard. Transforming renewable energy for chemically stored energy has the potential to open up a new energy industry in the arctic (Magnar Brekke et al., 2018). From the results of recent case studies, transitioning to a system based on renewable energy sources is feasible (Klis et al., 2021). It has been recommended that a solution based mainly on renewable energy with the inclusion of storage, hydrogen imports and adequate back-up capacity be considered for the settlement (Ringkjøb et al., 2020). This will improve the security and reliability of the energy supply during downtimes in renewable production.

A high voltage direct current (HVDC) power cable between Finnmark and Longyearbyen has also been considered. Such a cable would be approximately 930 km long and would require HVDC transmission with converter stations at both ends. While technically feasible, this solution would have a large impact on marine biodiversity during construction and operation. This includes sedimentation, noise and vibration impacts during construction and electromagnetic and thermal impacts during operations (Gill et al., 2005). As such, this solution has not been considered favourably in the MPE report (Tennbakk et al., 2018).

The MPE report concluded that the LNG power plant scored the best on both cost efficiency and security of supply without any significant environmental consequence (Tennbakk et al., 2018). Therefore, this option has previously been recommended as the most feasible. The renewable options were deemed to have a relatively insignificant effect on overall carbon dioxide emissions and were more costly than the LNG option. With the variability in wind power production there would be a high need for short term energy storage while solar solutions would require long term energy storage due to the overproduction in summer.

Offshore wind was not considered in the MPE study, with onshore wind turbines considered to have lower costs and less or equivalent environmental consequences. The study also conceded that some technologies (presumably including FOW) has not yet sufficiently matured to be a cost-effective alternative. With ever increasing improvements the FOW delivery, and the growing demand for renewable options, perhaps FOW can be considered as an energy source as well. Against the background of the growing energy demands in Longyearbyen, there is a clear need of planning the future energy supply and FOW should be considered amongst a vast array of options.

2.3 Arctic Offshore Engineering Challenges

The arctic region is characterised by extreme climate conditions and vulnerable environments, and as such requires unique solutions to provide energy supply (Morgunova et al., 2020). One particular challenge to overcome in the design of arctic offshore facilities is the interaction of ice with the structures. When designing FOW turbines in ice-covered seas, site-specific ice conditions are crucial to determine their impact. As such, the use of ice charts and ice reports in combination with temperature data provides more detailed information when compared with estimating ice growth from design standards (Tikanmäki & Heinonen, 2021).

2.3.1 Ice Conditions

Ice conditions forms the basis of the main challenge that is unique to cold climate and arctic engineering. Activity in the arctic marine areas of the world is increasing, and this includes shipping, offshore construction in commercial oil and gas as well as tourism. While extensive research has been devoted to understanding the interaction between ice and engineering assets, for this study a summary is provided in this Section for basic reference.

2.3.1.1 Sea Ice

The presence of sea ice is one of the main factors contributing to the complexity of operations in the arctic (Timco & Weeks, 2010). Floating sea ice is formed when the water temperature drops below freezing point. For sea water, depending on salinity and pressure, this freezing temperature is around -2^{o}C. Sea ice begins to develop as a thin film known as frazil which mixes into clumps known as grease ice. As the ice continues to grow thicker, a think elastic crust layer between 5cm and 10cm forms known as nilas. As waves and swell move nilas around, the pieces are shaped into discs known as pancake ice which can be 10cm thick and have a diameter of 30cm to 3m. As the ice accumulates into sheets, ridging and rafting can result in larger ice units with deeper keels and tall sails. Fast ice is a type of sea ice that forms and remains fixed to the coast. The ice forms above are known as first year ice. Sea ice that is able to survive a summer seasons melt is often referred to as old ice which is characterised by higher density.

A water area with a concentration of sea ice is referred to as a floe. As floating sea ice interacts with an arctic structure, global actions are applied and include ice crushing and pressure loading. It is important to understand the ice loading impacts when designing offshore structures in the arctic.

2.3.1.2 Icebergs

Iceberg management methods involve detecting, tracking and towing the icebergs away from the asset (Palmer & Croasdale, 2013). Icebergs originate from glaciers and break off the face during calving. Icebergs are often characterised by size and shape characteristics. Icebergs can be a significant risk to arctic offshore structures and vessels as they are often mostly submerged with an unknown volume and high momentum properties. They can also be unstable and can roll when towed. Icebergs can be monitored by radar, and the risk of iceberg collision can be reduced through properly implemented management plans.

Icebergs are more commonly found drifting during the summer months as they break away from the glaciers. Typically during winter, the glacier is stabilised and ice calving declines. Icebergs are formed by pure ice and melt at a faster rate than sea ice. Svalbard has many glaciers, and the estimated production rate is 1.3km^3/year (Broström et al., 2009).

2.3.1.3 Icing

Sea ice spray and atmospheric icing pose considerable hazards to the stability of floating offshore structures (Dehghani-Sanij et al., 2017). Wave impact sea spray and wind spray are the main sources of incoming water onto marine vessels and offshore structures. The incoming water can form ice that accumulates on the floating structure and impacts stability. The prediction of icing growth rate is therefore important to understand the risk of instabilities caused by icing (Deshpande et al., 2021). Spray generation is complex and difficult to model as it varies with factors such as wind speed, droplet size, water salinity, and trajectories. Several computer models have been developed in order to predict the spray generation and icing. These models also rely on the heat balance and mass balance equations that use thermodynamic theory to estimate the rate of accretion.

Anti-icing and de-icing methods are often implemented in arctic offshore structures. Anti-icing methods include thermal preheating and preventative designs including shape, material properties, coatings and surface treatment. De-icing methods include thermal heating through hot liquids and electrical warming, mechanical vibrations and manual removal and chemical flushing (Deshpande et al., 2021).

In addition to the floating structure stability, icing on wind turbine blades can degrade performance and durability (Pryor & Barthelmie, 2010). Icing on the turbine blades is caused by super cooled droplets from clouds freezing on the surface during contact. To minimise the formation of ice, the blades are designed with a unique shape and often heated.

2.3.2 Renewables in the Arctic

Offshore wind structures in ice-covered seas are subjected to actions from moving ice and ice crushing forces. The complex ice properties and flow behaviour is difficult to define when determining the actions, and advanced analysis with computer programs is often required (Wang & Muskulus, 2015). Because of the uncertainty of ice loads and ice-induced vibrations, unclear risks may arise in the structural design. The research on the interaction between FOW structures and sea ice is scarce and poses uncertainties in the dynamic behaviours (Yu et al., 2020). It is therefore essential to estimate the ice loading and ensure adequate safety factors are implemented through the design.

A SWOT (Strengths, weaknesses, opportunities and threats) analysis was recently conducted for renewable solutions in the Arctic (Morgunova et al., 2020). The SWOT analysis is summarised as follows in Table 2-1 with additional items identified through this literature review incorporated.

Table 2-1 SWOT Analysis (Morgunova et al., 2020)

Strengths	high wind potential, high solar potential during summer, availability of data and technical possibility of small-scale production.
Weaknesses	intermittent power supply, periods of equipment downtime, lack of technology adapted for arctic conditions, logistical difficulties, and high cost of equipment.
Opportunities:	reducing emissions and impact on arctic environment, governmental support, international cooperation, and vast unused land available for installations
Threats	harsh conditions, technical obstacles, lack of transport infrastructure, weak policy framework, and competition from other energy sources.

The uncertainty around the cost of a development is also a major challenge in arctic projects. It is a challenge to mobilise equipment and predict the impact of downtime. An estimated cost for arctic offshore wind developments was presented as 28000NOK/kW rating (Salo & Syri, 2014). This estimate is quite old, and since then technology developments has increased the efficiency of construction and reduced the cost. This cost rate however can be used to provide a preliminary cost estimate.

2.4 Site Conditions (Basis of Design)

Due to the position of Longyearbyen on the coast of Adventfjorden, which connects to the larger body of water in Isfjorden, the site conditions of Isfjorden and the west coast of Svalbard of particular interest for site selection for a FOW facility. These conditions will form the Basis of Design in future design development.

2.4.1 Air Temperature and Seasonal Variations

Svalbard is located in the arctic circle and as such experiences periods of midnight sun in the summer and polar darkness in the winter. These contrasting conditions bring severe temperature drops in the winter. During the coldest part of winter, the air temperature around Longyearbyen averages around -20°C, with a minimum of -40°C. During the warmest period of summer, the average temperature is 7°C (Tennbakk et al., 2018). At this temperature, consideration to the health of workers outdoors need to be given to prevent exposure and hypothermia. The energy systems also need to be reliable to heat the settlement as it gets cold quickly in the event of power outage.

The region is also susceptible to extreme storm events known as polar lows that can cause hazardous conditions. These storms predominately occur during winter. Figure 2-1 shows the frequency of polar low events per month.

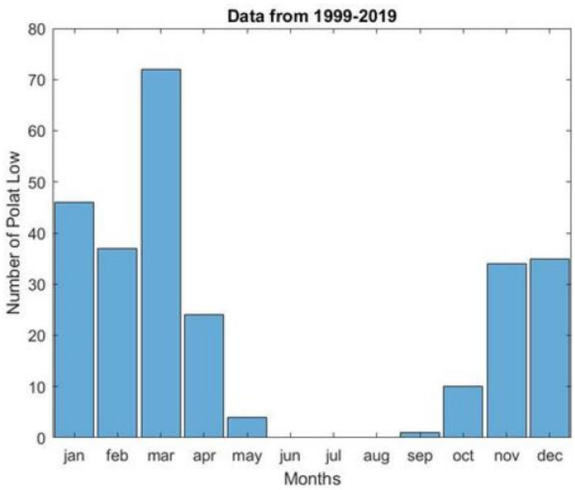


Figure 2-1 Frequencies of polar low events by month over the Nordic seas between 1999 and 2018 (Rojo et al., 2019)

2.4.2 Wind

A 3-hourly hindcast timeseries of average wind speed and significant wave height from NORA10 for the period between September 1957 and June 2021 (Reistad et al., 2011) was analysed to determine typical site conditions 60km offshore of the entrance at Isfjorden, as shown by the marker in Figure 2-2 for the reference location.

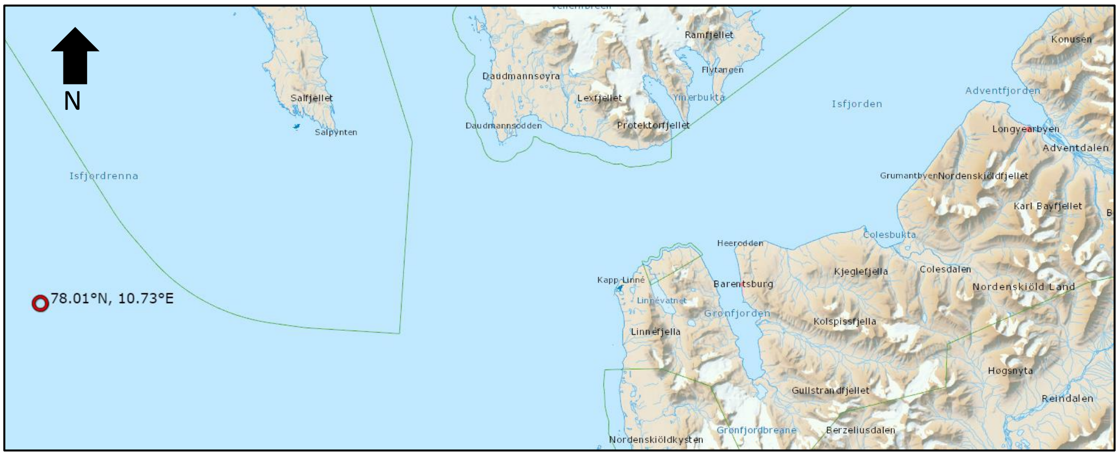


Figure 2-2 NORA10 Hindcast reference location (Kartverket, 2021)

To determine the characteristic extreme values, the hindcast data was fitted to a 3-parameter Weibull model using the method of moments as below (Zaiontz, 2021).

Weibull Cumulative Distribution Function:

$$F(x) = 1 - e^{-\left(\frac{x-\lambda}{\alpha}\right)^{\beta}} \tag{2.1}$$

Method of Moments:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \equiv \lambda + \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{2.2}$$

$$s_x^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2 \equiv \alpha^2\left[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)\right] \tag{2.3}$$

$$g_1 = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^3}{\left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2\right]^{\frac{3}{2}}} \equiv \frac{\Gamma\left(1+\frac{2}{\beta}\right) - 3\Gamma\left(1+\frac{1}{\beta}\right)\Gamma\left(1+\frac{2}{\beta}\right) + 2\Gamma^2\left(1+\frac{1}{\beta}\right)}{\left[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)\right]^{3/2}} \tag{2.4}$$

Left Side Equation		Right Side Equation	
Parameters from Hindcast		*Weibull Parameters*	
$\bar{x}$	Mean	α	Scale
s_x^2	Variance	β	Shape
g_1	Skewness	λ	Location

Extreme Value Estimation:

$$x(p) = \lambda + \alpha[\ln(2920p)]^{\frac{1}{\beta}} \tag{2.5}$$

p	Annual Exceedance Probability
2920	Number of 3hr periods per year

From analysing the hindcast date, wind speed characteristics are presented in Table 2-2.

Table 2-2 Hindcast 10m average wind speed characteristics

Characteristic	Wind Speed (m/s)
Mean	7.53
Maximum	27.21
Variance	14.81
Skewness	0.63

Using Equations 2.1 to 2.4, Weibull parameters $\alpha = 8.32, \beta = 2.00$ and $\lambda = 0.16$ were obtained and used in Equation 2.5 to determine the extreme values, as presented in Table 2-3.

Table 2-3 Extreme average wind speeds

ARI	AEP	Wind Speed (m/s)
1	0.63	24.28
10	0.1	26.78
100	0.01	29.60
10000	0.0001	34.56

These values correlate well with the averaged wind speed of 8m/s in the region from the ERA40 hindcast model for the period 1972 to 2001 (Barstad et al., 2012)

2.4.2.1 Reliability

The reliability of wind is of particularly importance for energy production. A study of Longyearbyen showed that wind conditions supported the installation and reliable use of wind energy (Grochowicz et al., 2021). The winter periods have more stable and higher production potential than the summer, at which point solar energy is available. The number of extreme events does not vary significantly each year and can be overcome during design. Energy storage could be used to compensate for calm days.

2.4.3 Waves

A similar analysis was conducted for waves using the hindcast data introduced in Section 2.4.2. The significant wave height (H_s) characteristics are presented in Table 2-4.

Table 2-4 Hindcast significant wave height characteristics

Characteristic	H_s (m)
Mean	1.67
Maximum	11.90
Variance	1.26
Skewness	1.53

Equations 2.1 to 2.4 were used to obtain Weibull parameters $\alpha = 1.42, \beta = 1.20$ and $\lambda = 0.33$ which were then used in Equation 2.5 to determine the extreme values, as presented in Table 2-5.

Table 2-5 Extreme significant wave height

ARI	AEP	H_s (m)
1	0.63	8.80
10	0.1	10.31
100	0.01	12.15
10000	0.0001	15.67

The waves at the site can be quite severe based on this analysis, which will require a specific dynamic analysis of the FOW structure. The wave characteristics are like that of the North Sea, so conditions are not unique or extreme for this site.

2.4.4 Currents

The west coast of Svalbard has a relatively mild climate due to the steady supply of mild air masses from the south and the warm North Atlantic Current part of the Gulf Stream system (UNIS, 2021). The West Spitsbergen Current is warm enough during winter to melt around 4m of ice, and as a result the west coast of Svalbard is generally free of ice the whole year. On the east coast of Svalbard, intense freezing occurs during winter (UNIS, 2021). Strong tidal currents occur, particularly along the east coast, with a maximum current speed of more than 1.0 m/s (Dallmann et al., 2015). A map of the main current system is shown in Figure 2-3.

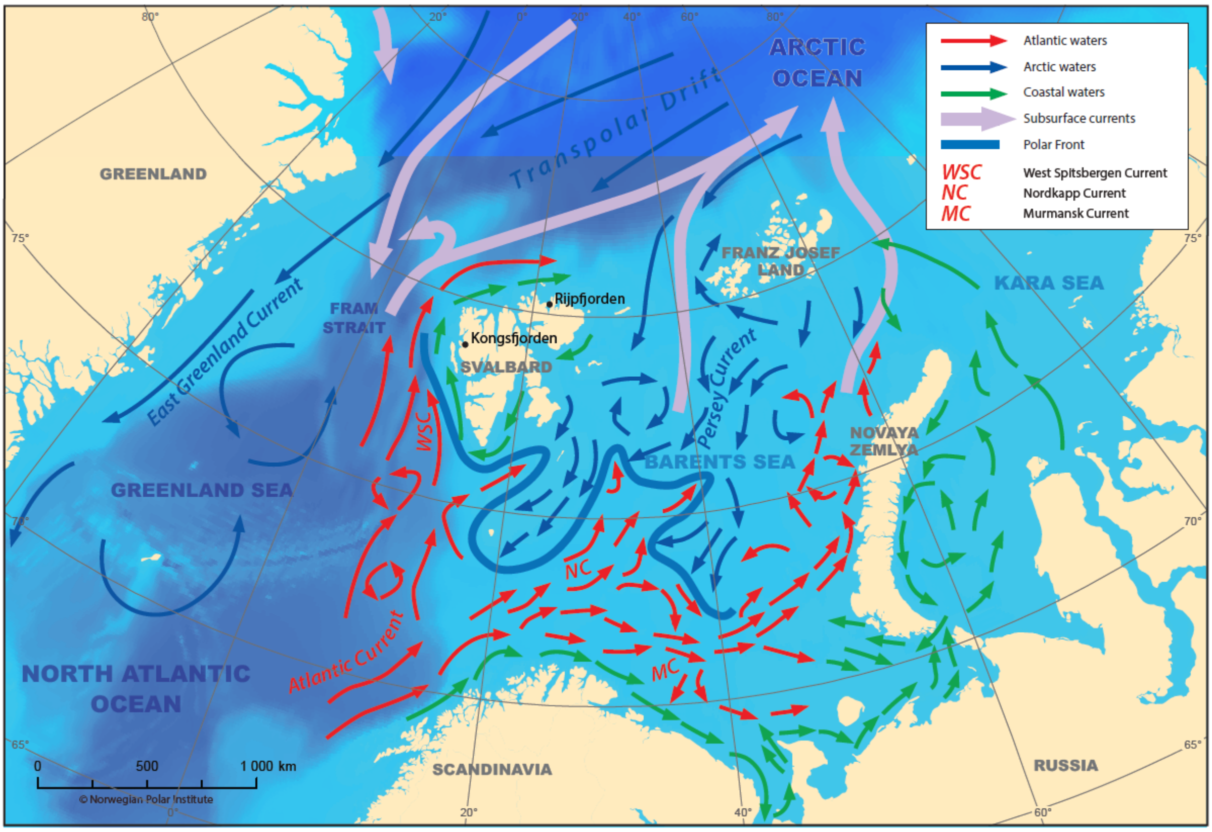


Figure 2-3 Map of the main current systems influencing the ocean climate around Svalbard (Dallmann et al., 2015).

2.4.5 Tide

The tidal plane for Isfjorden is presented in Table 2-6. This is representative for the conditions around a potential FOW site. The extreme surge water levels are also presented.

Table 2-6 Isfjorden tidal planes (Kartverket, 2014)

Tide	Level to Chart Datum (m, CD)
AEP 10^{-4}	2.63
AEP 10^{-2}	2.52
Highest Astronomical Tide (HAT)	2.11
Mean High Water Springs (MHWS)	1.82
Mean High Water Neaps (MHWN)	1.42
Mean Sea Level (MSL)	1.09
Mean Low Water Neaps (MLWN)	0.77
Mean Low Water Springs (MLWS)	0.37
Lowest Astronomical Tide (LAT)	0.00

2.4.6 Sea Ice

As mentioned in Section 2.4.4, due to warm currents, the west coast of Svalbard is mostly free of ice the whole year. An analysis of the Sea Ice Extent (SIE) was conducted using historical data from MET 2021. SIE is defined as the area covered by a significant amount of sea ice, more than 15% concentration. What is apparent is the changing extent of ice in the northern hemisphere as a result of climate change, which is shown in Figure 2-4 over the climatological reference period of 1981-2010. Also of interest is the SIE historical statistics in Svalbard waters over each month which is presented in Figure 2-5.

