Department of Mechanical and Aerospace Engineering

Electrification of the North Sea oil platforms with help of offshore wind turbines

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Signed: Aliihsan Sicim Date: 23.08.2019

Abstract

As a result of climate change, greenhouse gas emission such as CO_2 need to be restricted. As a |large portion of Norway’s CO_2 emissions is from the Oil and Gas activities in the North Sea the government need to limit the emission levels, especially post signing the Paris Agreement. One of the key alternatives to reduce the gas emissions in Norway is to connect the platforms with cables from shore to cover their energy demand, so the gas turbines on the platforms can be shut down.

This thesis is set out to investigate the possibilities of electrifying the platforms with the use of floating offshore wind turbines. This thesis is highlighting the different aspects of floating offshore wind turbine in the literature review., and simulation been performed to see the difference between the offshore location to the land location in terms of production and efficiency. Similar wind turbine was used in both scenarios, and only the location would differ.

The thesis conclude that offshore locations are outperforming the land site, but floating offshore wind turbines are still in test phase. However, if the prices of floating offshore wind turbine decrease with decrease in operation and maintenance cost at the same time, it will be an attractive solution both for grid connected platforms and platforms operated with only gas turbines, especially if the taxation on CO_2 increases and stricter or subsidising policies.

Acknowledgment

I would like to thank my supervisor Dr Paul Tuohy for his guidance. Furthermore, I would also thank all of my professors in Sustainable Engineering who have helped me gain the knowledge required to successfully complete and conduct this thesis.

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Contents

LIST OF FIGURES

LIST OF TABLES

1. Introduction

Consumption of energy has increased consistently since the industrial revolution (Medlock, 2009), with the increase in overall global population being a key driver (Ehrlich and Holdren, 1971). However, there have also been other factors that have had significant impact on the development, including the pace technology development (Medlock, 2009), which has led to increased energy consumption in some parts of the world more than other parts. This rapid progress in technology development, especially in agriculture, has made it possible for more people to meet their food demand, and also led to fewer people working in agriculture as a result of automated processed, increasing productivity and ultimately having a positive effect on the economy. An ever-increasing middle class growing out of poverty in many countries increases the energy consumption and consequently also the overall energy consumption (Gertler et al., 2016).

Energy prices have a direct impact on the development of countries, as it is a significant expense post for families (Belke et al., 2011)), and hence directly connected to people's ability to move out of poverty. As an example, over the past couple of years, there has been considerable fluctuations in the oil price, which has a measurable impact on both net importers and exporters of oil. However, with most developing and emerging economies being net importers, the falling oil prices had a positive effect on the overall economy. An increase in disposable income will ultimately lead to higher overall energy consumption (Belke et al., 2011). However, many countries today, primarily developing and emerging economies, have a very low base in terms of overall energy consumption versus the developed economies. The low energy consumption base, combined with demographics such as a young population, results in developing and emerging economies having the potential to increase their energy consumptions significantly. If they increase their consumption to western standards, the overall energy consumption increase considerably more then what is being used today (Soytas and Sari, 2003).

The current environment with climate change is increasing the risk of the population being exposed to natural disasters and changes in their living areas. The Intergovernmental Panel on Climate Change (IPCC) states that in order to minimise the negative outcomes of climate change, the temperature increase should maximum be limited to +1.5 degrees Celsius, which will lead to the negative impact on the biodiversity to be minimised (IPCC, 2018). If the temperature increase is not limited to +1,5 degrees Celsius one of the outcomes can be major changes to where people live, in turn contributing to an increase of environmental migration of people .