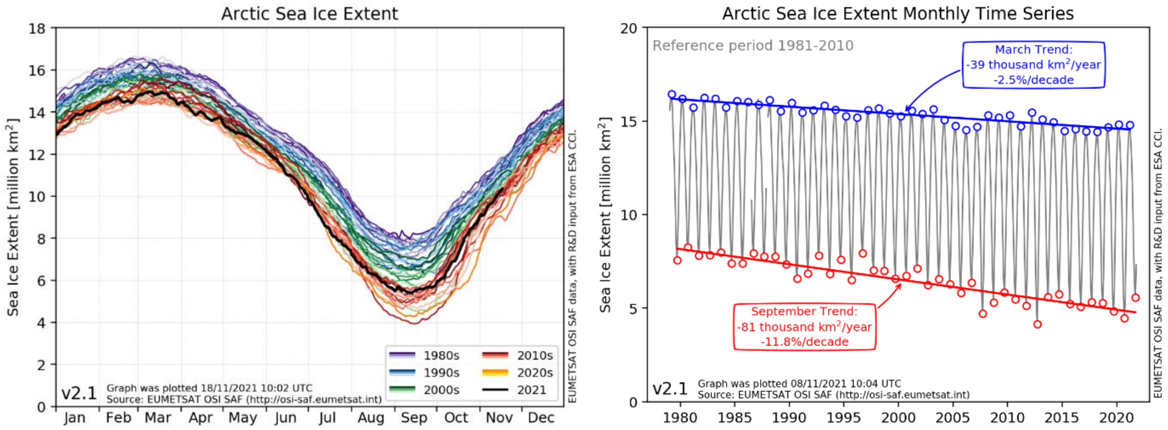


Figure 2-4 Left: Global sea-ice index from EUMETSAT OSI SAF for the northern hemisphere. Right: Global sea-ice index monthly trend for the northern hemisphere (MET, 2021)

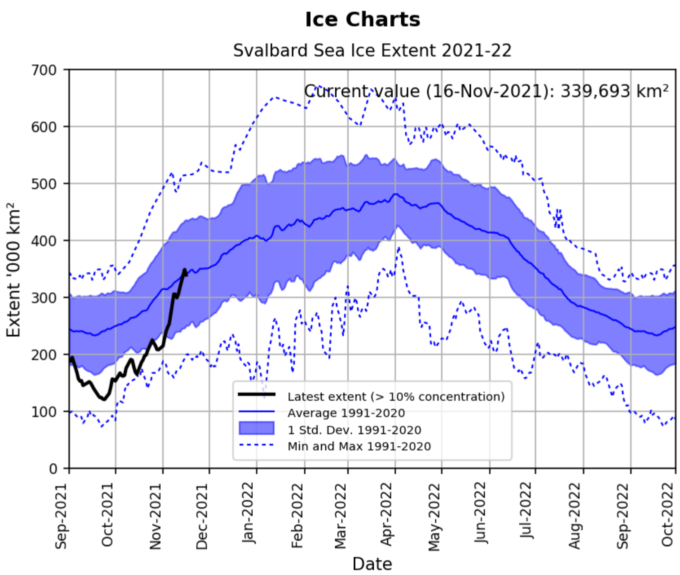


Figure 2-5 Svalbard sea-ice extent from Ice Charts (MET, 2021)

From the above plots it is apparent that the SIE is highest in late February and early March and is reducing every year. As such, one of the largest SIE extents on record was from 1981, and the largest most recent record was in 2013. Historical sea ice charts were analysed to gain a visual understanding of the extend of drifting sea ice around the area of interest on the west coast during the highest extent in early March. The earliest historical sea ice chart for Svalbard available was from 1996 and is shown in Figure 2-6. This chart however has a low resolution for Svalbard and indicates open drift ice with 40% to 60% concentration in the area of interest in the water nearby Longyearbyen. The resolution could be up to 25km, so this averages regions at the intersection of fast ice and closely concentrated drift ice in the shallow waters either side of the entrance to Isfjorden.

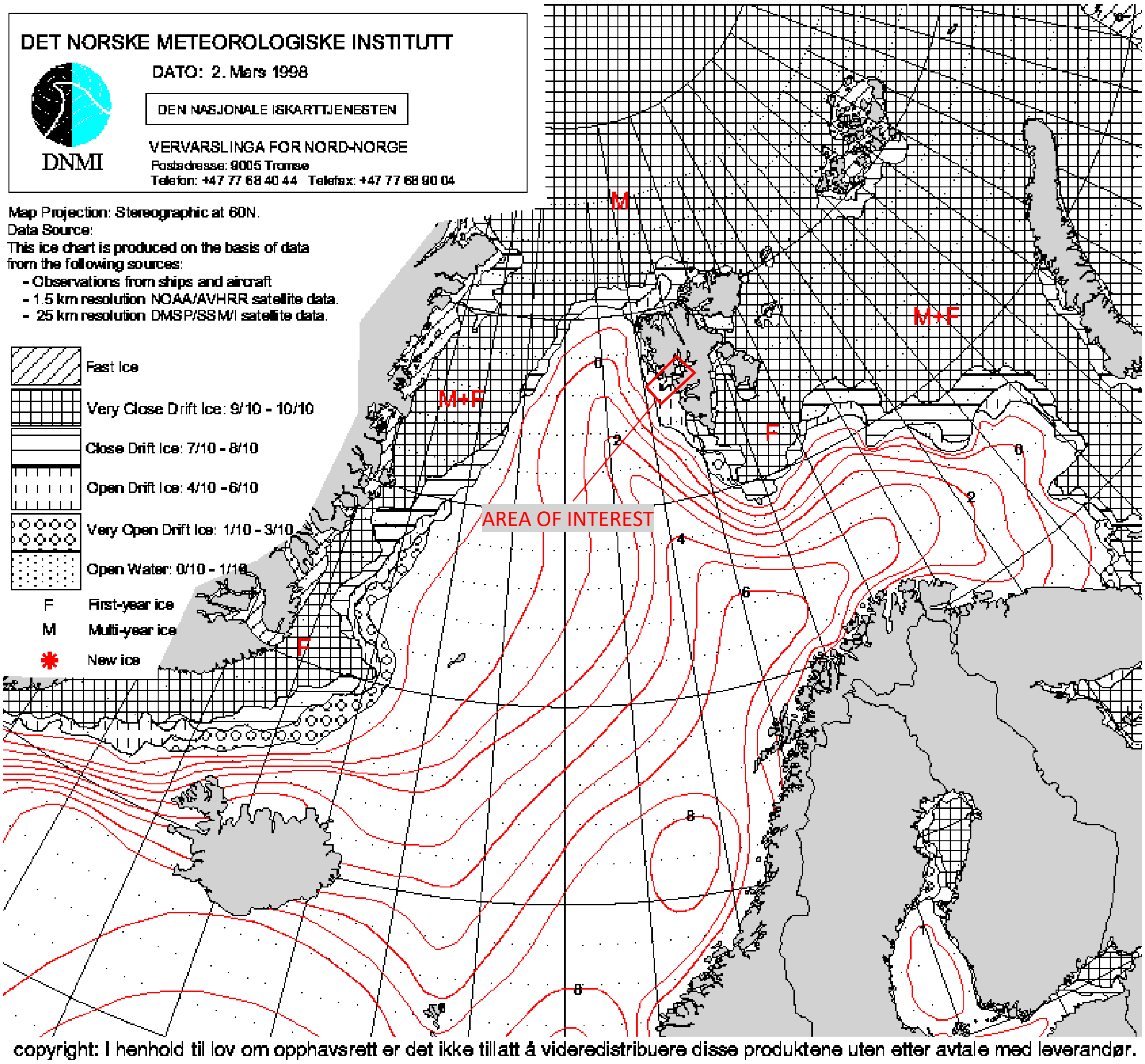


Figure 2-6 Sea Ice Chart from 2 March 1996 (MET, 2021)

For a higher resolution of sea ice around Svalbard, ice charts from the recent high SIE record from March 2013, as well as a more typical SIE record from March 2021 were analysed. These are shown in Figure 2-7 and Figure 2-8 respectively.

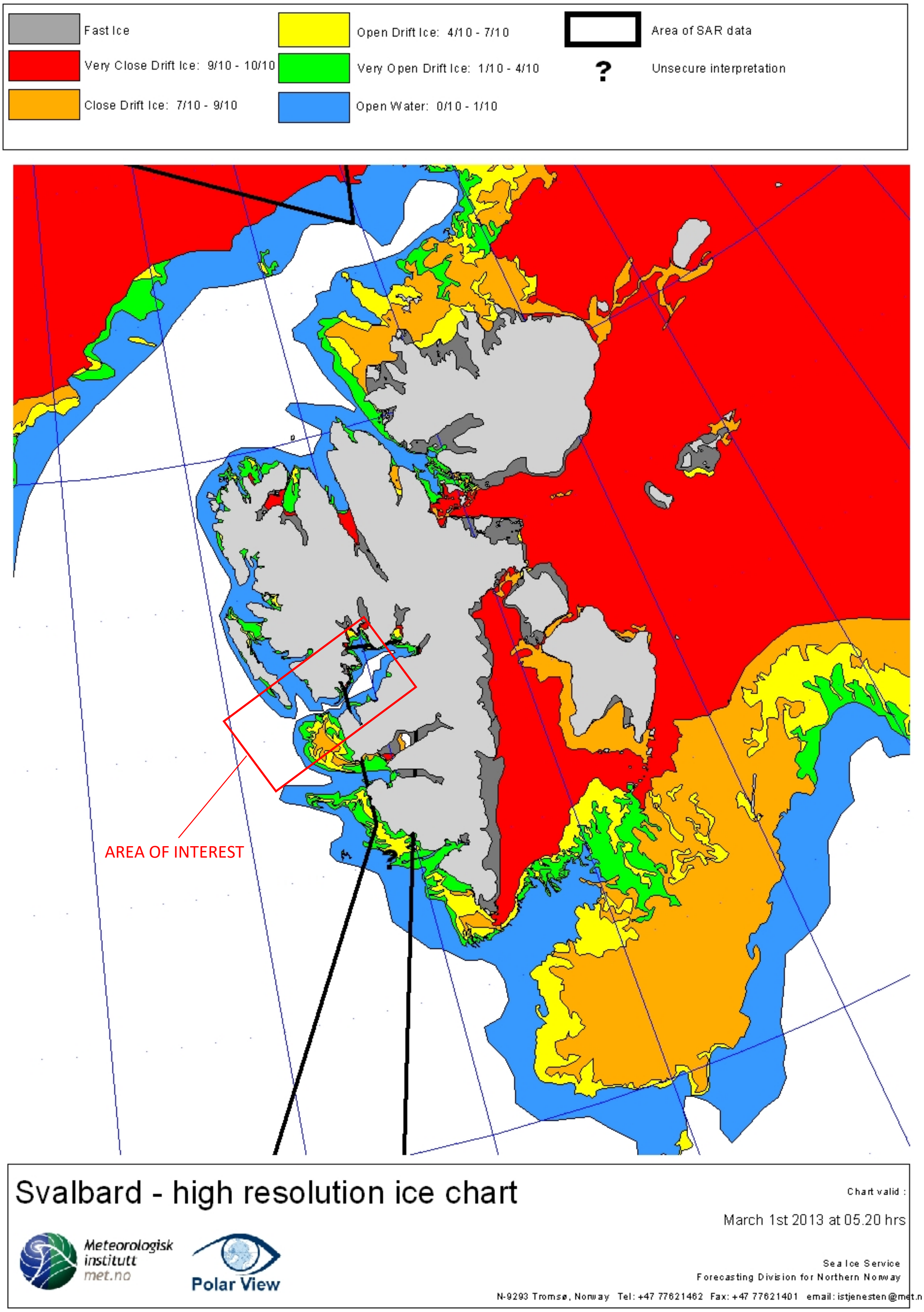


Figure 2-7 Sea Ice Chart from 1 March 2013 (MET, 2021)

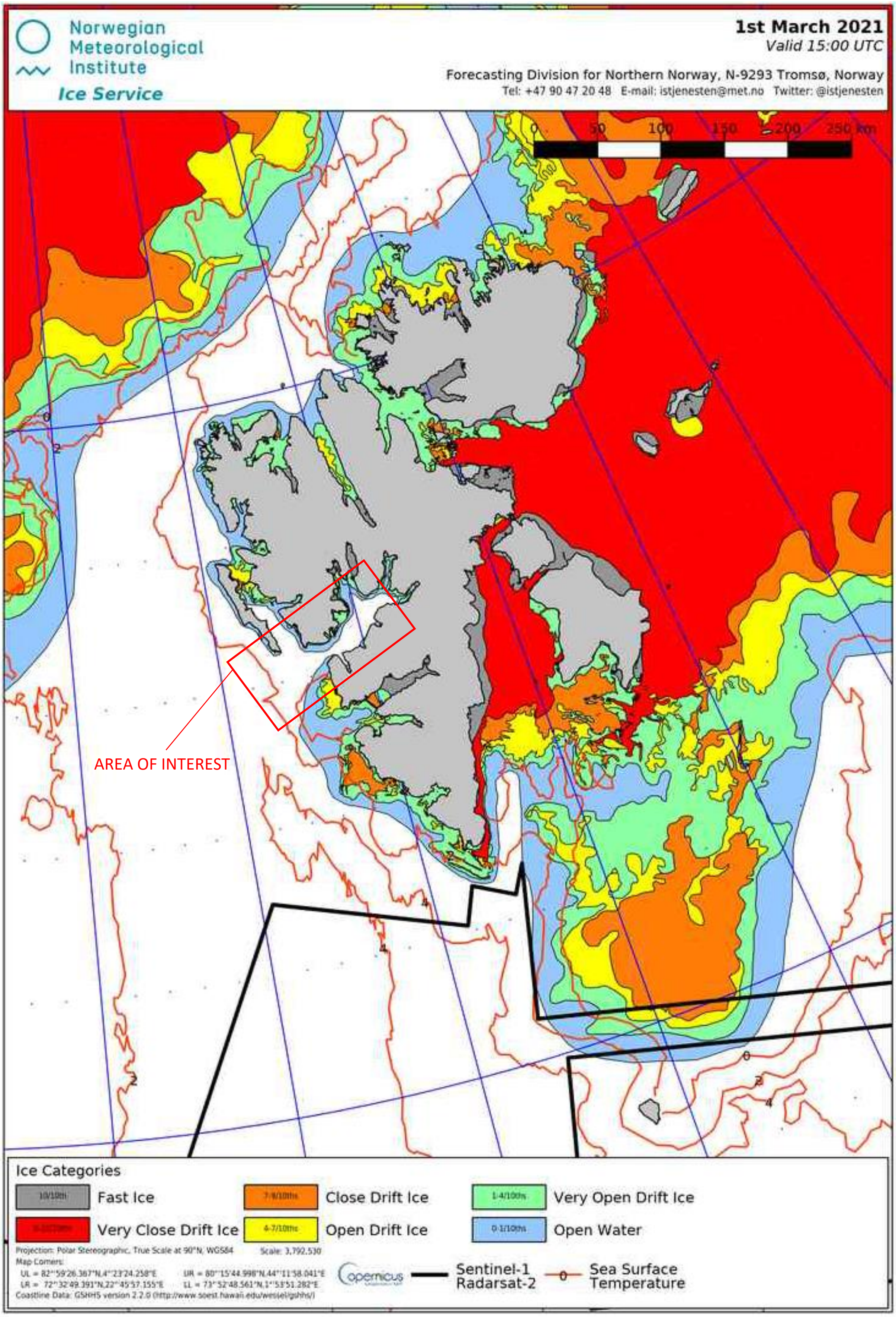


Figure 2-8 Sea Ice Chart from 1 March 2021 (MET, 2021)

From the more recent ice charts, for the region of interest it appears that the conditions are mostly open water with some areas with ice concentration below 10%. There is a region south of the Isfjorden entrance that has a higher concentration of drift ice, particularly in 2013, and this corresponds to a shallow bank (see Section 2.4.8), so it could be sea ice caught between land fast ice, or more likely caught between warm currents circulating Isfjorden and Bellshund. This is confirmed in the literature, where there has been a significant decline of fast ice and drift ice, and only limited drift ice appearing close to land in Isfjorden (Muckenhuber et al., 2016). This is clearly displayed in Figure 2-9. While drifting sea ice can be present around the area of interest, it would likely be of low concentration and only small surface pieces.

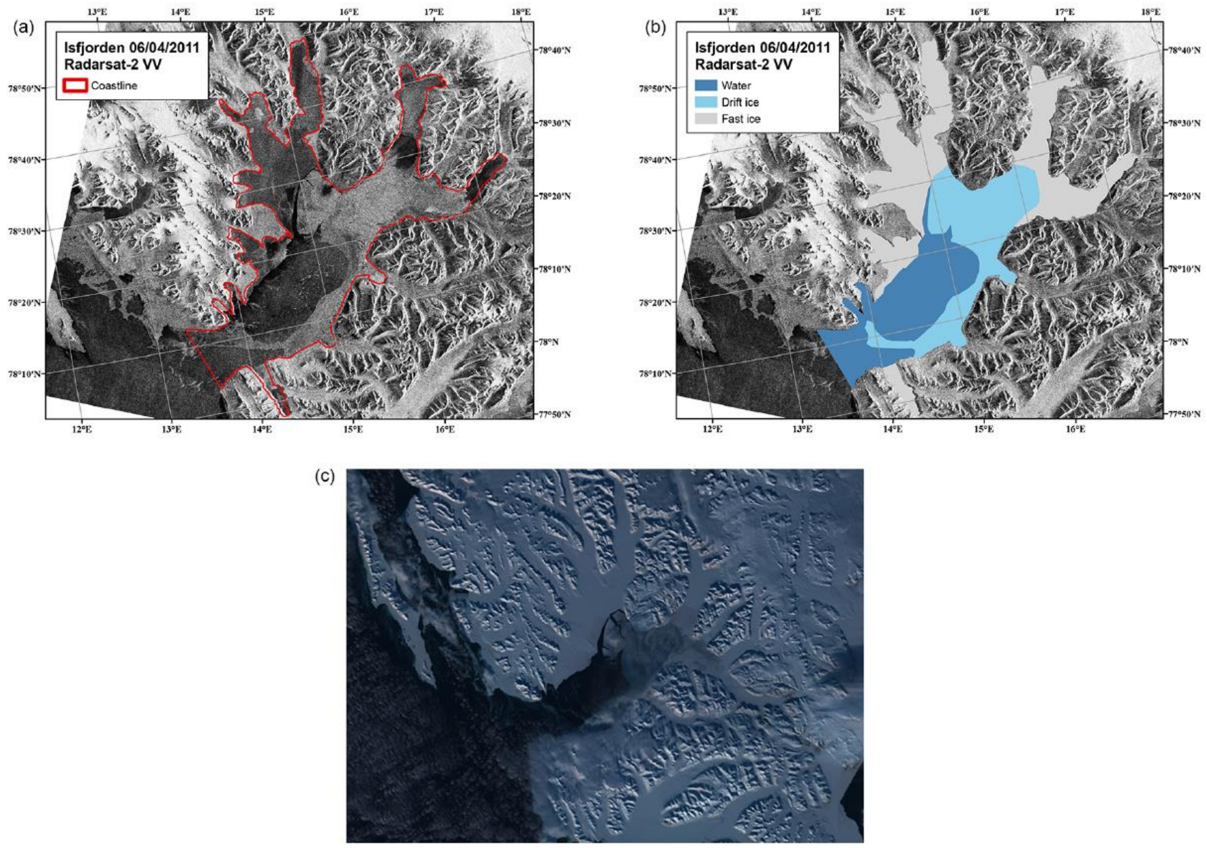


Figure 2-9 Radar-satellite (a,b) and aerial (c) images of Isfjorden taken on 6 April 2011 showing extend of sea ice (Muckenhuber et al., 2016)

2.4.7 Icebergs

While Svalbard itself is a source of icebergs, icebergs drifting from other locations would be considered rare due to the warm southerly currents, see Section 2.4.4. Icebergs in the Barents Sea have generally be found to originate from Franz Josef Land or the northern and eastern side of Svalbard (Broström et al., 2009). At the point of interest, icebergs would most likely need to originate from a glacier terminating in a fjord on the west coast. It would be rare for large icebergs in the Barents Sea to travel north as they have mostly been observed with a southward trajectory and icebergs around Svalbard typically melt quite quickly due to the warmer water (Broström et al., 2009).

During winter, fast sea ice and sea ice cover around the shoreline suppresses the drift of icebergs in the fjords (Dallmann et al., 2015). During the summer months, iceberg drift is more probably at the site coming from the fjord, however with several land and shallow water obstructions and warm water melting the icebergs, threatening ice features would not occur regularly at the region of interest.

2.4.8 Bathymetry Features

The fjords around Svalbard were formed from erosion by grounded ice streams draining ice sheets during repeated glaciations in the last 1.5 million years (Dallmann et al., 2015). Isjorden has 13 tributary fjords and bays, and has a length of approximately 100 km, width of about 20 km and depths up to 500m, see Figure 2-10. An interesting feature is the shallow Isfjord-Banken south of the entrance to Isfjorden. Also note the twin submarine communications cable between Svalbard and the mainland of Norway, as well as a twin cable diverting northward to Ny-Ålesund. There are also several protected areas with marine national parks located north and south of the entrance, roughly demarked by the magenta boundary, refer to protected areas in Section 2.4.11.

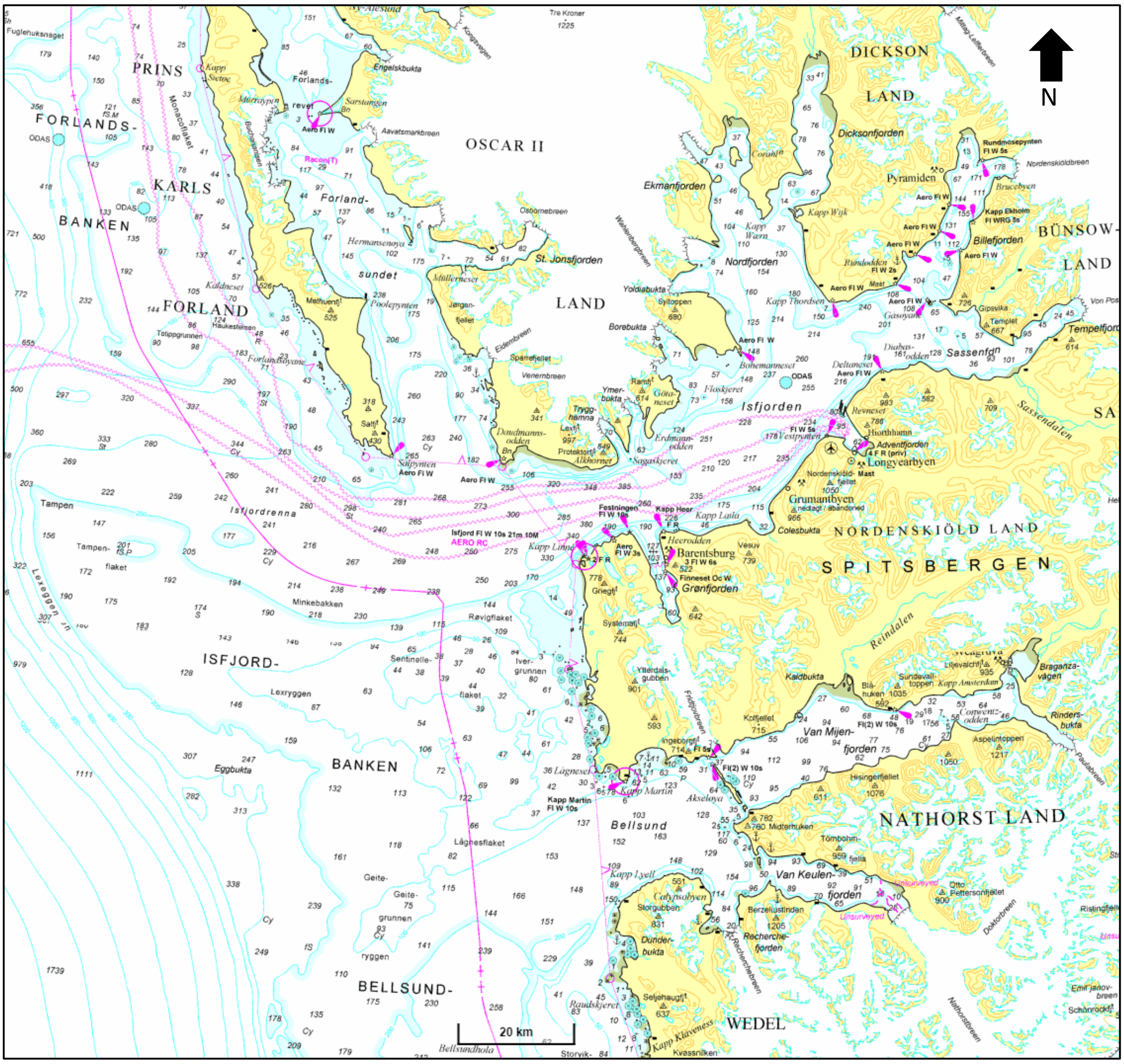


Figure 2-10 Nautical map of Isfjorden (Kartverket, 2021)

The water depth at the likely FOW site, approximately 60km from the entrance of Isfjorden (see reference location in Figure 2-2) would be around 200m. This is within an acceptable range for FOW installations.

2.4.9 Sub-Sea-Floor Geology

A study analysing marine seismic reflection data shows younger sedimentary cover is typical on the seabed around Isfjorden (Blinova et al., 2013). The sediments are received typically from tidewater glaciers and rivers and can be of any grain size ranging from clay to boulders, although clay and silt is typical (Dallmann et al., 2015). The largest deposits in Isjorden are around 4.5 km long, 1.7 km wide and 25 m thick, with a typical minimum thickness of 10m over bedrock (Dallmann et al., 2015). Figure 2-11 shows the cross section from the seismic profiling. The top stratum of the seabed is of interest for the anchoring of the FOW units. The clay deposits would be ideal for suction anchoring.

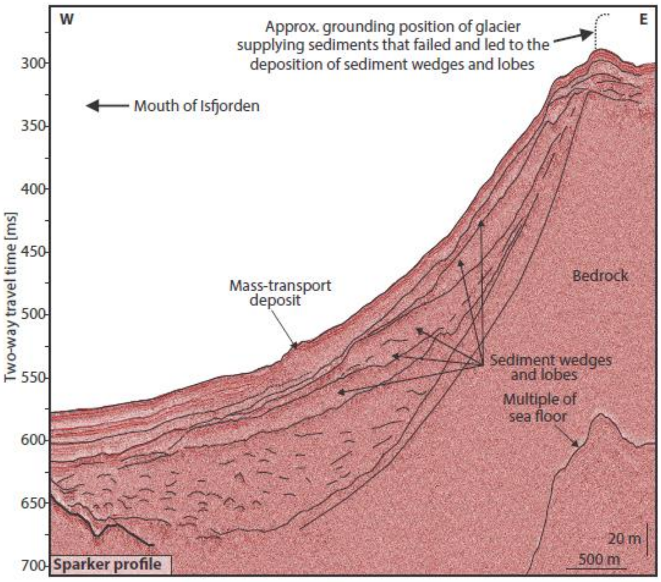


Figure 2-11 Seismic profile towards the mouth of Isfjorden showing multiple sediment wedges and lobes (debris deposits) above bedrock (Forwick & Vorren, 2010)

2.4.10 Water Temperature and Salinity Profile

A study of the water column properties had been conducted using an autonomous underwater vehicle (AUV) performing measurements during a yo-yo manoeuvre across the fjord (Klis et al., 2021). The transect of the measurements and recordings is shown in Figure 2-12.

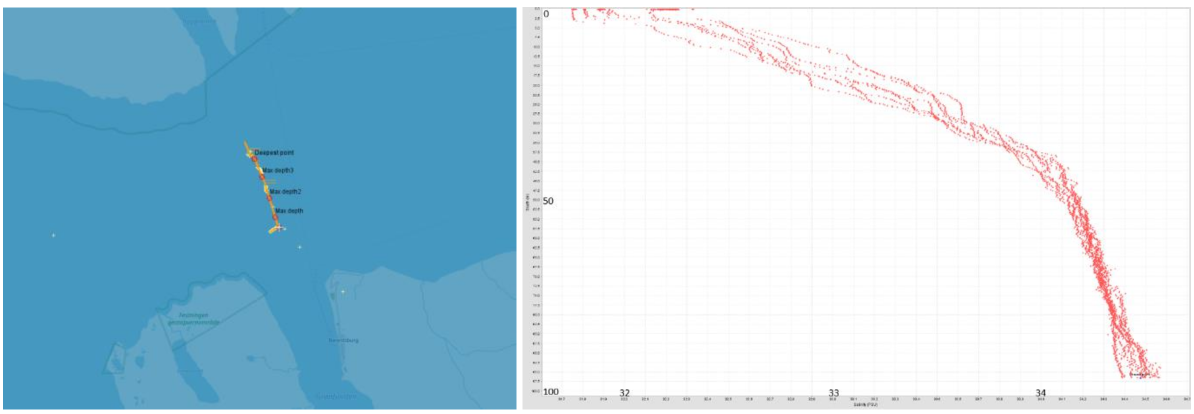


Figure 2-12 Left: AUV data collecting route near Barentsburg. Right: Measured depth vs salinity profile (Klis et al., 2021).

The water temperature is also of interest at the site, and recordings were made along the length of Isfjorden by UNIS (Søreide et al., 2019). The results of the measurements recorded in November are presented in Figure 2-13. Note there would be slight variance in temperatures in the water column based on seasonal factors.

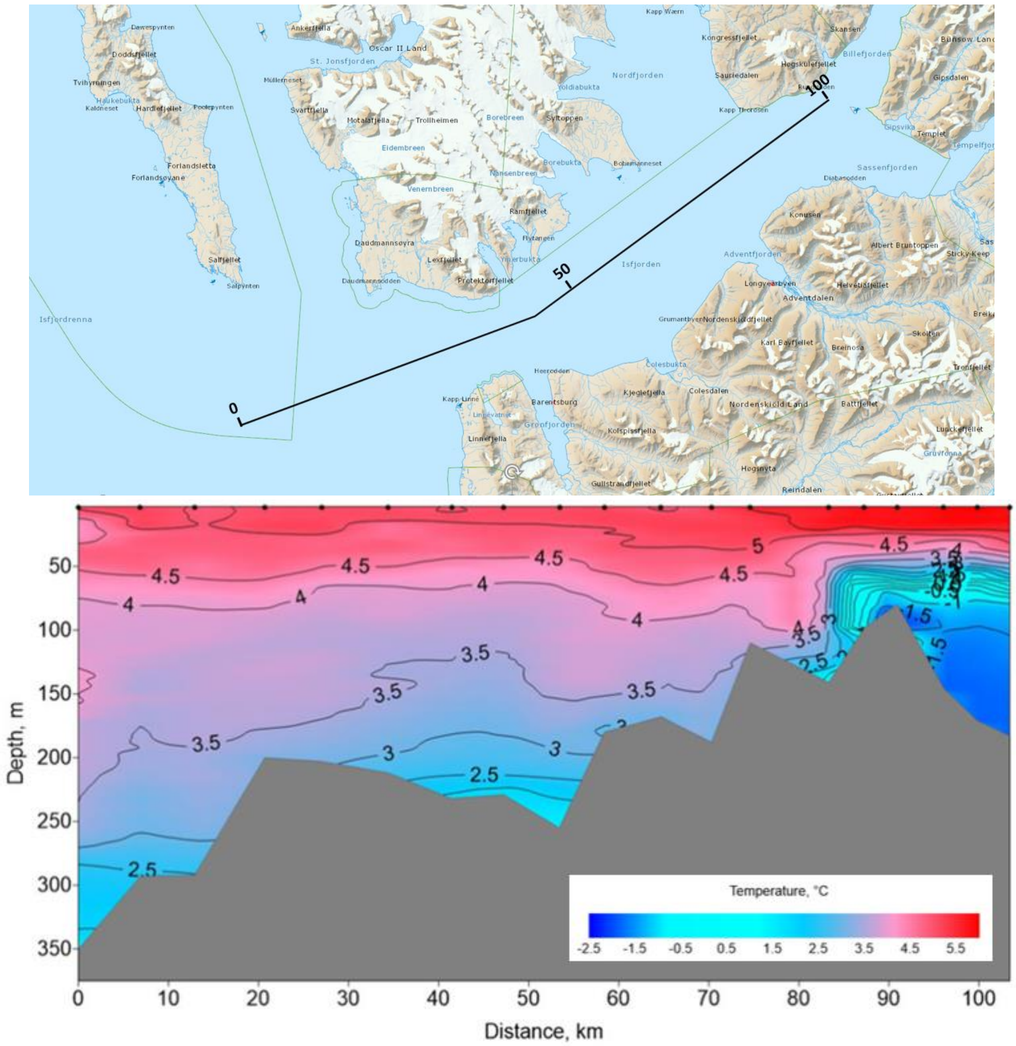


Figure 2-13 Top: Long section of recordings. Bottom: Cross section of temperature at Isfjorden (Søreide et al., 2019)

2.4.11 Flora and Fauna

The flora and fauna around Isfjorden has been well documented. The area around Isfjorden is one of the most lush, containing over three quarters of all vascular plant species found in Svalbard (Barr, 2020). The vegetation found around Isfjorden includes arctic tundra, edge heather, dry reindeer rose rabbits, dwarf birch, cress, arctic bluebell and polar blueberry (Barr, 2020). Many of these species are rare.

The local wildlife is highly productive. In Isfjorden, there is a large production of phytoplankton that feeds the ecosystem of crustaceans and fish including capelin and polar cod (Barr, 2020). The plankton provides a nutritional basis for many seabirds and marine mammals including whales and seals. There are large nesting colonies of seabirds on the banks of Isfjorden as well as many terrestrial species including grouse, reindeer, geese and arctic foxes.

In the fjord it is also common to find many seal and whale species, including ring seals, walruses, fin whales, minke whales and belugas. Polar bears are also regularly seen in the fjord. During the authors 4 month stay in Svalbard, many whales and even polar bears were seen in Isfjorden, see Figure 2-14.

Figure 2-14 Vulnerable marine mammals native to Isfjorden (Drummond, 2021). Top: Fin whales at the entrance of Isfjorden. Bottom: Polar bear family playing on a glacier calving in Isfjorden.

As such, in the area of interest outside Isfjorden there are many vulnerable species that need to be properly cared for during any installation works. There exists several national parks that aim to restrict certain activities in order to preserve the native wildlife. Installation activities will be excluded from these protected areas. The protected regions are shown in Figure 2-15.

Figure 2-15 Location map of National Park protected areas in Svalbard n.t.s. (Sysselmesteren, 2022)

3 FOW Theory

To understand the potential for FOW solutions in Svalbard, the fundamental theory and background should be explored. In this Section, a brief overview of the common FOW solutions will be presented to provide context for the case study.

3.1 Floating Substructures

FOW solutions are best characterised by their floating substructure, with the cost, construction time and methodology greatly reliant on this component (Skår, 2021). As such, the main substructures that are used in industry are introduced in this Section. These are SPAR (Single Point Anchor Reservoir), semi-submersibles and TLP (tension leg platform) systems as illustrated in Figure 3-1 (Castro-Santos & Diaz-Casas, 2016). While other concepts do exist, there are not commonly used in industry and have not been considered relevant to explore in detail for background knowledge.

Figure 3-1 FOW substructure concepts (IRENA, 2016)

3.1.1 Buoyancy Stabilised Platforms

Semi-submersible and barges are types of buoyancy stabilised platforms that have been used in the FOW industry. They depend on the volume of the submerged body for stability and mooring systems for station-keeping. The barge typically has a larger waterplane area while semi-submersibles use columns. The buoyancy stabilised platforms are heavy weighted and have a much lower draft than alternative platforms, and as such have lower roll, pitch and yaw performance due to static and dynamic stability (Rindvoll & Erikstad, 2020).

Semi-submersibles have been used extensively in the oil and gas industry for their stability in waves (Castro-Santos & Diaz-Casas, 2016). In FOW, the structure typically comprises of three ballasted columns that provide the submerged volume and a supporting frame connecting the columns and providing rigidity and a deck. There is a trend for turbines to increase in size and move further offshore in deeper water, so the semi-submersible platform has been undergoing upscaling to accommodate the larger loads (Leimeister et al., 2016). This has resulted in optimised semi-submersible solutions that have become an attractive option for FOW farm development. The semi-submersible substructure can be constructed on shore and towed to site which can be an advantage and offer greater program flexibility against other options (Thiagarajan & Dagher, 2014). They do however have a complexity in manufacturing due to the welding of multiple steel components.

3.1.2 Mooring Stabilised Platforms

The TLP is a floating structure that is stabilised by taut mooring lines that provide stiffness to resist dynamic motions (Castro-Santos & Diaz-Casas, 2016). The restrained platform provides greater performance for the turbine however the platforms are comprised of complicated mooring arrangements. Typically, a TLP is comprised of a central column with three or four arms that support tensioned tendons. The tensioned tendons submerge the floating platform deeper to restrict roll pitch and heave motions. The tendons are restrained to the seabed using tension piles, gravity anchors and suction anchors.

Construction and installation are typically complicated, and ballasting is required during installation and removal following anchor installation. Maintenance planning is also difficult with restrictions of towing and complex components that submerged being difficult to access. These are the primary shortcomings to the TLP designs. TLP is mostly a concept for FOW, with no major installations deployed currently.

3.1.3 Ballasted Stabilised Platforms

SPAR platforms are the main ballasted stabilised platform, typically comprised of a single cylindrical steel or concrete vertical foundation with a small waterplane area (Rindvoll & Erikstad, 2020). The SPAR is ballasted with water or solid material to maintain stability and as such has a deep draft. A deep-water quay is then required for construction before it can be towed to site which can be a disadvantage depending on port availability (Castro-Santos & Diaz-Casas, 2016). Station-keeping is provided by a mooring line system, which also counteracts aerodynamic loads on the turbine.

The shape of the foundation is susceptible to vortex-induced vibrations (VIV) which can lead to fatigue. To counteract the VIV, it is common to employ strakes or other drag and total mass manipulating structures which increase the complexity of the design.

3.1.4 Hybrid and Concept Platforms

Most floating substructures can be categorised as above, however alternatives employing a combination of platform characteristics are often explored at concept level. There are also concepts that aim to integrate wave and solar energy into a single system (Qu et al., 2021). There are also alternative concepts to single turbine platforms, integrating multiple turbines on a single platform, however close placement of turbines can reduce efficiency due to the generated wakes (Castro-Santos & Diaz-Casas, 2016). These options are still in concept development and may take many years before they are adopted by industry.

3.1.5 Comparison

During FOW concept development, the floating substructure needs to be selected. The comparison between the options needs to consider the strengths and weaknesses in terms of construction, installation, maintenance, and operations. The concepts may also be selected based on availability of port and construction resources and environmental conditions that are local to the site.

An important difference between the three main substructures is the global responses. Due to the coupled hydrodynamics and aerodynamics, the platform behaviour shouldn't be evaluated separately, and experimental works have been conducted to properly evaluate the dynamics of the concepts. Such an experiment includes a scaled physical model of the three concepts which is excited by both wind and wave forces. The natural frequencies resulting from these experiments is summarised in Figure 3-2.

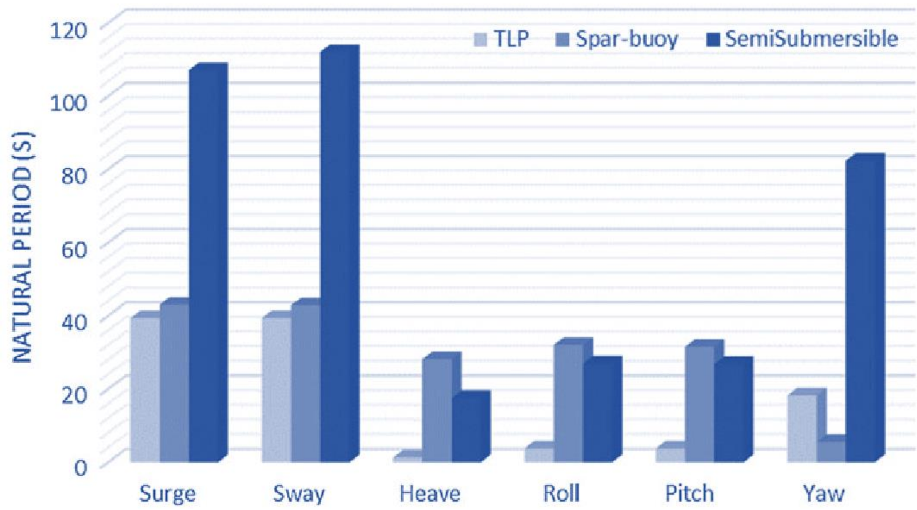


Figure 3-2 Natural periods of floating substructure concepts from scale physical models (Castro-Santos & Diaz-Casas, 2016)

Surge, sway, and yaw natural periods are significantly longer for the semi-submersible in comparison to the TLP and SPAR. The TLP has shorter natural frequencies in all motions due to the stiff structure. The longer natural frequencies can be a disadvantage particularly when considering the aerodynamic performance and fatiguing of the turbine. A summary of general strengths and weaknesses is then presented in Table 3-1. Each concept has unique advantages and disadvantages, and concept selection can be difficult.

Table 3-1 Summary of strengths and weaknesses of floating substructures (Skår, 2021)

Substructure	Strengths	Weaknesses
Buoyancy Stabilised Semi-submersible	▪ Shallow draft ▪ Shallow water assembly ▪ Simple vessels required for installation ▪ Onshore turbine and substructure assembly ▪ Mass production available ▪ Stable for towing	▪ Complex steel structure ▪ Difficult construction ▪ Complicated welding ▪ Difficult ballasting systems ▪ High structural mass for ballasting ▪ High material cost ▪ Complex mooring ▪ Highly dynamic
Mooring Stabilised TLP	▪ High dynamic stability ▪ Simple fabrication ▪ Preassembly possible ▪ Small footprint ▪ Less materials in mooring ▪ More efficient turbine	▪ Difficult installation ▪ Complex mooring system ▪ Not commonly used in industry ▪ Towing difficulty ▪ Maintenance difficulty ▪ Cost in construction ▪ Large forces on tendons
Ballasted Stabilised SPAR	▪ Simple hull geometry ▪ Small waterline area ▪ Simple mooring system ▪ Simple ballast system ▪ Stable ▪ Mass fabrication ▪ Proven track record	▪ Deep draft ▪ Deep water assembly ▪ Complicated turbine assembly ▪ Difficult towing operations in and out of port ▪ Material usage

3.2 Mooring and Anchoring Systems

3.2.1 Mooring Lines

The floating substructures need to be secured to the seafloor for station-keeping, and this is typically achieved with a mooring and anchor system that can resist environmental loading and operational procedures (Castro-Santos & Diaz-Casas, 2016). The most common forms of mooring configurations are either catenary as used on semi-submersibles and SPAR solutions, or taut-leg lines used on TLP systems. Catenary mooring consists of several lines hanging freely on the seabed, with the restoring force mostly provided by the weight of the chain line. They can incorporate buoys and complex shape arrangements as well, however generally they require little precision in their placement which reduces installation costs. Shared mooring systems can also be one of the most cost effective solutions in reducing mooring costs (Munir et al., 2021).