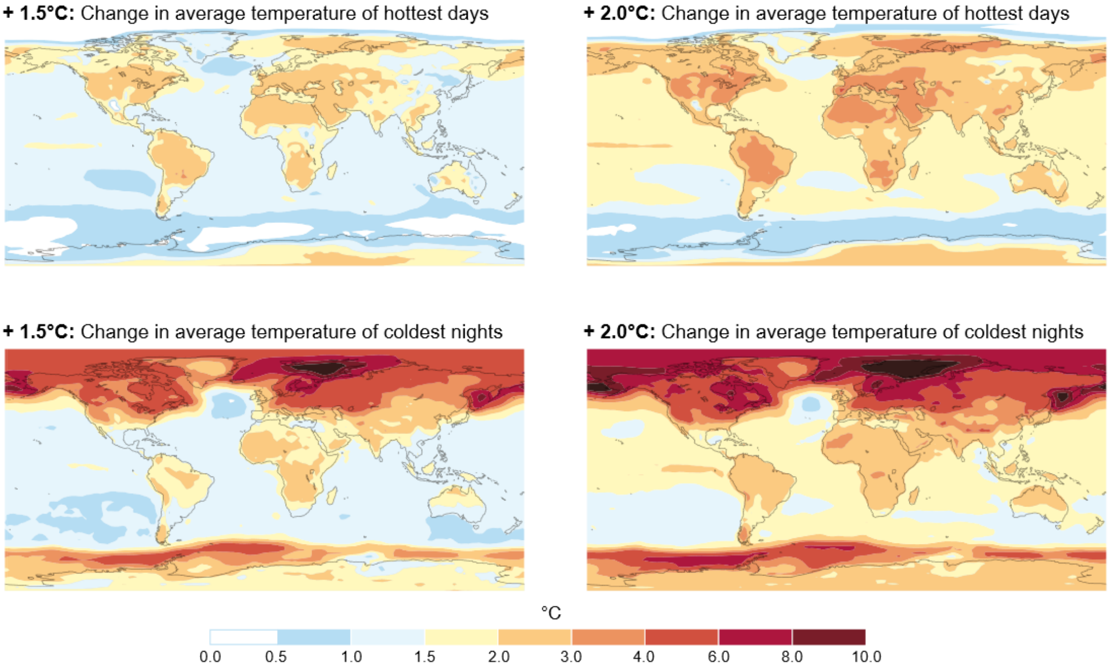

Figure 1: Temperature change is not uniform across the globe. Projected changes are shown for the average temperature of the annual hottest day (top and the annual coldest night (bottom) with 1.5 °C of global warming (left) and 2 °C of global warming (right) compared to pre-industrial levels (IPCC, 2018).

The Paris Agreement is trying to proactively manage the unfavourable trend, with many countries decided to cut CO_2 emissions to limit the temperature rise (Nations, 2016). European countries are among the participants that have agreed to have the most significant cuts of greenhouse gasses since they are one of the more significant contributors to the release of climate change gasses (commision)(Boden et al., 2009). Fossil fuelled energy sources such as oil, gas and coal are the most significant contributors of greenhouse gases in the form of CO_2 (Boden et al., 2009), which are all sources that will be used many years to come, specifically as petroleum is used in aircrafts fuel and within the chemistry industry, and many others (IEA, 2019). In order to achieve the emission reduction objectives, put forward in the Paris Agreement, countries need to diversify the energy sources in the direction of renewable sources and have cleaner oil and gas production, by cutting out native electricity production with diesel and gas generators.

Oil and gas is a major contributor to the Norwegian economy, and employs around 300,000 people directly or indirectly, with the income from the petroleum sector contributing estimated to reach 263 billion Norwegian Kroners to the national budget (Finansdepartement, 2019). It also contributes to the Government Pension Fund, which has the intention of ensuring responsible and long-term management of income streams from Norway's oil and gas resources in the North Sea so that this wealth benefits both current and future generations (Management, 2019).

Renewable energy systems, in contrast to fossil-based sources, are abundant and will not go empty, with the main renewable energy systems being solar power, hydropower and wind power . Common characteristics of most of the renewable energy sources are that they are periodic and cannot be turned on and off after demand, but is dependent on natural conditions (Demirbaş, 2006, Dincer, 2001, Bilgen et al., 2004). However, excess electricity production from renewable energy systems can be stored, allowing the overall supply and demand to be managed more efficiently (Denholm et al., 2010, Barton and Infield, 2004).

As a result of the environmental effect of fossil, Norway is increasingly looking into renewable sources for energy. Norway's solar capacity factor is low and would not be suited for large scale energy production; however, Norway has already developed most of its hydropower capacity, with the remaining places are protected areas that cannot be built on (Løvseth, 1995).

However, having exploited two of the three most frequently used renewable sources, Norway still has numerous opportunities for wind turbines, both on land and offshore (Lundsbakken, 2019). Wind power has had a slow start in Norway, as Norway's electricity production is 95,% renewable with hydropower, which is a less expensive way for electricity generation (Sentralbyrå, 2018, Førsund, 2015).

1.1. Problem Definition

Due to climate changes Norway have agreed to the Kyoto and Paris agreements, which implies that Norway must reduce CO_2 emissions. Norway categorises its CO_2 emissions in two ways, one for the mainland and one for offshore. In order to not to increase the CO_2 emissions further from the oil sector, new oil platforms in Norway need to operate with electricity from the mainland(Torvanger and Ericson, 2013), which implies a cable from mainland to be puld to the respective platforms. This is more expensive to implement versus traditional sources as the distance from the mainland to the oilfields are relatively long (Oljedirektoratet, 2019). Cross-section of the cable is decided by the distance and the electricity demand, which is dependent on the platform and production capacity. The origin of the electricity produced will be having a European carbon footprint since the European electric grid is integrated and the European electric production is not 100 % renewable as mainland Norway (Agency, 2018).