3.2.2 Anchor Systems

There are a number of anchoring solutions available, and typically drag anchors, pile anchors, suction anchors or gravity anchors are used, see Figure 3-3. The selection of the anchor type mainly depends on site conditions and the expected loading from the mooring lines.

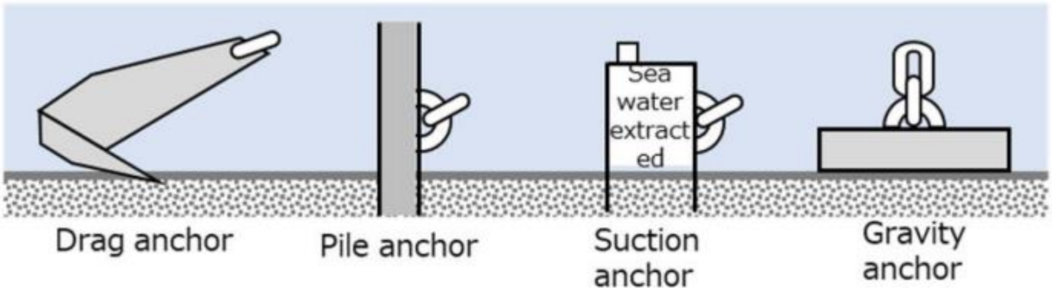


Figure 3-3 Mooring anchor systems (Zhao, 2021)

Drag anchors are commonly used for non-permanent moorings for vessels. They have a triangular geometry that allowed them to dig into the seabed when pulled horizontally. Drag anchors perform best when they are buried in the seabed and a horizontal load is applied, and they do not perform well for vertical loads. As such, this anchor would not be suitable for a TLP.

Pile anchors consist of long cylindrical tubular piles that are driven or vibrated into the seabed. They are able to resist horizontal and vertical loads by soil friction. It is able to withstand large loads and is suitable for TLP. The installation however is more costly than other options and is difficult to remove. The use of a hammer is also limited when there is a presence of marine mammals in the area, and more equipment needs to be mobilised to install these anchors.

Suction anchors are commonly used for anchorage of offshore structures (Zhao, 2021). This anchor is a cylinder container with an opening at the bottom for soil to penetrate. The anchor is installed by pumping water from inside the pile to create a pressure difference that embeds the pile and creates suction to the seabed. This anchor can be easily installed and has great vertical and horizontal load capacity. Suction anchors have been used successfully in FOW projects.

Gravity anchors consist of simple geometries that support horizontal and vertical loads by seabed friction and their own weight respectively. Overtime, the heavy anchor will sink into the seabed which will progressively increase the load capacity. This anchor is versatile however the units are large and heavy which poses installation difficulties.

3.3 Wind Turbines

The wind turbine converts wind energy to electrical energy through the rotation of blades driving a power generator. Wind turbines have been used in large onshore projects for many years, so the turbine technology has been through ongoing development and optimisation for some time. The turbine components used in the FOW solutions are not substantially different to those onshore (Skår, 2021). There is signific amounts of literature on the onshore wind turbine development which will be briefly introduced in this section. The big difference between onshore and offshore turbines is the foundation structure, which is more technical and dynamic for a floating solution. Wind turbines constitute the second highest component cost of a FOW development, see Figure 3-4, so there is a great need for understanding the turbine development for its selection in a project.

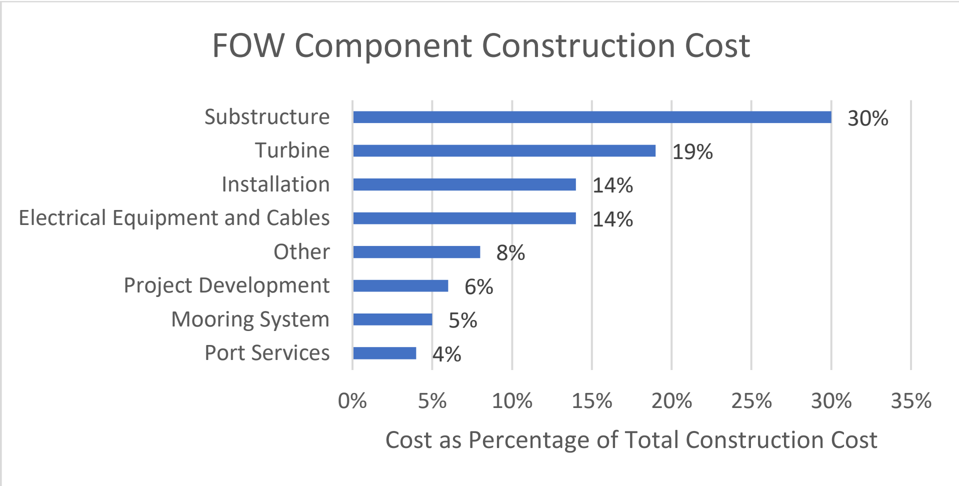


Figure 3-4 FOW component construction costs (Zhao, 2021)

There are two common types of wind turbines currently in production. The horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). To date, a HAWT with three rotating blades is predominately used and will be the turbine of focus for this study. This turbine consists of a tower with a mounted nacelle containing several components which contribute to the energy conversion process. The main components including the turbine rotor, transmission system, generator, power electronics, control system, transformer, and connection to the grid, see Figure 3-5 (Letcher, 2017).

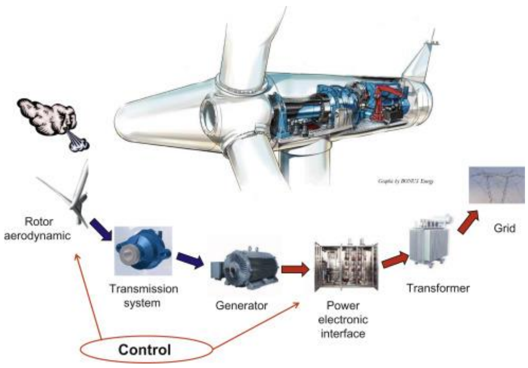


Figure 3-5 Turbine components (Letcher, 2017)

When categorising different turbine options, the power rating is most often used. Most FOW concepts today use a turbine with a power rating of 10MW. As wind technology evolves, the blades increase in size and the potential energy output increases. There has been significant research and development dedicated to upscaling the turbine output to 12MW and even 15MW, however these are still conceptual and not used in production currently.

3.4 Power Cables

To export the power generated from the turbines power cables are installed. The power cable is connected through the turbine by a service pipe which provides protection from the splash zone. Turbines are connected to each other through inter-array cables before they are fed into a substation and a HVDC export cable to land (Rindvoll & Erikstad, 2020). The power cables are dynamic around the floating structure to cater for movements, and statically submerged and protected from trawling between the farm and land.

3.5 Historic Development and Trends

The first multi-megawatt wind turbine was developed in Denmark in 1978 (Nissen et al., 2009). With a capacity of 2MW and rotor diameter of 15m, it far exceeded the output of the 10-110kW competitors of the time. Since then, turbine technology advances have resulted in much larger turbines with greater capacity. This trend is observed in Figure 3-6 below.

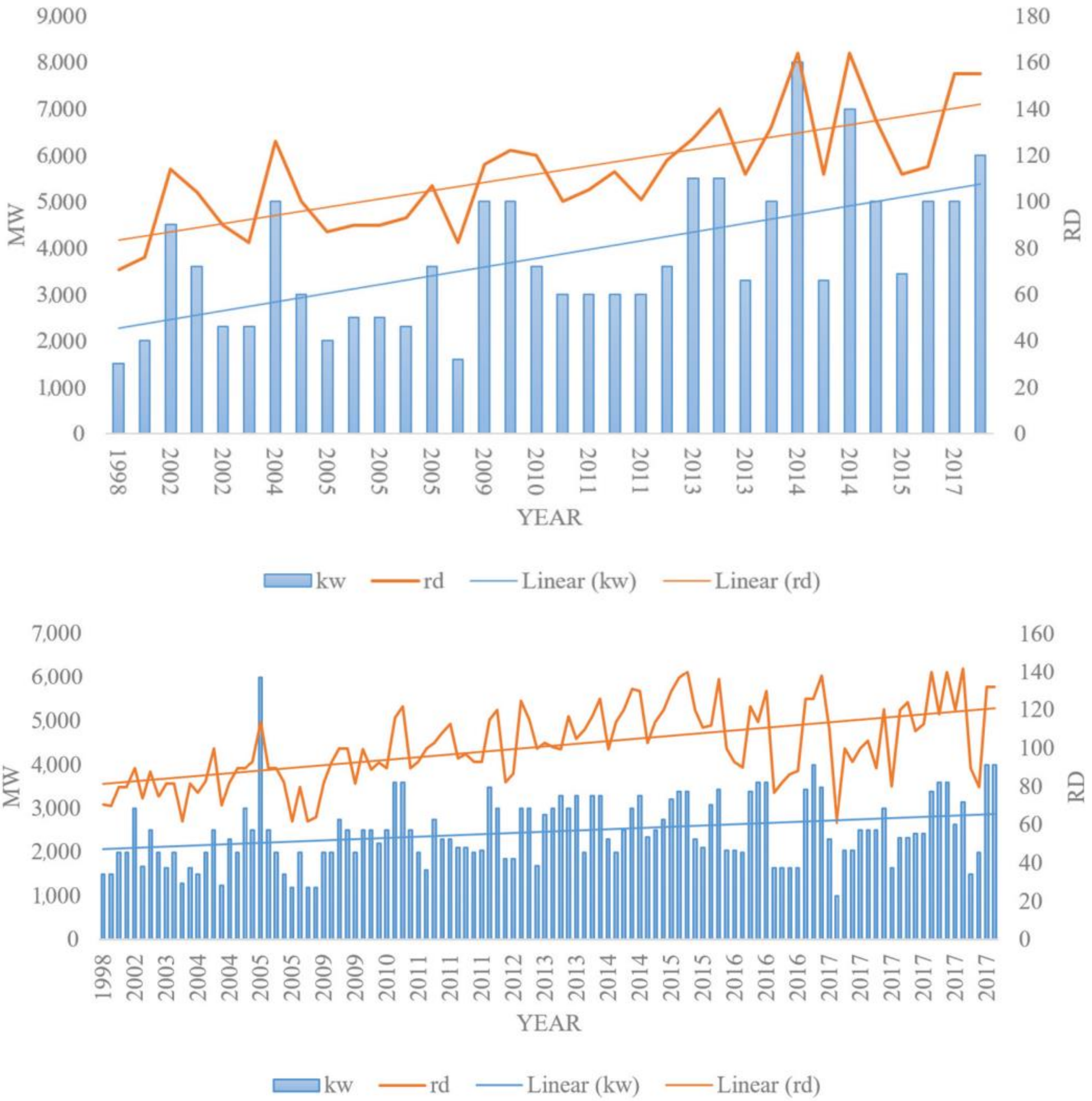


Figure 3-6 Development of rotor diameters (RD) and power output over time (Enevoldsen & Xydis, 2019). Top: Onshore. Bottom: Offshore.

In new offshore developments, there is a substantial difference in the size of turbines compared to onshore structures. This increases the potential power output of the offshore turbines due to the higher mean wind speeds than those present onshore and fewer regulations on the maximum allowable size of the turbines. As the turbine size increases, the development costs become more scalable and cost savings can be observed that offset some of the cost increases of a marine project (Henderson & Witcher, 2010).

The floating foundation structure has also undergone significant development in the recent past. The first floating wind farm, the 30MW Hywind Scotland pilot project, was completed in 2017 and demonstrated the feasibility of SPAR FOW units (Equinor, 2017). In this project, the floating SPAR structures were towed 500km from the production yard in Stord Norway to Aberdeenshire Scotland. This project cost 2 billion NOK to complete. The first semi-submersible floating wind farm, the 25MW WindFloat Atlantic in Portugal, was completed in 2020 (OE, 2020). This wind farm consisted of three 8.4MW turbines that were towed from a shallow port to the field.

Following from the success of these floating wind farms, several other projects are currently underway. A summary of these main projects is included in Table 3-2. It is apparent that the turbine ratings have increased in relation to the wind farms introduced above. This supports the trend that larger turbines with a larger capacity are being developed for the scalable reduction on cost.

Table 3-2 FOW projects currently underway or scheduled (Zhao, 2021)

Expected Completion	Project	Developer	Country	Capacity (MW)	Turbine Rating (MW)	Foundation
2022	Eoliennes flottantes du golfe du Lion	Engie, EDP, Caisse des Depots	France	30	10	Semi-sub
2022	EolMed (Gruissan) Pilot Farm	Qair, Total	France	30	10	Barge
2022	Provence Grand Large	EDF Energy	France	25.2	8.4	TLP
2023	Eoliennes flottantes de Groix et Belle-Ile	Shell/EOLFI, China General Nuclear Power Group (CGN)	France	28.5	9.5	Semi-sub
2022	Hywind Tampen	Equinor	Norway	88	8	Spar
2022	AFLOWT	EMEC, SEAI, Saipem	Ireland	6	6	Hexafloat
2023	Aqua Ventus I	University of Maine	US	11	11	Semi-sub
2022	Goto Offshore Wind Power	Toda Corporation	Japan	22	2～5	Spar
2021	Jie Yang	Three Gorges Corporation	China	5.5	5.5	Semi-sub
2026	Donghae-1	Korea National Oil Corporation, Equinor	South Korea	200	Unknown	Spar

3.6 Marine Operations Considerations

The planning process of marine operations is important to ensure that the procedures are safe, and the risk is as low as reasonably practicable. For a FOW project, there will be several activities during the construction and installation that can be classified as marine operations. This includes crane lifting operations using heavy lift vessels, sea transport by barge and towing with tugs, cable installation with the pipelaying vessel and subsea installations. Towing is one of the most common marine operations and includes transporting the FOW units to or between sites as well as transporting objects such as anchors and mooring systems.

Clear methodologies and coordinated procedures are required to manage the risks associated with marine operations. Often a point of no return is defined during an operation, where an activity cannot be reversed past a certain stage. This is typically defined in lifting operations and can also be applied to towing over long distances, where a safe harbour may need to be sought in case of an emergency. Careful consideration to environmental conditions is required for conducting operations safely. The duration of a marine operation is defined by the reference period (T_R), which is the sum of the Planned Operation Period (T_{POP}) and contingency time (T_C) which covers uncertainty and weather sensitivities, see Equation 3.1.

$$T_R = T_{POP} + T_C \tag{3.1}$$

Weather restricted operations should be planned to have a limited duration, ideally less than 72 hours. A favourable weather forecast is required to ensure that the operation is conducted inside environmental limitations. Depending on the complexity and risks of the activity a meteorologist may be required on site. This would likely be required for a turbine towing operation. A weather window is also defined for an operation. The weather window is a period of time set by a weather forecast (OP_{WF}) which is sufficient for an operation to be completed with conditions below the operation limit (OP_{LIM}). A factor of safety is also added to this time to account for the uncertainty in the weather forecast.

These operational considerations are environmental limitations are important to safely conduct the works. For FOW developments, the most economical installation method is assembling the substructure and turbine onshore and then towing to site. Whilst onshore in a protected port, environmental conditions are typically more favourable reducing the risk of downtime to operations. The marine operations are the high-risk tasks to the project. Downtime is extremely expensive while a vessel is mobilised, so it is important to schedule tasks during favourable weather periods like summer. The successful towing of the FOW units to site with towing vessels or tugs is highly dependent on weather. Light construction vessels or heavy lift vessels installing the mooring lines and anchors also depend on favourable weather conditions. These operational limitations imposed by weather will be further explored at the Svalbard site through a simulation of downtime, see Section 4.3.

3.7 Impact on Environment

While wind turbine solutions are often viewed as attractive renewable solutions due to the lower environmental impact, they are still quite disruptive to local habitats. During construction, habitats are physically disrupted by the intrusive footprint of the structure and operating machinery. During power production and operations, noise and disturbances often result in loss of habitat. Bird species are also impacted by turbines, with collision risks changing migration patterns (Tennbakk et al., 2018). In addition to the biodiversity impacts, the visual and noise impacts can affect tourism and quality of living. Many of these impacts are reduced by offshore placement of the turbines, however electromagnetic fields and acoustic disturbances still impact on habitat. There are also positive impacts through habitat gain around the founding and mooring structure as well as protected fishery exclusions zones.

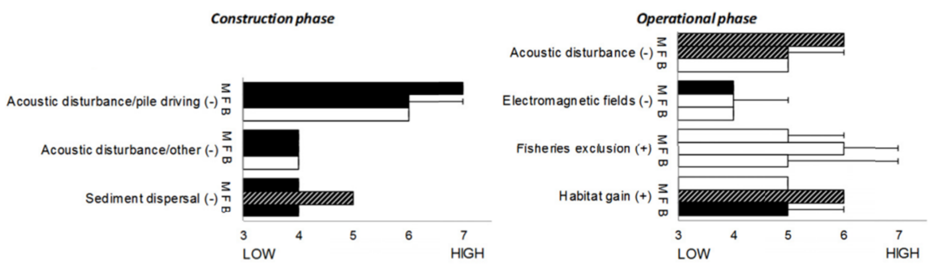


Figure 3-7 Summary of impacts from FOW on marine mammals (M), fish (F) and Benthos (B) (Bergström et al., 2014)

4 Case Study

An example case study of a possible FOW concept has been developed in order to determine whether a possible solution is feasible in Svalbard. In this section, the concept case will be assessed for feasibility against the detailed site conditions explored in Section 2.4. An ice loading simulation and waiting on weather (WOW) simulation will be conducted on the concept selection.

4.1 Concept Selection

4.1.1 12MW WINDMOOR FOW Turbine Concept Selection

The 12MW WINDMOOR FOW design is currently being developed as an upscale from similar 10MW models that have been successfully implemented in the field. Whilst 10MW turbines are commonly used in the market today, the trend is to increase the size of the turbine for greater output and more scalable production. 15MW turbines are also likely to be featured soon, with the National Renewable Energy Laboratory, Denmark Technical University and University of Maine partnering up to develop the International Energy Agency 15MW turbine concept (Gaertner et al., 2020). While larger scale turbines are identified as being up and coming, from past trends the turbine ratings appear to increase more gradually. In this study, it is therefore anticipated that a 12MW turbine will be close to development phase to able to be implemented in Svalbard. Based on historical trends, such a turbine may be in the field within the next 3 to 5 years, which aligns well with the timeline of the coal power plant shut down in Longyearbyen.

As such, the 12MW WINDMOOR FOW turbine concept has been selected for this case study. While significant work has been dedicated to understand the concepts mooring system and platform hydrodynamics (Souza et al., 2021) there has not been any research to date on ice loading or challenges to the concept in arctic environments. This will form the basis for the case study to determine whether a standard concept can be applied at the site. A conceptual image is provided in Figure 4-1 below.

Figure 4-1 12MW WINFMOOR FOW turbine and semi-submersible concept

This turbine was analysed in previous case studies (Klis et al., 2021) due to its upgrade in power rating, larger size, flexible deployment and likely inclusion in future Equinor projects. Details of the concept are provided in Table 4-1. These dimensions and details have been modelled in the ice loading assessment and the WOW simulation.

Table 4-1 12MW WINDMOOR Properties

Property	Value
Column Diameter (m)	15.0
Column Height (m)	31.0
Column Centre-centre Distance (m)	61.0
Pontoon Width (m)	10.0
Pontoon Height (m)	4.0
Total Mass (t)	14176.1
Draft (m)	15.5
Centre of Gravity Coordinates (m) [x,y,z]	[0.0,0.0,4.23]
Radii of Gyration (m) [x,y,z]	[43.7,44.2,30.3]

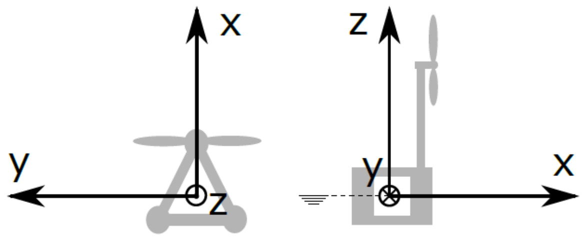


Figure 4-2 Local coordinate system at waterline and plan taken from the geometric centroid

4.1.1.1 Semi-Submersible Floating Substructure

As established in Section 3.1.1, the semi-submersible structure is an established platform in the oil and gas sector. The structure is reliable and has been implemented in FOW projects previously. The structure is attached to the seabed using mooring lines and suction anchors which allow the concept to be in deep waters. The suction anchors will perform very well in the ideal founding conditions of clay as identified in Section 2.4.9. Semi-submersible structures for FOW turbines typically have a triangular base with three hollow cylinders (Liu et al., 2016) which is also seen in the 12MW WINDMOOR concept. The wind turbine is installed on one of the cylinders while the remaining two cylinders are ballasted to balance the structure.

The structure can be fabricated in shallow waters which is advantages for flexibility in the construction program and when considering the likely port selection as described in Section 4.1.2. The semi-submersible has benefits over a SPAR or Tension Leg Platform at this site due to the ability for onshore assembly and stability for towing to the remote location (Thiagarajan & Dagher, 2014). There is also a potential for mass fabrication, which would lower costs if the units can be procured from locations outside of Norway. The units can then be towed to site by tugs which simplifies the offshore operations. As such, for a challenging arctic site, any simplifications to the project would be welcome and such a concept would likely be favourable.

4.1.1.2 Wind Turbine

The wind turbine in the concept has a 12MW output rating, which has been upscaled from the IEA 10MW using the classical upscaling rules. The main properties of these turbines are shown in Table 4-2. These properties have been used in the analysis of wind demand and power output requirements for the Longyearbyen settlement. The rotor diameter and hub height are of particular interest in the feasibility phase of the project, as the wind outputs are mostly related to these variables.

Table 4-2 Properties of the IEA 10MW and WINDMOOR 12MW turbines

Parameter	IEA 10MW	WINDMOOR 12MW
Rated electrical power (MW)	10	12
Specific power (W/m2)	324.8	324.8
Rotor diameter (m)	198	216.9
Hub height (m)	119	131.7

The expected power output of a single turbine was estimated using the 3-hour NORA10 hindcast data introduced in Section 2.4.2 and the power curve as outlined below.

4.1.1.2.1 Power Curve

The most widely used tool for illustrating a turbine's power characteristic is the power curve. The power curve relates wind speed at the hub to a power output. The formula for determining the theoretical power curve is presented in Equation 4.1, and the resulting power curve is shown in Figure 4-3.

$$P = \frac{1}{2} C_p \rho A U^3 \tag{4.1}$$

Parameters
P Power
C_p Power coefficient = 0.593 (Betz limit) theoretical max value
ρ Density of the air =1.225kg/m3
A Rotor swept area = 36950m2
U Wind speed

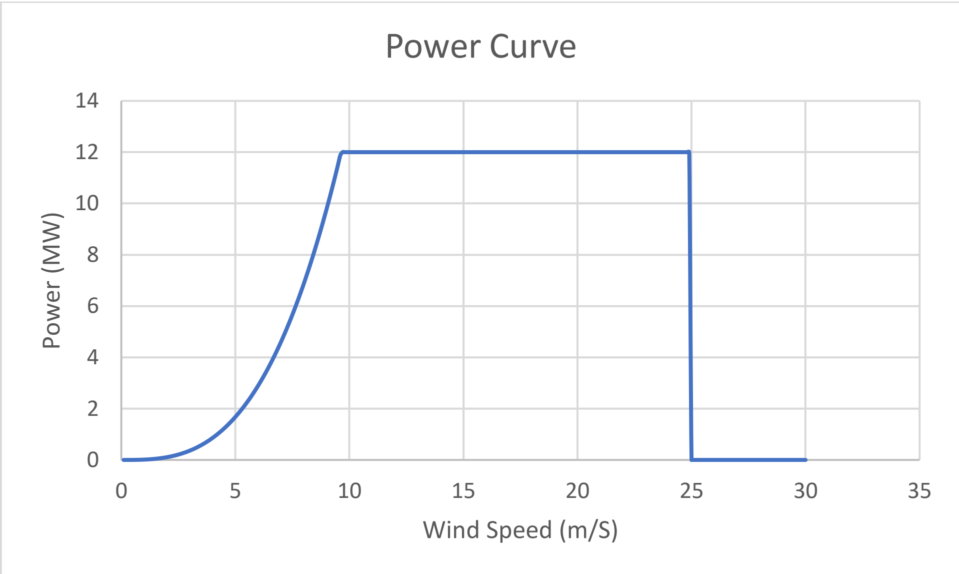


Figure 4-3 Power curve of the 12MW WINDMOOR concept

For wind speeds below 10 m/s the energy production increases from 0MW to 12MW as per the cubic formula in Equation 3.1. As the wind speed exceeds 10 m/s, the turbine produces maximum energy of 12MW which is the rated output of the turbine. After exceeding the cut off wind speed of 25 m/s, the wind turbine is shut down and no power is produced. Using the relationship between wind speed and power output, the average power output from a single turbine can be determined using the hindcast data.

4.1.1.2.2 Power Output

The hindcast data at the site (see Section 2.4.2) was taken from a reference elevation of 10m above MSL. This reference elevation needs to be projected to the hub height of 131.7m. To do this, the wind profile as described in Eurocode NS:EN 1991-1-4.2005 + NA:2009 was used as in Equation 4.2.

$$U(z) = U_{bas} k_r \ln(z/z_0) \tag{4.2}$$

Parameters
U(z) Wind speed at z elevation
U_{bas} Basic wind speed
z Elevation
z_0 Roughness length = 0.003 for terrain category I (open sea)
k_r Terrain factor

Using Equation 3.2, the reference height of 10m was able to be scaled up to 131.7m as shown below.

$$\frac{U(z_{131.7})}{U(z_{10})} = \frac{\ln\left(\frac{131.7}{0.003}\right)}{\ln\left(\frac{10}{0.003}\right)} = 1.32$$

Therefore, the reference wind height of 10m can be scaled to the 131.7m hub height by using the 1.32 multiplication factor. This factor was applied to the hindcast data series to continue the analysis below. A histogram was created for the hindcast series to give an indication on the wind potential at the site, see Figure 4-4.

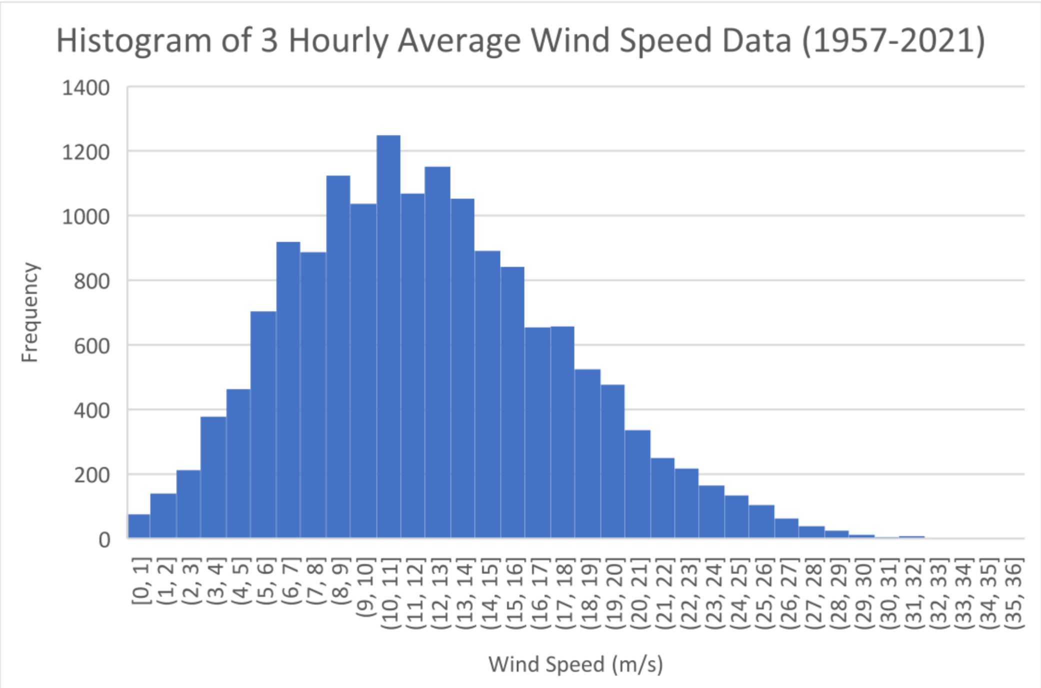


Figure 4-4 Distribution of wind speed at hub height at the entrance of Isfjorden

It is visible from the distribution of 3-hourly average wind speed that the conditions are very favourable for power production at the site, with the bulk of wind speed occurrences between 10m/s and 25m/s (the optimal production range). The wind data has then been applied to the power curve to determine the power production. This has been analysed monthly, as there is a large degree of variance between the wind data over summer and winter. This is observed in Figure 4-5 below.

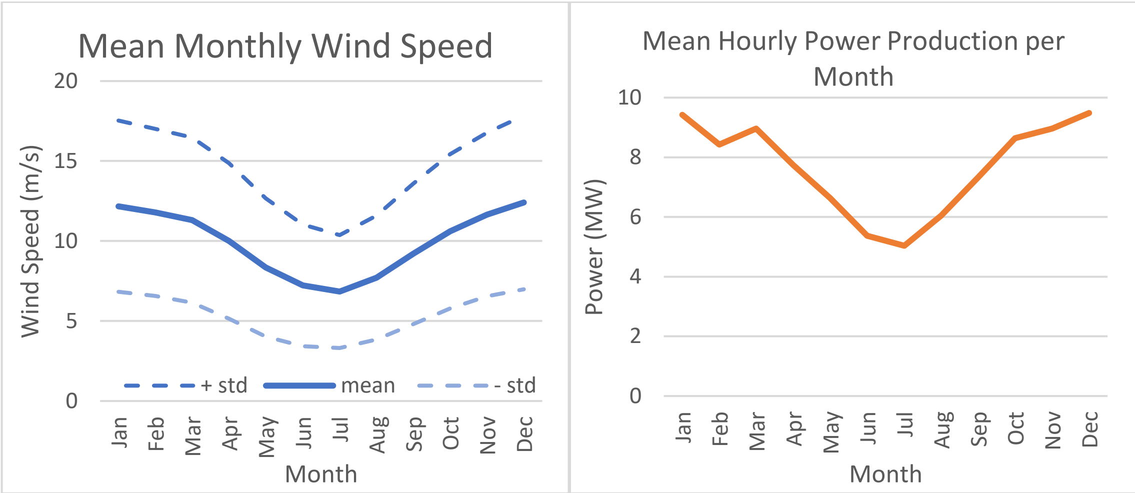


Figure 4-5 Left: Mean hourly wind speed at the hub per month. Right: Mean hourly power production per turbine per month.

It is apparent that the wind speeds are on average much greater in the winter than in the summer. This is due to the larger storms that occur in the winter over the summer. The corresponding average hourly power production per month was also calculated which is also higher in the winter and lower in the summer. The total monthly average power was then extracted, as shown in Figure 4-6. Note that the power output aligns well with the peaks in energy demand during winter, where heating the community and providing light in the dark season is essential. This could also open the opportunity for a complimentary system of solar energy utilised in the long daylight summer period to make up the shortcomings of wind supply.

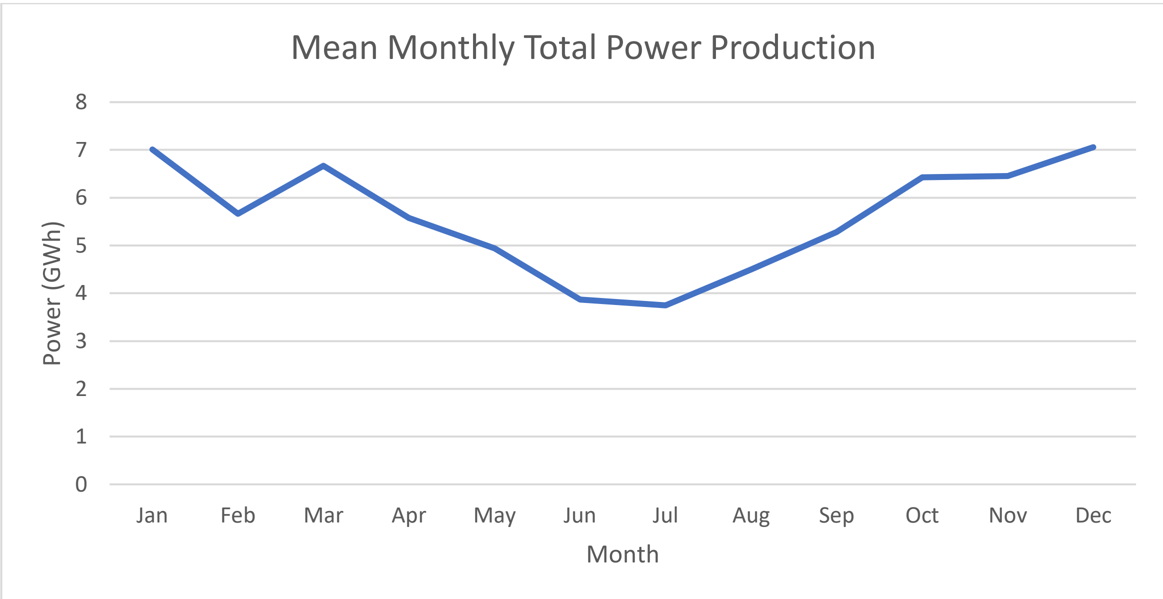


Figure 4-6 Mean total power production per turbine per month

On average, the total power produced by a single 12MW turbine at the site would be 67GWh per year. Assuming the turbines operate at 35% efficiency, a single turbine should contribute approximately 23GWh per year. When the current energy demand for Longyearbyen is 130GWh per year, 6 turbines at 35% efficiency should be adequate to service the community. Therefore, in this case study 6 turbines will be used to assess the constructability and feasibility of the project.

4.1.2 Port Selection and Layout

The installation and assembly port would also need to be selected. It would be advantageous to select a well-established port as close to the site as possible to minimise the risk of downtime during installation. Hammerfest then would be the obvious choice, located far north in the mainland of Norway. Polar Base Hammerfest is a privately owned port that services the oil and gas industry. It has a storage area of around 350000m^2 and a quay depth of approximately 20m (Indrevær et al., 2021). Whilst the quay depth would not be suitable for deep floaters, the construction and assembly of shallow floaters like the semi-submersible supporting the 12MW WINDMOOR concept. The large storage area also supports favourable logistics for the assembly of the turbine components. See Figure 4-7 below for a layout plan of the site.

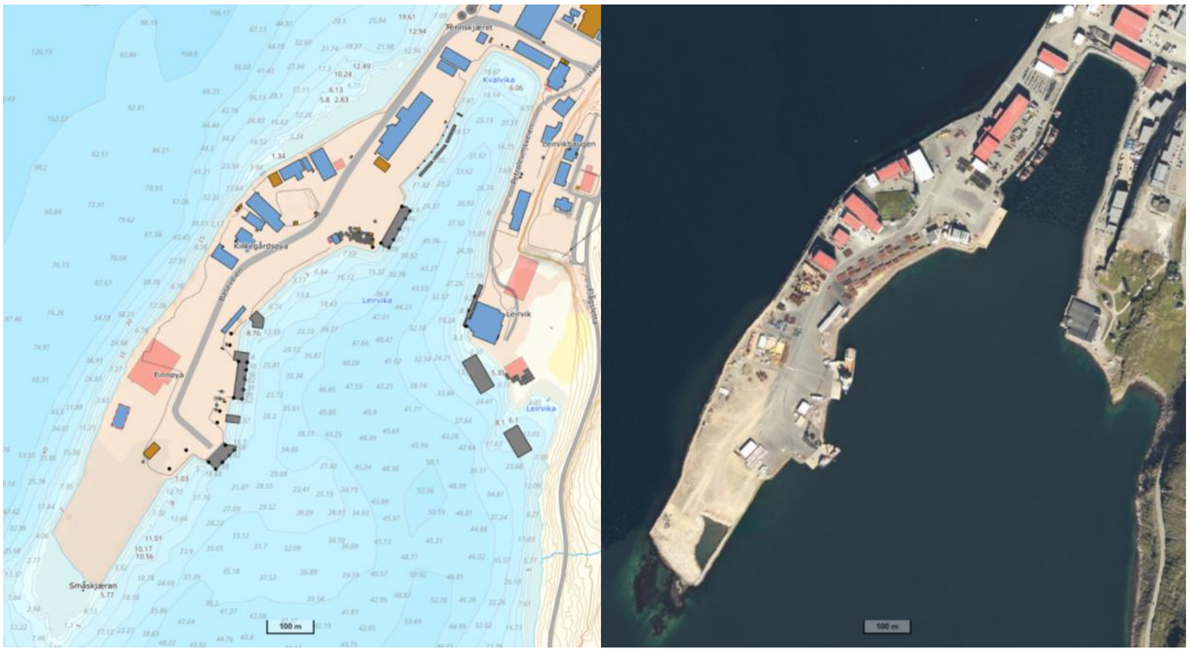


Figure 4-7 Norsea Polarbase (Kartverket, 2021). Left: Nautical. Right: Aerial.

Alternatively, Norsea Polarbase could be used to support the project through a smaller part of construction, like the turbine assembly. This way the floating units could be procured from a mass production site that is distributing to multiple fields and lowing costs through scalable production. For simplification in this feasibility assessment, the Norsea Polarbase is assumed to be available for the whole assembly and is the port of choice for the case study.

4.1.3 Site Selection and Layout

The FOW site should be located as close to Longyearbyen as practically possible, considering environmental restrictions, public sight and amenity, vessel routes and other environmental conditions. With reference to the site conditions explored in Section 2.4, the most likely location for the selected site is 60m west of the entrance at Isfjorden as shown in Figure 4-8. This has been assessed as feasible in terms of wind potential, with the hindcast data reference location providing a good representation of the site. This location avoids the marine protected areas and is away from the twin submarine communications cable between Svalbard and the mainland. The founding conditions are also ideal for the suction anchors and the depth is suitable for the mooring arrangement. The site also offers the opportunity for future expansion with power connections to other settlements in Svalbard, like Ny-Ålesund and Barentsburg. This could be staged similar to that illustrated in Figure 4-8.

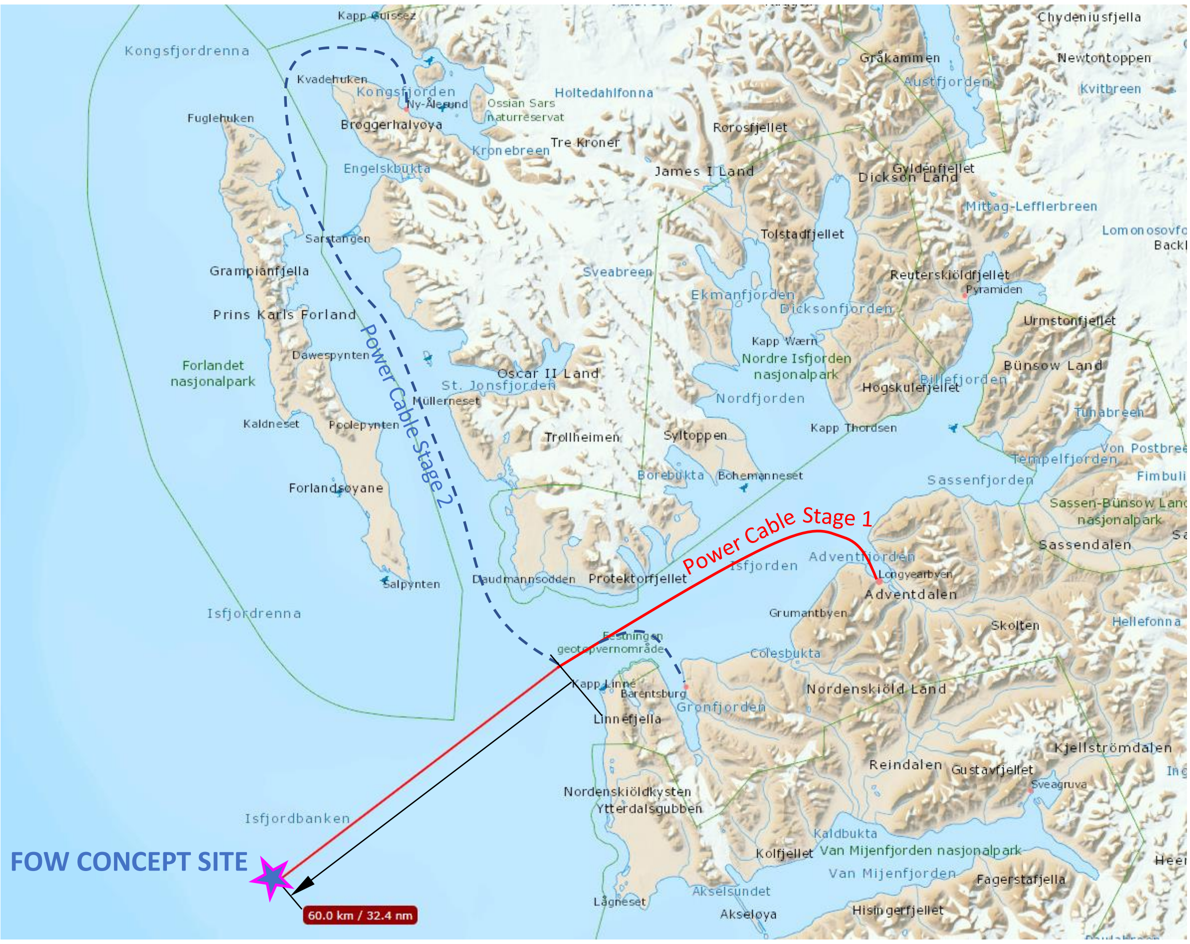


Figure 4-8 FOW concept site selection

The location is also further away from sources of land fast ice, drift ice and even icebergs that can be experienced around Isfjorden in the winter, refer to Figure 2-7. This reduces the risk of ice impact loading and provides time for the ice to melt in the warmer waters on the west side of Svalbard, or for a local vessel to mobilise and tow any larger pieces away. As such, considering the environmental conditions, the concept site would be the most likely choice of location for a FOW solution. It is likely that this location would not receive great stakeholder resistance in comparison with alternative solutions.