Oil platforms energy demand is in most of the cases covered by gas turbines. The gas turbines used on the platforms have an efficiency of around 30-35%, while land-based combined heat and power plants (CHP) have around 60-80 % efficiency (Nguyen et al., 2014). Emissions from land-based CHP plants also have fewer emissions since they are more efficient and have better cleansing systems of the exhaust gas since weight and space are not as important as on a platform where there are limitations on the weight.

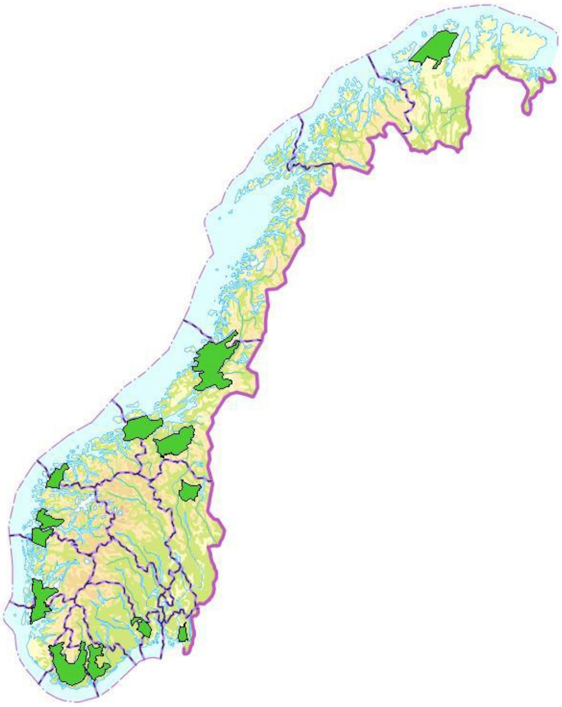

Figure 2: Map of Norway with the 13 selected areas for wind turbine generation (NVE, 2019a).

The last couple of years construction of wind turbine farms have gained traction in Europe. Substantial development has taken place in the UK (Scotland), Denmark and Germany (WindEurope, 2018). Germany has invested heavily in renewables and wind farms after the Fukushima disaster. Norwegian Water Resources and Energy Directorate

(NVE) have made a national framework for wind power onshore on behalf of the Ministry of Petroleum and Energy (MPE) in Norway, as Norway has one of the best wind resources in Europe (NVE, 2019a). The proposal from the NVE consists of two parts; a map of the most suitable areas for wind power and an updated knowledge based on the effects of wind power (NVE, 2019a). Figure 2 shows 13 green areas that have been appointed for wind power development in Norway.