The field layout can also be optimised during the design phase. There is ongoing research into the dynamic behaviour of shared mooring and anchoring arrangements for FOW units, and it seems likely that in the near future that these arrangements will be optimised. Figure 4-9 shows the potential layout plan of the FOW units, where the turbines are anchored at three points with anchor sharing. This solution is optimised and saves cost with the installation of only 11 anchors compared with the traditional 18 anchors in today’s farms. The layout can further be optimised with mooring line sharing arrangements. This however may induce complex dynamics on the lines that need to be properly understood before implementation. Note in the layout plan, adequate space has been provided between the turbines to avoid loss in efficiency from turbine wake.

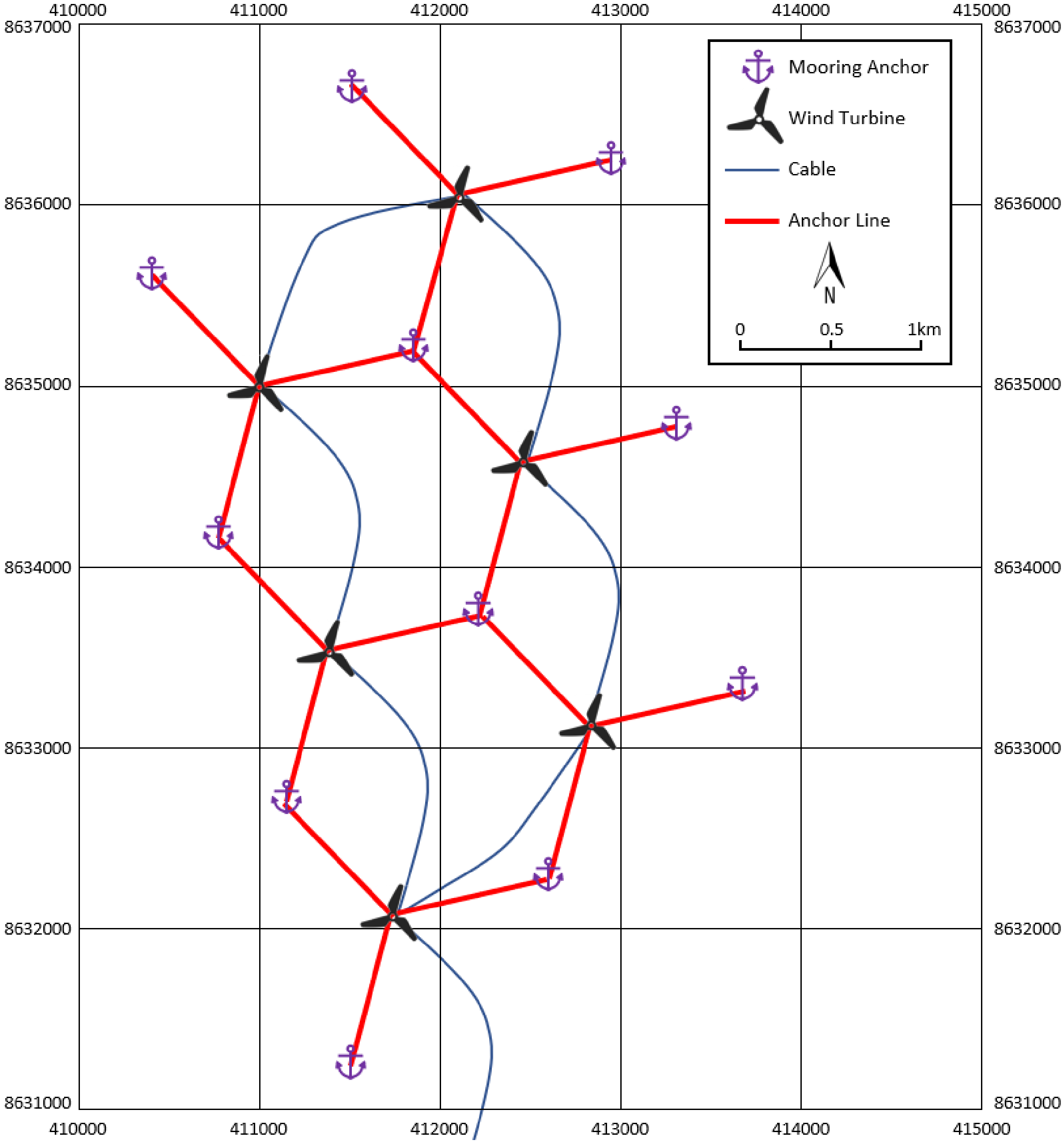


Figure 4-9 Conceptual Layout of the six FOW turbines

4.2 Ice Impacts

4.2.1 Sea Ice Loading using SAMS

An analysis of sea ice loading on the semi-submersible structure was conducted for the selected FOW concept. A simulation was run using the Simulator for Arctic Marine Structures (SAMS) program developed by ArcISo. The purpose of this simulation is to understand how the semi-submersible structure would behave with nominal ice floe loading. The 12MW WINDMOOR concept and mooring system has previously undergone extensive hydrodynamic analysis using SIMA and the results indicate that the structure can be implemented in the field (Souza et al., 2021). As this analysis has already been conducted, it is of interest to subject ice condition on the concept.

4.2.1.1 Methodology

To be able to simulate ice loading in SAMS, firstly a scaled object file was developed for the 12MW WINDMOOR semi-submersible concept using Autodesk's AutoCAD (computer-aided design) software, see Figure 4-10. The model was developed to scale of the submerged part of the structure and to the top of the columns, so that the water line interaction could be subjected to ice floes in the simulation. The dimensions were taken from Table 4-1. In order to save computation time in the simulation, the 3D model was optimised into a triangular mesh, converting the cylinder into a triangulated sphere in MeshLab. The 3D object file developed from MeshLab was able to be used in the SAMS program. The centre reference of the 3D object file had to be assigned as the centre of gravity of the structure, and the weight of the concept and radius of gyration was inputted from the values presented in Section 4.1.1.

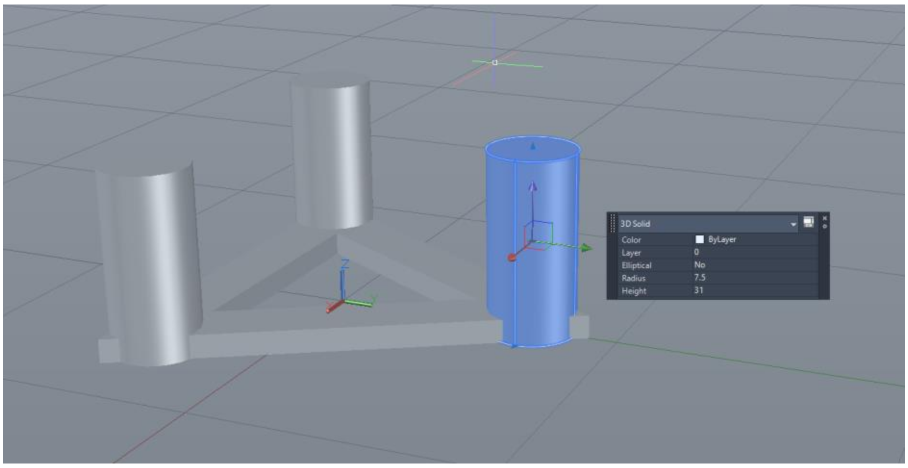


Figure 4-10 CAD 3D 12MW WINDMOOR semi-submersible

Simulation conditions needed to be applied to the correctly scaled 12MW WINDMOOR 3D object in SAMS. Based on the site conditions investigated for ice in Section 2.4.6, a worst-case ice flow field was generated in the software. With consideration of the worst conditions observed in available ice charts, Figure 2-7, a pancake ice floe field with a concentration up to 10% could be expected. This ice would have a nominal diameter between 30cm and 3m and thickness of 10cm. This floe field was generated in SAMS, with a standard distribution of ice pieces between the nominal diameter and thickness generated with random placement to cover 10% of the water surface area. The ice mechanical properties and friction coefficients were selected from a standard template in the software.

The SAMS program can be used for moving vessels or fixed structures and models the interaction between a vessel path and the ice or a fixed structure and the ice movement by current. For this simulation, the semi-submersible structure was placed in a fixed position by station keeping mooring input mechanism. The radii of gyration, added mass and dynamic damping properties were taken from the 12MW WINDMOOR SINTEF report (Souza et al., 2021). No wind was included in the analysis to limit the investigation to ice loading. A current of 1m/s was selected for the simulation, as per the worst-case conditions identified in Section 2.4.4.

The inputs for the simulation had then been finalised and the frequency and time duration needed to be set. After a few dummy runs, a frequency of 100Hz for a one minute simulated resulted in adequate accuracy and convergence. Preliminary ice loads could then be obtained. For the selected site, the input conditions could be considered as worst case, and would be highly unlikely to occur in the warming region. The results should be somewhat conservative and used as indicative only. A schematic of the simulation is provided in Figure 4-11.

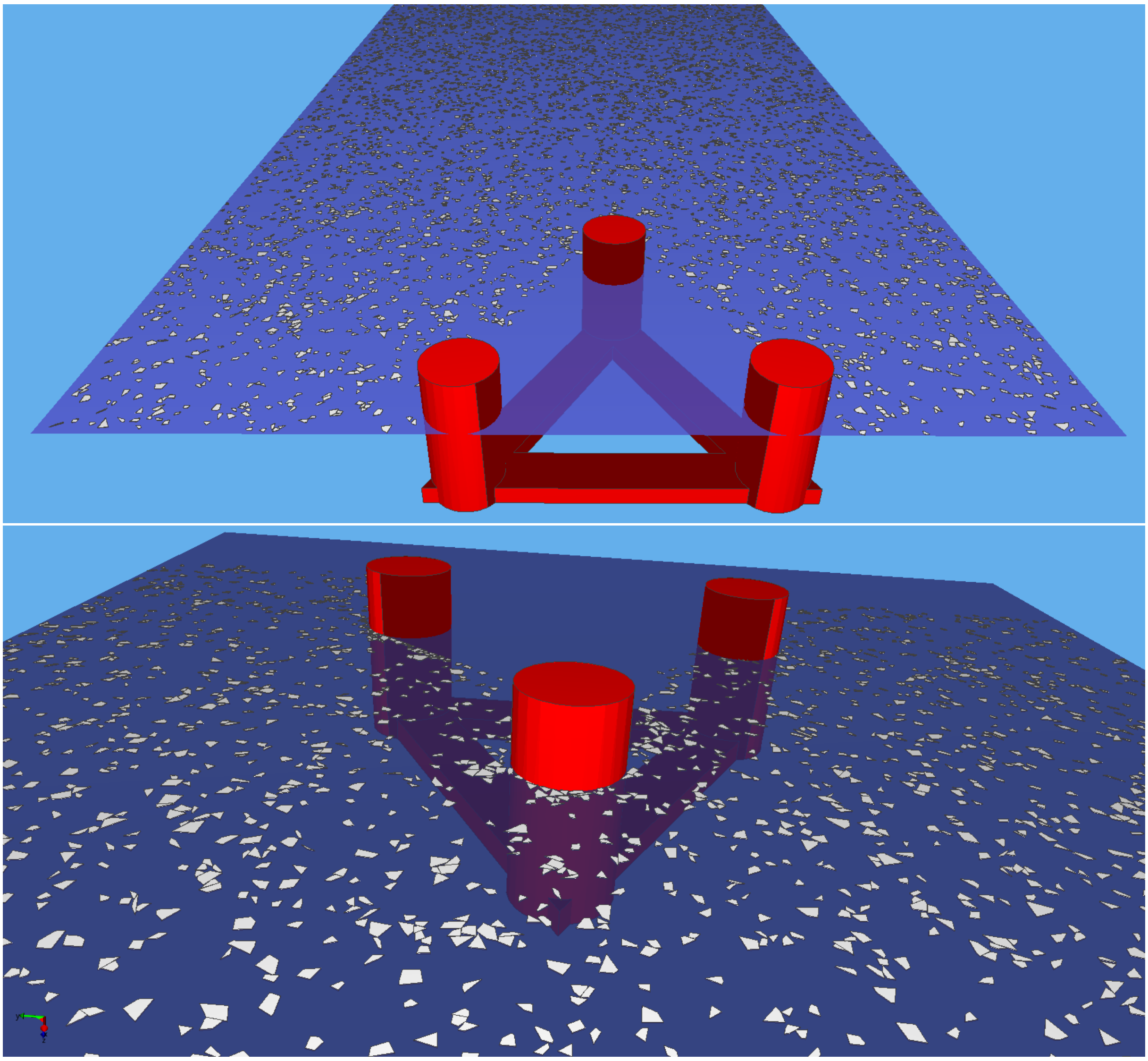


Figure 4-11 SAMS simulation of the 12MW WINDMOOR FOW concept. Top: Simulation set-up. Bottom: Ice accumulation during simulation.

4.2.1.2 Results

Once the simulation was completed, results of the ice forces could be analysed along with the dynamic movements of the semi-submersible. It was possible to visualise the simulation in real time as well and it was noted that ice pieces began interacting with the point of centre of gravity of the structure. Many attempts were made to rectify this, however the same issue kept arising. It is possible that the software was unable to understand multiple waterline plane areas and a centre of gravity that was not inside the 3D object. This resulted in some ice accumulating at the centre, which would increase the ice loading results.

Therefore, the results are deemed to be conservative for the project. The software was able to generate plots of the structure interaction with ice. The plots of the results are shown in Figure 4-12 below.

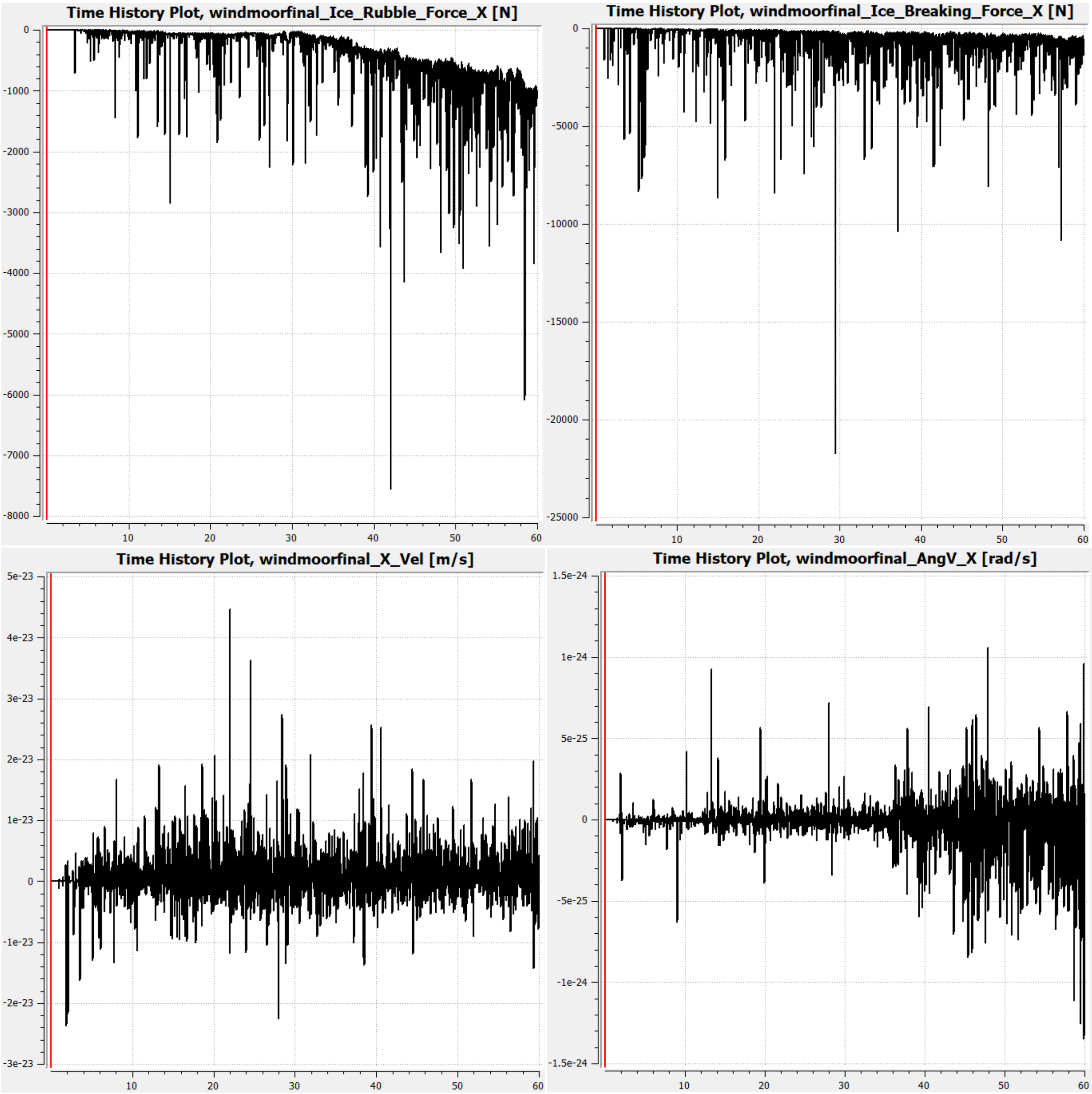


Figure 4-12 SAMS results. Top Left: Ice rubble force. Top Right: Ice breaking force. Bottom Left: Surge velocity. Bottom Right: Pitch velocity.

From the results, it appears that the ice has very little impact on the stability of the structure, based on the very small velocity amplitudes in surge and in pitch. Environmental loading in the SINTEF report resulted in dynamic amplitudes in the order of 10^{-6} whereas in the ice loading analysis the amplitudes are in the order of 10^{-23}. This is significantly smaller and indicated that the loading is significant for the worst-case ice floe field at the site. The ice floe field is comprised of relatively small ice pieces which indicates that the little ice that is present won't cause any major stability issues.

Also, when analysing the global forces from ice rubble and ice breaking on the structure is in the order of 4kN and 8kN respectively. There are occasional spikes, however it is likely that these are outliers when considering the instability of the simulation around the centre of gravity. To provide context of how small these forces are, a comparison is made to the theoretical drag force of flowing water on a cylinder. A hand calculation of the current drag forces acting on a single cylinder column was done using the drag equation, Equation 4.3 below. The drag coefficient was determined using the same cylindrical shape parameters and simulated flow conditions. For the aspect ratio of submerged length

(15.5m) to diameter (15m) of 1.03, for laminar and transitional flow conditions, the drag coefficient C_D is empirically derived to be 0.64 (Blevins, 1992). The reference area was taken as the draft multiplied by diameter.

$$F_D = \frac{1}{2}\rho v^2 C_D A \tag{4.3}$$

The drag force on a single column was determined to be 80kN. Although further analysis would be required to determine the actual environmental loading on the whole semi-submersible structure, the hand calculated drag force on only one column is far greater than that induced by the simulated ice loading. As such, the ice forces can be deemed as minor and inconsequential in comparison.

Although sea ice loading was identified as a major risk to a FOW project in the arctic, from the simulation the loading that can be expected at this site is minor and would not deem the project infeasible.

4.2.2 Icing

Icing could be another risk for FOW units in Svalbard. The combination of low temperature, high humidity and strong winds would likely result in ice formation on the rotor of the wind turbine. This is undesirable because it lowers the production efficiency and increases navigation and safety risks (Tennbakk et al., 2018). This, along with icing from sea spray on the semi-submersible, can be a critical risk to the concept.

While the accumulation of ice on the structure can impact stability, it is difficult to estimate the accumulation and no modelling software was available due to constraints and limitation of the study. This is beyond the scope of this study, however is an important element that needs to be further investigated. It is likely that physical modelling may be required, and some additionally stability and buoyancy measures be implemented in the design to reduce the icing impact. As there are other floating structures currently in use in the arctic, it would be likely that this challenge can be overcome and not impact on the feasibility of the project significantly.

4.2.3 Ice Management

Ice protection techniques may be required at the site, including active, passive and hybrid measures. Active anti-icing/de-icing technologies could be implemented, including mechanical, thermal, or chemical removal from the surface as ice builds up. This could be wired into a small storage system serviced by the substation for example. Passive anti-icing/de-icing techniques can prevent or reduce icing by adapting the surface properties of the structure. A hybrid combination of the approaches could also be implemented, however it has been observed previously that full protection is difficult and costly to achieve (Shi & Duan, 2021).

Monitoring would be required at the site to ensure that any build-up of ice is properly managed. It would also be required to ensure that the turbines remain operation and there is no damage or maintenance required. The monitoring could be remote. It is not anticipated that sea ice will be a major issue, however the occasional iceberg may be present at the site. This could be monitored by radar and a towing vessel, like the MS Polarsyssel which is berthed at Longyearbyen, could be quickly mobilised. If an iceberg is on a trajectory towards these assets, the vessel could tow the iceberg away. The MS Polarsyssel has previously been used for towing icebergs in several UNIS research projects.

4.3 Installation Assessment

A high-level installation assessment has been performed in this Section in order to assess the general feasibility from a project development perspective. To undertake this assessment, an overview of the installation methodology is established and a simulation of downtime as a result of WOW is conducted. The installation phase of the project is arguably the most difficult and costly, and would ultimately define the feasibility of the project provided operation costs are reasonable.

4.3.1 Installation Method

For this case study, it is assumed that the 12MW WINDMOOR turbines will be assembled on the mainland of Norway in Hammerfest and towed to site using tugs, as shown in Figure 4-13. Assuming tugs towing speed is 5 knots, it will take 4 days to reach to site which is 477 nautical miles from the Norsea Polarbase production yard. It is likely three tugs will be required to tow these larger FOW units, with one tug providing most of the pulling and the remaining two stabilising the structure.

Figure 4-13 Example of tug towing semi-submersible FOW (Tomic, 2020)

Before the towing operations, the semi-submersible substructure would need to be fabricated. This could be done at the Norsea Polarbase or be procured from a future established mass production site. Either way, the fabrication of this structure is facilitated by many on land activities which reduces some of the weather downtime risk on the project. This section of the installation has not been included in the downtime simulation, as the marine operations are considered higher cost and higher risk. The fabrication program could be scheduled with a better estimate of downtime and delays. This would also include the assembly of the turbine components from the port storage area to the semi-submersible structure.

Beyond the on-land construction, fabrication and assembly of the FOW units, and the transport to site, the only construction activities on site would include the installation of moorings and anchors, the power connections and power cable lay and commissioning. Suction anchors will be used to attach the wind turbines by catenary mooring lines to the seabed. This is a simple and well-established operation. The suction anchors would be transported to the wind farm site by a separate barge, an offshore crane vessel or anchor handling vessel which would be used to lift and place on the seabed before it is pressurised to embedment. This operation can utilise the local Svalbard quays as well if required. The highest risk stage of the project therefore is the marine operations, and in particular the towing. A schematic of the vessel voyage plan is shown in Figure 4-14 below.

Figure 4-14 Vessel voyage plan (Kartverket, 2021)

4.3.2 Installation Downtime

The installation period would be mostly limited to the summer months where the weather is typically calmer, and visibility is greater during full days of sunlight. It would not be practical to perform the marine operations during the winter season where environmental conditions are unfavourable and include storms, high winds, high swells and polar night darkness. There would be days where the weather becomes dangerous and installation is not possible, and the towing operation should be scheduled with close attention to the forecasts. Planning for shut down for ice, wind and waves should form part of the programming of the installation.

It is therefore important to accurately predict and price for downtime due to waiting on weather. Although there is going to be a high degree of variance in weather events each year, it is important to plan for downtimes and schedule the project so that complex operations are completed in favourable weather periods in the year. A simulation of installation downtime has been conducted to aid the assessment of feasibility for a FOW project in Svalbard.

4.3.3 Computer Simulation of WOW using Shoreline Software

Shoreline was developed in 2014 as a simulation tool for the programming of offshore wind construction projects (Shoreline, 2022). The simulation software allows for accurate scheduling, cost estimating and prediction of downtime due to weather. This software was selected to understand the likely downtime due to WOW for the concept project. Installation downtime is a major risk to the project and an important element in pricing the project. As such, the marine operations are critical to the feasibility of the project.

4.3.3.1 Methodology

The Shoreline program has an easy-to-use online interface that allows project specific variables to be assigned in an input library to define the simulation. A port or base for the construction activities was defined in the program at the Norsea Polarbase Hammerfest. At this base, the berth capacity was defined to control the rate of assembly and loadout operations. This was defined as 2 units at a time, which would be likely for such a large storage and quay area at the port.

The field layout is also defined in the program. Six FOW turbine units were added in the library, with the same output and specifications as the 12MW WINDMOOR concept, see Section 4.1.1. The loadout port, power curve, nacelle height and weather operating criteria were defined for the concept. The six turbines were placed at the site location discussed in Section 4.1.3. The turbines were spread out over an area at the site location to define the construction location. This is as shown in Figure 4-15 below.

Figure 4-15 Shoreline wind farm layout of the 6 individual 12 MW WINDMOOR FOW turbines at Isfjorden (n.t.s.)

In addition to the floating turbines, mooring anchors, mooring lines, substation, inter array cables and export cables were also defined for the simulation. After multiple attempts to coordinate these activities in a logical sequence in the simulation, it was decided that the installation should be simplified to just include the turbines, mooring anchors and mooring lines. This way the activities can be separated into on land assembly by crane, towing operations and field installation.

Weather conditions were also able to be defined for the simulation, and the hindcast data from Section 2.4.2 and Section 2.4.3 was uploaded. This weather data included wind speeds at 10m reference height which could be upscaled to the hub height in the program, as well as wave data. This defined the limiting criteria during operations, which would result in downtime due to WOW.

The installation logistics were also specified for the simulation. A library with existing vessels was available for selection. These vessels were used as it too early in the project stage to select a vessel, and contractor engagement would be required to understand the available vessels for the project. For the purpose of this simulation however, the vessel information is simplified, and specific vessel parameters don't need to be defined. The vessels selected for the simulation included a towing vessel to transport the units to the field, and an anchor handling vessel to install the anchors and mooring lines. Weather parameters and cycle time was also defined for each activity stage of the vessel, including mobilisation, loadouts, transit, installation, demobilisation and completion.

The installation strategy and staging of the marine operation packages was defined. This included start dates, lags, and predecessors. This defined the staging of the simulation and the interfaces between the assembly port and installation at the field. The weather model could also be selected for the simulation. The weather could be disabled, set by historical or incremental start year, or based on a Markov randomised model based on the hindcast data. While cost inputs and personnel work hours could be scheduled, this was beyond the scope of this study due to limitations discussed in Section 1.5. For more details on the configuration of the Shoreline simulation cases, see Appendix A.

For the purpose of this analysis, the simulation was run using the Markov randomised weather model for a installation start date in May which was identified as the start of the calmer weather period in Section 2.4.1. This was the base case, and a sensitivity analysis was conducted around these base conditions. The simulation was then run using 100 seed runs for each case. A visualisation was available for the simulation which was useful in ensuring that the activities were coordinated as defined.

4.3.3.2 Shoreline Simulation Results

The simulation for the base case of Markov weather model with a May start date resulted in minimal project downtime. The mean project duration for the base case was 58.6 days, with the main activities of the wind turbines, mooring anchors and mooring lines taking 41.6 days and 20.9 days respectively as in Table 4-3.

Table 4-3 Simulated project duration

Component	hrs	days
Wind Turbine	999.3	41.6
Mooring Anchor and Mooring Line	501.1	20.9

The simulation time for marine operations is relatively short, with these marine operations being completed in around 2 months. The total project duration would extend beyond this with the unit fabrication, assembly, power hook-up, cable laying and commissioning activities not included in this analysis. This time however is not unreasonable for the marine operations of only 6 FOW turbines. This is advantageous as the project can be scheduled to reduce the risk of downtime during expensive marine activities.

The breakdown of duration to activities for the marine operations is presented in Table 4-4 below. The towing and transit operations between Hammerfest and the site represents the largest activity duration. This is then one of the highest exposed activities to weather impact and would require careful planning to ensure a safe operation.

Table 4-4 Activity breakdown

Activity	Asset and Vessel Cycle (hrs)
Mobilising	9
Loadout	25.8
Mooring Anchor Loadout	6
Mooring Line Loadout	6
Towing to Wind Farm	587.9
Transit to Wind Farm	107.9
Wind Turbine Hook Up	78.4
Mooring Anchor Installation	129.6
Mooring Line Installation	129.3
Transit to Next Asset	17.5
Transit from Wind Farm	396.9
Arrival at Base	6

The downtime recorded due to weather limiting the operation activities is recorded in Table 4-5. The downtime over these two months is very low, around 1%, indicating that weather risks can be limited based on start time and careful project scheduling.

Table 4-5 Downtime results

Result	Anchor Handling Vessel	Towing Vessel
Downtime (hrs)	39.08	19.03
Downtime to Project Duration (%)	1.10%	0.43%

The probability distribution for the 100 seed runs is shown in Table 4-6 and graphically in Figure 4-16.

Table 4-6 Probabilistic distribution of project duration based on multiple seed runs

Probability	Duration (hrs)
P0	53.9045
P10	55.4462
P20	56.217
P25	56.6545
P30	57.1337
P40	57.7587
P50	58.1962
P60	59.3004
P70	59.842
P75	60.4879
P80	61.4045
P90	62.3004
P100	64.6219

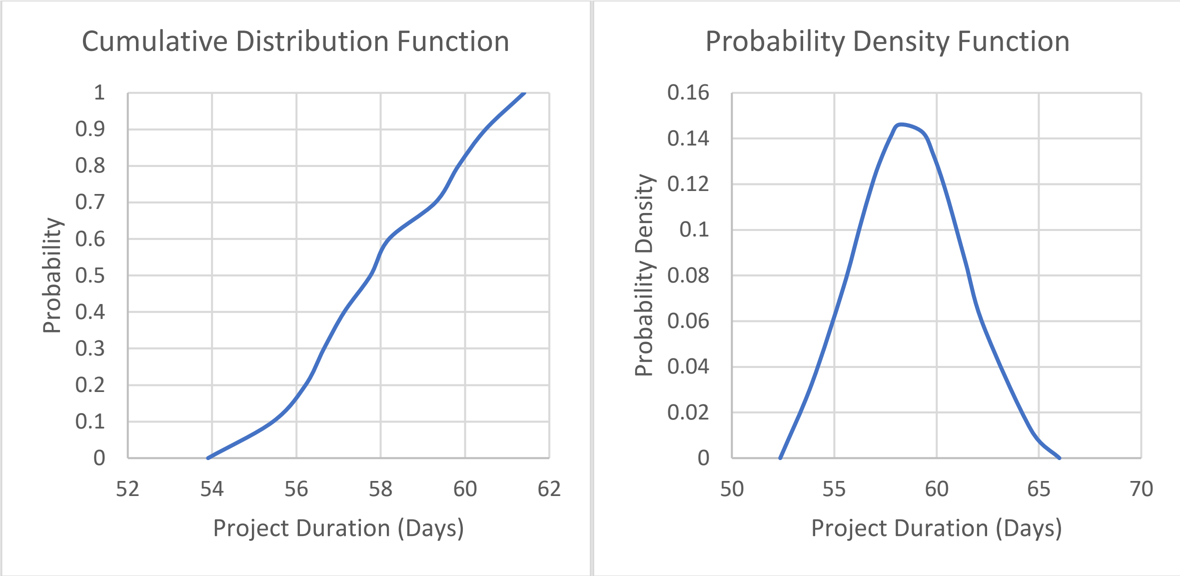


Figure 4-16 Cumulative and probabilistic distribution of project duration

The probability distribution indicates that there isn't a significant spread in duration based on the randomised weather model. The project duration could vary between 54 days and 65 days based on this standard distribution. The mean project duration of 58 days included downtime due to WOW of around 2 days total. When considering the minimum time for completion was 54 days, the delays from WOW including remobilisation would result in an average 4-day extension to the project or 8% of the duration. This is in an acceptable range. On the higher end, the project duration could be up to 65 days which is an 11-day extension or 18% of the duration. This is a high risk to the project however the risk is minimised by the short installation duration for these activities.

The results indicate that marine operations scheduled in the summer period could result in more predictable and reasonable delays caused by WOW. If the risk is properly managed through scheduling, the downtime can be minimised. The arctic weather risks should not impact the feasibility of the project significantly based on these results.

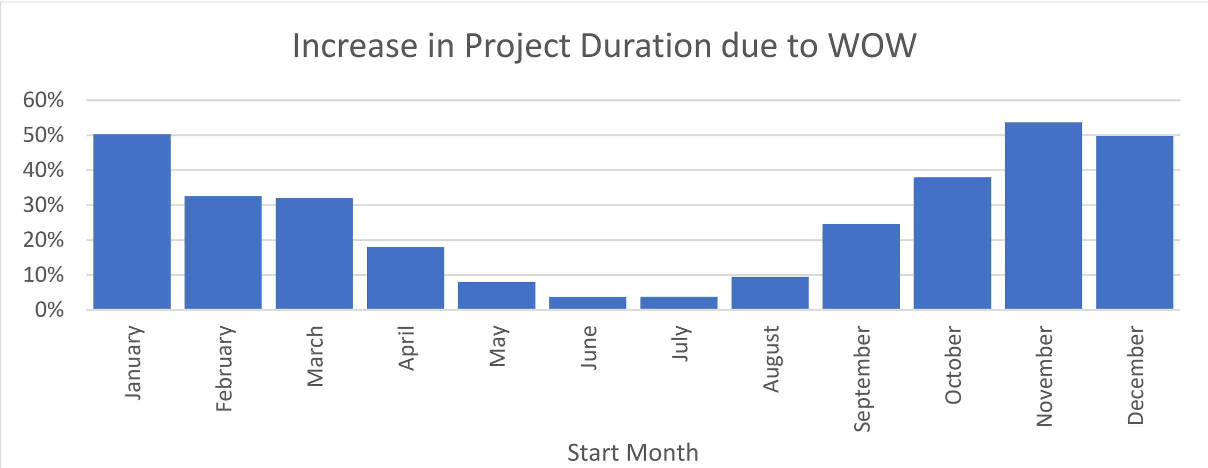
4.3.3.3 Shoreline Simulation Sensitivity Analysis

To confirm the reliability of the simulation, a sensitivity analysis was conducted. The weather model, start time and operations weather limiting criteria variables were adjusted to compare with the base case scenario. The base case as analysed in Section 4.3.3.2 used a Markov randomised weather model, project start date in May and operations criteria as presented in Appendix A.

The sensitivity of the project increases due to WOW based on start month was first tested. The base case for this comparison was a simulation that did not consider any impact from weather. This project duration was 53.9 days, the minimum installation time as referenced in Table 4-6. The duration based on start date was compared with this base time. The results are presented in Table 4-7, where the recorded duration is the mean or P50 distribution for the 100 seed runs. The results are also graphically presented in Figure 4-17.

Table 4-7 Sensitivity study of downtime as a function of start month

Start Month	Duration (days)	Increase due to WOW (days)	Increase due to WOW (%)
Base	53.9		
January	81.0	27.1	50%
February	71.5	17.6	33%
March	71.1	17.2	32%
April	63.7	9.8	18%
May	58.2	4.3	8%
June	55.9	2.0	4%
July	56.0	2.0	4%
August	59.0	5.1	9%
September	67.2	13.3	25%
October	74.4	20.5	38%
November	82.8	28.9	54%
December	80.8	26.9	50%
AVERAGE	**68.5**	**14.5**	**27%**



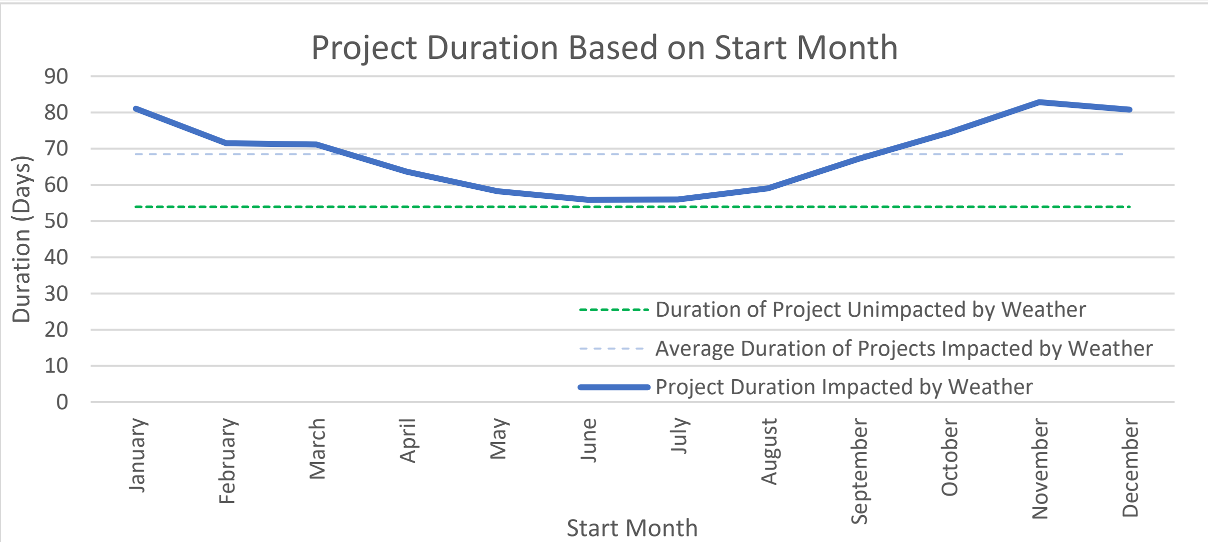


Figure 4-17 Top: Increase in project duration due to WOW based on start date. Bottom: Project duration based on start date

It is apparent that the increase in project duration is higher in the winter months than in the summer which could be anticipated based on the site conditions explored in Section 2.4. The increase in project duration is smallest for the June and July start months at 4%. The longest duration is experienced with a November start date resulting in a 54% increase. The project is quite sensitive to start date, and although the May start does not result in the shortest duration, this start time would be recommended to minimise the risk of delays if the project extends into the Autumn months. Other marine activities will also need to be coordinated, so a May start day appears practical from this high-level analysis.

The sensitivity of the weather selection on the results has also been analysed. Assessing against the 53.9 day duration of the no weather impact case, the Markov randomised weather model and historical weather model were tested. The results are presented in Table 4-8 and in Figure 4-18 below.

Table 4-8 Sensitivity study of downtime as a function of weather model in May

Case	Project Duration	Increase in Duration Due to WOW	Increase due to WOW %
No Weather	53.9		
Markov Weather Model	58.2	4.3	8%
Historic Weather (2021)	55.3	1.4	3%
AVERAGE	**55.8**	**2.9**	**5%**

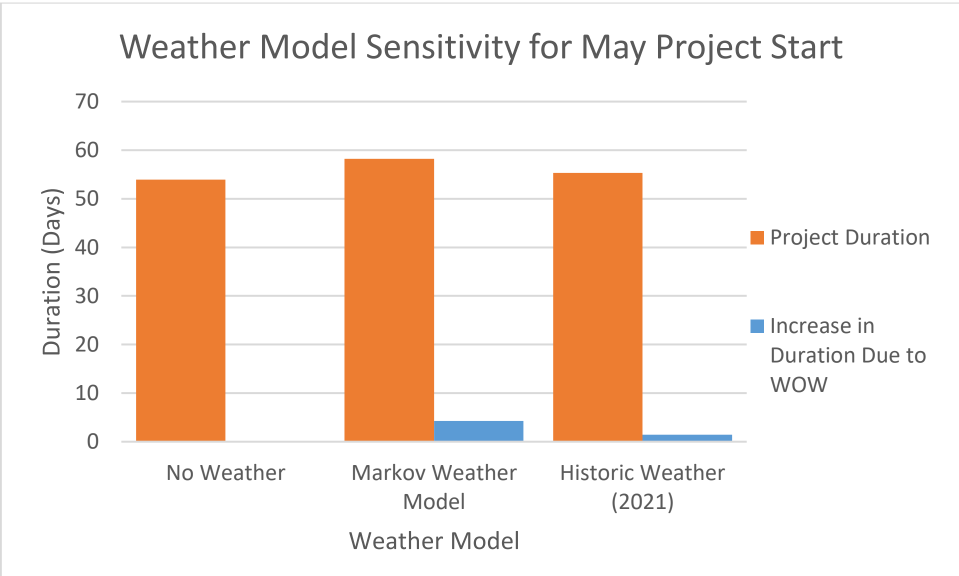


Figure 4-18 Sensitivity of project duration as a result of the selected weather model

The Markov weather model resulted in the highest increase in project duration and is this model is a function of the entire hindcast series, it is recommended that these results are used. It also results in the most conservative estimate and longest project duration. The Markov weather model should be okay for this assessment and the results presented in Section 4.3.3.2 would be the most representative of Svalbard conditions. The historical weather model only took into account the most recent time record in the previous year to the project start date, so it did not consider the worst recorded year and the results would be for an optimistic scenario.

Finally, a sensitivity analysis on the operational criteria was conducted. To do this, the operational weather restrictions were adjusted from those presented in the base case criteria in Appendix A, Table A 2. The base case wind speed and wave height restrictions were adjusted as well as the weather window for operations. The start month was consistent and kept at May.

A relaxed operational restriction was tested, where the operational wind speed limits were increased by 5m/s and the wave height limit increased by 0.5m. A strict condition was also tested, where the operational wind speed limits were tightened by 5m/s and wave height reduced by 0.5m. The required weather window for start of towing and transit operations was also increased to 100hrs. The results are presented in Table 4-9 and Figure 4-19.