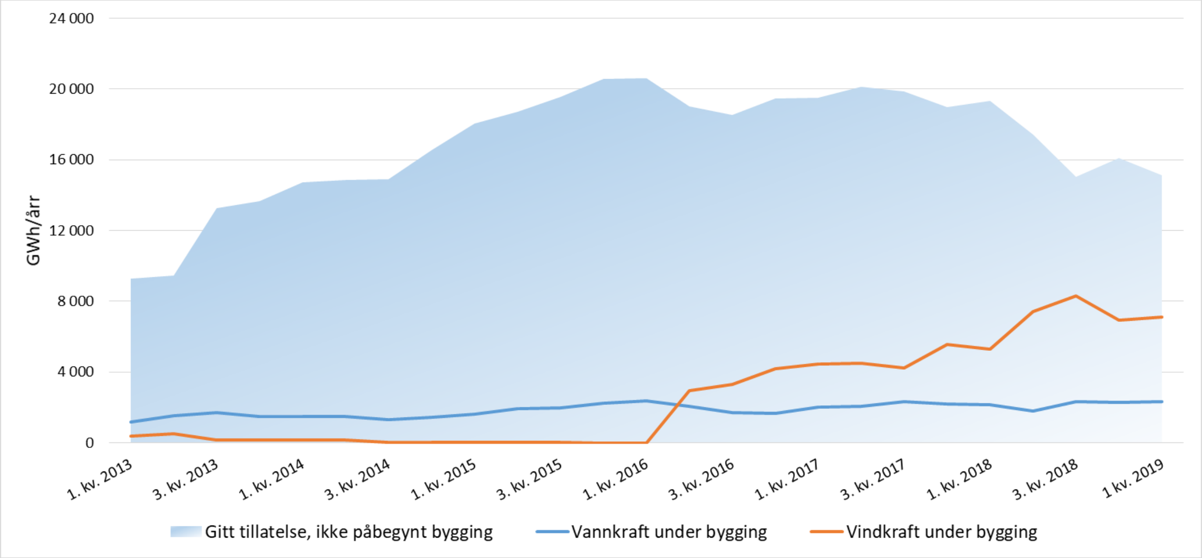

Figure 3: development per quarter, total for final permits that haven't started, blue line is hydropower and orange line for wind power under construction (NVE, 2019b).

With more development of wind power plants, the resistance to wind farms has increased in Norway (Leif Rune Løland, 2019, Viseth, 2019). The increased resistance against wind turbines even led to a local authority to withdraw construction permit from the development of a wind farm (Rognstrand, 2019).

1.2. Aim and objectives

The aim of this report is to look at the possibilities of electrification the oil platforms with the use of wind turbines and look at the differences in production on land and offshore. The goal is to test the differences between offshore and onshore wind turbines.

1.3. Approach and Thesis Structure

The approach taken was first to carry out a focused literature review (chapter 2) outlining relevant topics to be discussed throughout the thesis, covering CO_2 emissions, renewable energy solutions and the Norwegian continental shelf. Further, this thesis defines the method to be adopted for the investigation (chapter 3) of electrification of oil platforms in the North Sea with the help of floating offshore wind turbine, followed by the case studies including discussions around the results, and finally, the thesis concludes with a discussion highlighting limitations and recommendations for future work (chapter 5), and final conclusions made.

2. Literature Review

2.1. The Environment

Human influence on climate has been the leading cause of the observed warming since the mid-20th century. Numerous regions of the world have already greater regional-scale warming, with 20–40% of the global population (conditional on the temperature dataset used) having experienced over 1.5°C of warming in at least one time of year. Temperature increase to date has already resulted in reflective changes to human and natural systems, including increases in droughts, floods, and some other different types of extreme weather; sea-level rise; and biodiversity loss – these changes are causing unparalleled risks to vulnerable persons and populations The most affected people live in low- and middle-income countries, some of which have experienced a decline in food security, which in turn is partly linked to rising migration and poverty (IPCC, 2012). Minor islands, megacities, coastal regions, and high mountain ranges are likewise among the most affected (Albert et al., 2018). Worldwide, numerous ecosystems are at risk of severe impacts, particularly warm-water tropical reefs and Arctic ecosystems (IPCC, 2014).

The Paris Agreement was put in place December 2015 and brings all nations that are part of the agreement into a common reason to undertake ambitious efforts to combat climate change and adapt to its effects, with improved support to assist developing countries to do so. As such, it charts a new and essential path in the global climate effort. The Paris Agreement's main aim is to strengthen the global response to the danger of climate change by keeping a global temperature increase this century well under 2 degrees Celsius but also chase efforts to limit the temperature increase even further to 1.5 degrees Celsius.

Appropriate financial flows, a new technology framework and an improved capacity-building framework are needed in order to reach the objectives of the agreement, thus supporting action by developing countries and the most vulnerable countries. The Agreement also provides for enhanced transparency of action and support through a more robust transparency framework.

Norway was among the first countries to formally sign up to the Paris agreement after the Norwegian government agreed on the following five key focus areas in the environmental efforts

- Reduce the Co2 emissions from the transportation sector
- Develop low emission technology
- Co2 emission handling
- Strengthen Norway’s position as a supplier of renewable energy
- Environmentally friendly shipping

Norway aims to adhere to the Paris Agreement in coherence with the EU by using the quota system called the Emission Trading System (ETS). The current goal is to reduce emission from non-quota industries with 40% from 2005 to 2030.

2.2. The Oil and Gas Industry

Most of the offshore O&G installations that are operative is self-supplied with open cycled gas-fired turbines (OCGT) supplying the required electrical, heat and mechanical energy for the onsite compressors and is located on the platforms. A few noteworthy exceptions are the installations powered from shore with AC transmission links (e.g. Gjøa (Communications, 2010-08-23) and Goliat (ABB)) or with HVDC transmission links (e.g. Valhall (ABB) and Troll (Jones and Stendius, 2006)). The efficiency of offshore gas turbines for electricity generation is significantly lower (e.g. 30% - 35%) then their comparison onshore combined cycle gas turbines (CCGT) gas power plant that has an efficiency around 50%-60%.