Table 4-9 Sensitivity study of downtime as a function of operation restrictions

Case	Project Duration	Increase/Decrease Due to Operation Restrictions	Increase due to WOW %
Base	58.2		
Relaxed	56.7	-1.5	-3%
Strict	61.4	3.2	6%
Weather Window Increase	66.4	8.2	14%

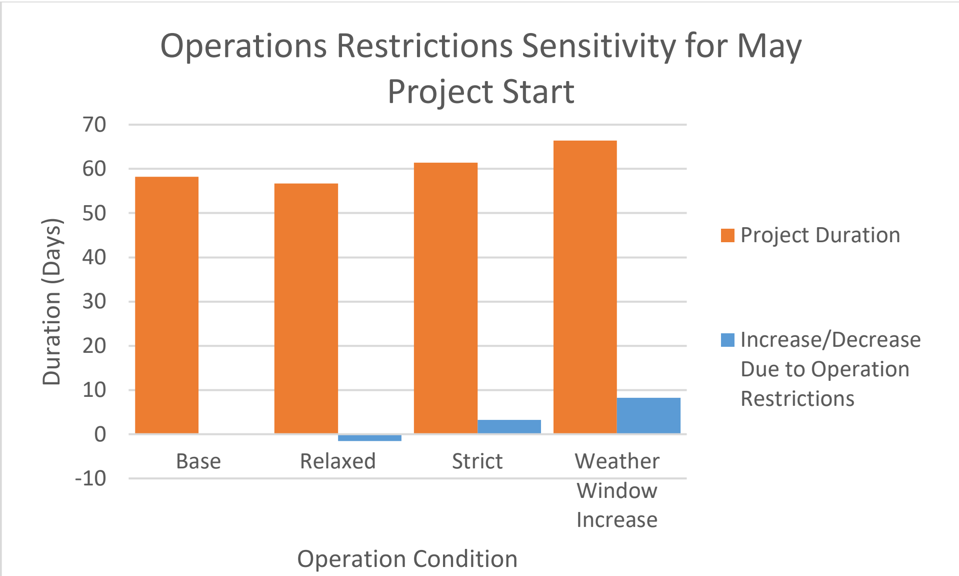


Figure 4-19 Sensitivity of project duration as a result of the operational requirements

The results indicate that adjusting the operational criteria won't result in a significant change to project duration for a May start date. Possible during winter the operational criteria would have a larger impact on the duration. It is interesting however that increasing the required weather window to start operations did result in a large increase in duration. This stresses the point that the operational dependency on good weather windows would need to be closely considered during the program development.

This sensitivity analysis does indicate that the results presented in Section 4.3.3.2 are reliable and represent the WOW risk to the project. Overall, the WOW delays are not so large to deem the project infeasible. While weather would be a large risk to the project, with careful scheduling and planning, the small construction project can be technically achieved with minimal challenges.

4.4 Preliminary Cost Evaluation

Cost is arguable the most important factor when considering the feasibility of the FOW project in Svalbard. While a detailed cost estimate and cost benefit analysis has been excluded from the scope of this study due to the limitations identified in Section 1.5, a high-level preliminary cost evaluation has been conducted here to provide some context.

In a previous study on the operational and logistic challenges of a theoretical offshore wind farm at Svalbard, a total transport cost is estimated to be around 9 million NOK considering the delays and typical day rate of the tugs (Klis et al., 2021). This is in combination of the 2 billion NOK estimate for the construction using 28000NOK/kW rating (Salo & Syri, 2014). Additional design costs, cable lay and hook up as well as contingencies could put the CAPEX for the case study project to around 1.5 billion NOK. This estimate considers the 28000NOK/kW rate is 8 years old and would have likely reduced around 40% with developments increasing the efficiency of construction (IRENA, 2019). Although there is still going to be an additional cost with mobilising in the north of Norway and constructing in the arctic.

The installation of five 6MW SPAR turbines in the Hywind Scotland pilot project, completed in 2017, cost 2 billion NOK to complete. In this project, the floating SPAR structures were towed 500km from the production yard in Stord Norway to Aberdeenshire Scotland. The Svalbard project costs would likely be in the same ballpark, with six FOW units being towed 900km and considering the cost reduction with increased efficiency in installation.

The cost is projected to decrease significantly in the future as a result of increased efficiency throughout the project development and production. Figure 4-20 below shows the trajectory of the cost reduction for various wind turbines. For FOW units, costs can be expected to reduce around 40% by 2030. This will make FOW much more desirable in comparison with expected costs of today.

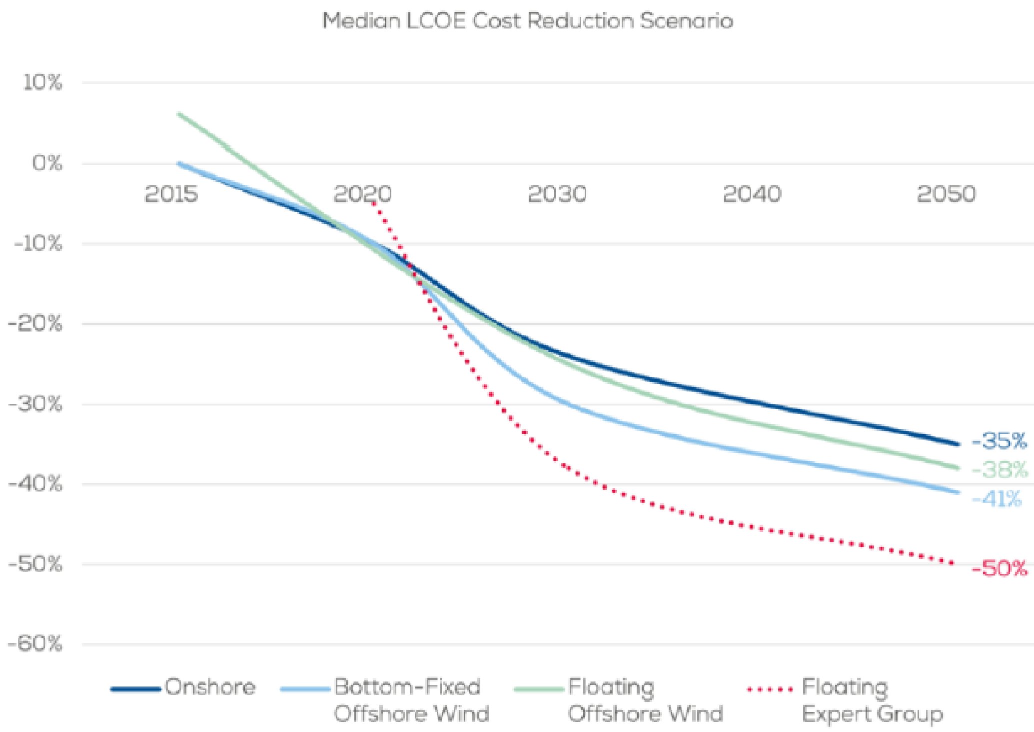


Figure 4-20 Cost reduction trajectory of wind production (WindEurope, 2017)

While OPEX estimates aren't considered in this study, some analysis into the competitive pricing of the produced electricity can also be useful in assessing the feasibility. In 2019 the average cost of electricity produced by offshore wind turbines was 1.12NOK/kWh globally and 0.84NOK/kWh in Scandinavia (IRENA, 2019). Although this figure includes fixed bottom structures, it remains competitive against the cost of electricity in Svalbard of 1.07NOK/kWh (CTT, 2022).

In summary however, the extremely large CAPEX will likely make the project undesirable for such a small field layout and population. Although it is desirable to have a fully renewable system, the FOW alternative may not be feasible compared to alternatives with respect to cost.

5 Discussion

Through this research project and case study many arctic challenges have been identified that will impact the feasibility of a FOW facility in Svalbard. Of these challenges, sea ice was identified as a critical environmental condition for the design of offshore structures in the arctic. At the selected site however, due to the warmer and more favourable climate conditions on the west coast of Svalbard, sea ice is expected to be small and in low concentrations. A worst-case scenario of ice cover for the region was determined to be 10% concentration of pancake ice with a nominal diameter between 30cm and 3m and thickness of 10cm. This floe field was artificially generated in the SAMS software and applied to the 12MW WINDMOOR concept at the maximum expected current of 1m/s.

The results from the SAMS simulation that replicated the adverse sea ice conditions on the FOW concept showed that sea ice would likely be a minor issue. The expected impact on dynamic stability from ice loading was very small and current and wave forces are anticipated to be much larger at the site. The global force from ice on the structure was simulated as 8kN which is insignificant in comparison with expected maximum current drag force of 240kN. This provides greater confidence in the feasibility of the concept, showing that one of the major challenges in the arctic would not be a concern at the selected site.

Although more investigations are required, icebergs are not considered to be a significant threat to the site (Broström et al., 2009). Towing vessels stationed in Longyearbyen harbour (including the MS Polarsyssel) could be mobilised quickly to tow and divert hazardous icebergs. Icing however could be an issue to the efficiency of power production as well as on the stability of the semi-submersible structure (Pryor & Barthelmie, 2010). More investigation would be required to understand these impacts.

Other environmental and site conditions were favourable for a FOW project in Svalbard, particularly the sub-sea-floor geology being composed of silts and clay which is ideal for suction anchors (Castro-Santos & Diaz-Casas, 2016). Additionally, the seasonal variations enable construction activities to be undertaken over a significantly calmer period in summer, where polar low storm events are infrequent. The FOW concept also may have the least impact of all the alternative energy systems on the surrounding ecosystem (Bergström et al., 2014) which is of great importance to the sensitive arctic area. The local stakeholders have held reservations about alternative energy sources, and while FOW options have not been presented in significant detail, it would be likely that this option is considered less intrusive to the community and environment. Other stakeholders in shipping and fishing industries would also need to be consulted.

The designed FOW case would be able to meet the energy needs of Longyearbyen with the large wind demand at the selected site. The six 12MW turbines operating at 35% efficiency at the site would produce on average 138GWh per year. This would meet the current energy demand for Longyearbyen. The wind is generally reliable at the site (Grochowicz et al., 2021) and should be adequate to service the community with the aid of energy storage. There would also be an opportunity to develop a hybrid system with solar energy for example to compliment the times of lower wind energy during the summer. This would also require further investigation, along with coupling with other energy and storage systems.

Another significant challenge that would be present for the FOW concept in Svalbard is the marine operations during installation. The Shoreline simulation was conducted to determine the likely delays to the marine operations as a result of WOW. The results indicated that with careful programming, downtime could be limited below 5% of total operations, and the risk minimised. If the marine operations are initiated in May for example, there would likely only be minor delays and a low-cost impact. The towing and anchoring activities would be expected to occur over 2 months in a regular summer.

One of the largest risks identified during the project delivery would be the transit and towing between the mainland and to the site at Svalbard. There is a significant distance to cover between the two locations, and in the region the weather can change quickly and pose a significant hazard during operations. Bjørnøya, a small island between Svalbard and Hammerfest could be used for safe harbour in the eventuality that weather conditions become dangerous.

This methodology however is not unique, with the world's first floating wind farm installed in a similar manner. The 30MW Hywind Scotland pilot project was completed in 2017 and demonstrated the feasibility of installing five 6MW SPAR FOW units (Equinor, 2017). In this project, the floating SPAR structures were towed 500km from the production yard in Stord Norway to Aberdeenshire Scotland. This project cost 2 billion NOK to complete. For the Svalbard case, the towing operations would be over 900km, which is at a similar scale to the Scotland project.

There are still significant logistical challenges that need to be further investigated and understood so that solutions can be proposed to ensure the project would be successful. However, while this study confirms that FOW is feasible in Svalbard from an engineering and technical perspective, a detailed cost estimate and business case analysis should be conducted prior to the selection of an alternative energy system. It is likely that this project may be too costly for any funding to be secured.

It will also be dependent on the future environmental policy as to what renewable solution is feasible at the location. For example, restrictions are tightening on onshore wind farms due their impact on migrating bird species (Adomaitis, 2020). The coal power plant in Svalbard must be removed soon, as the Norwegian government is keen to discontinue their last operating coal production plant and pursue greener options (Nilsen, 2021). The coal resources are also running out in the nearby mine, and an alternative energy supply will be sought over the commissioning of a new mine.

The preliminary cost analysis identified that the initial CAPEX outlay could be extreme and too high to justify for the small population it would service. The field only consists of 6 turbines so the fabrication and construction is not scalable. The preliminary cost estimates valued the project around 2 billion NOK which would likely deem the solution infeasible for the small Longyearbyen population. This could change in the future as cost projections are decreasing. If the CAPEX could be reduced by 40% in the next 10 years as projected, then possibly the project will be more attractive. The issue then however is that the mine will not be open beyond 3 years due to the diminishing supply of coal from the local mine. The energy costs to the community however is likely to be competitive against the current coal plant, at around 1.07NOK/kWh (CTT, 2022).

In summary, although the project is feasible from a technical and engineering perspective, the CAPEX is likely to be too high for the project to develop beyond this concept stage. There is potential for this option however to be affordable within the decade. If the floating sub-structure units could be procured from a mass production yard, costs would likely decrease significantly. The semi-submersible structure has the potential to be mass produced in a production line assembly port (Thiagarajan & Dagher, 2014), and such an advancement would lower the cost of FOW projects globally. The concept needs to be developed further to a point that it is more affordable. If this solution is preferred, perhaps an interim energy supply solution should be implemented with a design life of around 10 years to allow for the FOW technology to become more competitive.

Although many technical challenges have been explored in this study, some that are unique to the arctic, it is ultimately the high cost that would likely deem this solution infeasible in today's market.

6 Conclusion

With Longyearbyen's current coal energy plant due to close in the near future, alternative energy sources need to be explored and selected to meet the demands of the community. While many renewable alternatives have been explored in the MPE report (Tennbakk et al., 2018), the merits of FOW have not been explored in detail for Svalbard. Through the analysis of FOW at Svalbard, it appears that this renewable energy solution would have a smaller impact on the environment than many other alternatives (Bergström et al., 2014). While it appears that FOW is feasible from an engineering perspective, it is difficult to see a project of this size approved in the sparsely populated region due to funding constraints. Perhaps the best hope for such a project is the mass manufacturing of the semi-submersible units along with continued reductions in cost from increased efficiency in development. A standardised FOW turbine could be implemented globally and easily brought to site in Svalbard.

The research question sought an analysis into the feasibility of FOW as well as the identification of critical challenges that would be encountered during construction, installation, commissioning and operation. While weather conditions can be harsh in the arctic and downtime could be larger than other sites, there should be adequate operation windows that enable works to progress during the summer months. Using a semi-submersible platform also provides the opportunity for onshore fabrication that limits the downtime risk. The ice conditions were explored through a SAMS simulation, and it appears that sea ice will have little impact on the dynamic stability and operability of the concept.

In addressing the research question, extensive research and testing was carried out however the study was not able to address all challenges pertaining to the project. Several hypotheses were proposed to answer the research question. The first hypothesis was confirmed through this study, in that a FOW farm was a feasible solution to meet the energy needs of Longyearbyen. The wind potential at the selected site was found to be adequate to service the needs of the community. The second hypothesis was also confirmed that the FOW farm would likely be technically feasible, however financing barriers would likely result in this solution being dismissed. It is also apparent that the third hypothesis would also hold true, in that if the current cost and optimisation projections are realised, the solution would be more appealing and affordable, improving the feasibility of the concept.

In conclusion, the study demonstrated that FOW could technically be implemented in Svalbard. The engineering challenges could be overcome, and a solution could be developed that would adequately service Longyearbyen. The project however would not be deemed feasible during the time of writing due to excessive costs associated with the construction. The solution could still be appropriate in the future, and the findings from this thesis could be utilised in a future study should FOW become an attractive energy alternative in Svalbard.

6.1 Future Work

More research is required to progress the FOW concept to development. The most critical information required would be costs, and a detailed cost estimate and business case analysis should be conducted initially before any further progression of works. Any proposed development would need political support and identifying the budget and appetite for such a project is an important consideration. Additionally, more detail on the construction methodology and installation program would be required to develop more accurate cost projections. Greater detail on the concept development is also required and would include further dynamic simulations for the site conditions. Stakeholder engagement and an environmental impact assessment would also need to be conducted for the project.

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APPENDIX A – Configuration of the Shoreline Cases

Photo taken by author during stay in Svalbard

Table A 1 Shoreline simulation activity assumptions

Category	Item	Assumptions	Number	Units
Port	Hammerfest	Repair Slots	20	units
		Loadout Berth Capacity	20	units
		WT Capacity	2	units
Assets	12MW FOW Semi-sub	Turbines	6	units
		Mooring Line	6	units
		Mooring Anchor	6	units
Logistics	Crane	Assembly Capacity	1	units
		Availability	0700-2000	
	Anchor Handling Vessel	Mooring Line Capacity	20	units
		Mooring Anchor Capacity	20	units
		Transit Speed	10	kn
		Dynamic Positioning Speed	2	kn
		Dynamic Positioning Activation Time	1	h
	Towing Vessel	WT Capacity	1	units
		Transit Speed	10	kn
		Towing Speed	5	kn

Table A 2 Shoreline simulation operation inputs

Logistics	Activity	Time (hrs)	Weather Window (hrs)	Wave Limit (m)	Wind Limit (m/s)
Crane	Mobilisation	1			
	Secure substructure	5			
	Prepare lifting	1	2		15
	Install Tower	15	18	2	10
	Install Nacelle	10	16	2	10
	Install Blade 1	6	10	2	10
	Install Blade 2	6	10	2	10
	Install Blade 3	6	10	2	10
Anchor Handling Vessel	Mobilisation	3	4	2	15
	Mooring Anchor Loadout	6	8	2	15
	Mooring Line Loadout	6	8	2	15
	Sea fastening	4			
	Port Manoeuvring	1			
	Transit		4	2	18
	Mooring Anchor Installation	18	20	2	18
	Mooring Line Installation	18	20	2	18
Towing Vessel	Mobilisation	3	4	2	15
	Loadout	4	6	2	15
	Towing		4	2	18
	Turbine Hook up	10	12	2	18

Table A 3 Shoreline simulation activity breakdown for May start date and Markov weather model

Operation	Duration, [hours]
1. Loadout, transport and piling for Batch 1	
1.1. Loadout for piling	6.01
1.2. Transit to next asset	54.06
1.3. Mooring anchor (Wind turbine 1)	19.01
1.4. Transit to next asset	2.06
1.5. Mooring anchor (Wind turbine 2)	18.01
1.6. Transit to next asset	1.42
1.7. Mooring anchor (Wind turbine 3)	41.94
1.8. Transit to next asset	1.24
1.9. Mooring anchor (Wind turbine 4)	18.00
1.10. Transit to next asset	2.34
1.11. Mooring anchor (Wind turbine 5)	18.00
1.12. Transit to next asset	1.67
1.13. Mooring anchor (Wind turbine 6)	18.01
1.14. Transit to port	49.39
1.15. Arrival at port	0.00
2. Loadout, transport and foundation for Batch 2	
2.1. Loadout for foundation	6.01
2.2. Transit to next asset	53.82
2.3. Mooring line (Wind turbine 1)	19.00
2.4. Transit to next asset	2.06
2.5. Mooring line (Wind turbine 2)	18.01
2.6. Transit to next asset	1.42
2.7. Mooring line (Wind turbine 3)	18.01
2.8. Transit to next asset	1.24
2.9. Mooring line (Wind turbine 4)	18.00
2.10. Transit to next asset	2.34
2.11. Mooring line (Wind turbine 5)	18.00
2.12. Transit to next asset	1.67
2.13. Mooring line (Wind turbine 6)	18.01
2.14. Transit to port	49.38
2.15. Arrival at port	0.00
3. Loadout, transport and installation of Batch 3	
3.1. Loadout for installation	4.01
3.2. Transit to next asset	99.11
3.3. Installation of Wind turbine 1	10.01
3.4. Transit to port	50.02
3.5. Arrival at port	1.00

4. Loadout, transport and installation of Batch 4	
4.1. Loadout for installation	4.01
4.2. Transit to next asset	98.28
4.3. Installation of Wind turbine 2	43.72
4.4. Transit to port	49.89
4.5. Arrival at port	1.00
5. Loadout, transport and installation of Batch 5	
5.1. Loadout for installation	4.01
5.2. Transit to next asset	97.94
5.3. Installation of Wind turbine 3	10.01
5.4. Transit to port	49.69
5.5. Arrival at port	1.00
6. Loadout, transport and installation of Batch 6	
6.1. Loadout for installation	4.01
6.2. Transit to next asset	97.86
6.3. Installation of Wind turbine 4	10.01
6.4. Transit to port	49.68
6.5. Arrival at port	1.00
7. Loadout, transport and installation of Batch 7	
7.1. Loadout for installation	4.01
7.2. Transit to next asset	97.47
7.3. Installation of Wind turbine 5	55.03
7.4. Transit to port	49.49
7.5. Arrival at port	1.00
8. Loadout, transport and installation of Batch 8	
8.1. Loadout for installation	4.01
8.2. Transit to next asset	97.28
8.3. Installation of Wind turbine 6	10.01
8.4. Transit to port	49.39
8.5. Arrival at port	1.00