Offshore operations without connection to shore has been studied both in terms of fuel savings and CO_2- analysis shore ((He et al., 2010, Aardal et al., 2012, Korpås et al., 2012) and in the view of power stability and control (Årdal et al., 2011, Årdal et al., 2012, Årdal, 2011, D'arco et al., 2011, Svendsen et al., 2011). Promising behaviour in terms of power system stability can be achieved through a HVDC-link show studies (Marvik et al., 2013, Kolstad et al., 2013).

One of the significant development costs for offshore wind projects is the transmission cables to the onshore grid and the AC or DC offshore substations. For offshore wind power plants that are located remotely, the transmission infrastructure investment represents approximately 20%-30% share of the total cost. By connecting wind power plants with close by offshore O&G installations we can bring down costs, through optimising and shortening the export cables to the O&G platforms instead of long export cables to the shore. Additionally, providing offshore O&G installations with renewable energy from wind power plants can have a reducing effect of total CO_2 emissions, which would be positive for the industry. Moreover, wind power plant and the O&G operators can share the investment cost between themselves.

Increasing energy demand in the Norwegian Continental Shelf is a new challenge for the O&G industry for existing and new offshore field installations. Some of the challenges can be summarized as:

- Mature fields need measures to increase production, for example, water and gas injection
- Increase of compression and pressure support, because counteract reduced reservoir pressure
- Transition to the transport of more significant amount of gas, long distances, instead of traditional oil production
- The requirement of a larger compressor with higher power capacity (increasing the compression & transport pressure) with discovery of new oil and gas at deeper sea depths and longer distances from the shore

Greenhouse gas emissions are expected to further increase since the power demand per produced petroleum is expected to grow in the future if the industry does not implement technologies to reduce the emissions. An innovative solution expected to attract more attention is supplying offshore O&G installations with renewable energy from offshore wind power plants. An O&G-installation cannot entirely rely on wind as the wind power generation is intermittent by nature. This implies that backup generation and/or some flexibility on load shedding of noncritical loads are essential (Årdal et al., 2014), however, the renewable solutions are still more environmentally friendly.

2.3. The Norwegian Oil and Gas industry

Utsira formation

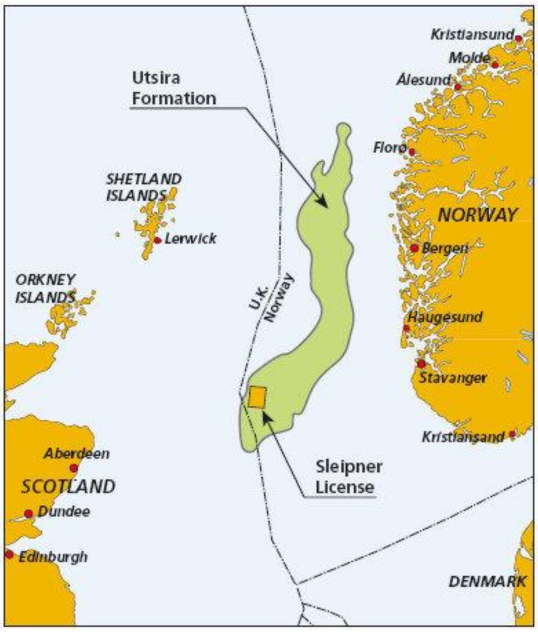

Figure 4: Utsira Formation (Solomon, 2007)

The Utsira height is located south-east part of the geological rift Vikingtrauet in Norwegian part of the North Sea. Utsira height is located 200 km west from Rogaland in mainland Norway and has a depth around 100-120 m. In the southern part of the Utsira height the Johan Sverdrup, Ivar Aasen, Gina Krog and Edvard Greig petroleum fields are located. (Askheim, 2018).

Johan Sverdrup

Johan Sverdrup is an oil and gas field located in the North Sea more specific Utsira height. This field is considered to be the 5th largest oil fields in Norwegian continental shelf. In 2010 *Avaldsnes* and in 2011 Aldous Major North and Aldous Major South were discovered. Ministry of Petroleum and Energy announced in January 2012 that the findings in Avaldsnes and Aldous would be named Johan Sverdrup field, after the politician Johan Sverdrup. Plan for development and operation got approved by the parliament on June 2015. The oil field will be constructed in several phases, production from the first phase will start in late 2019 with electricity from mainland. The second construction phase will have scheduled start-up in 2022, with extensions in process platform and modifications riser platform.

Figure 5: Location of Johan Sverdrup (Oljemuseum, 2019).

Estimates of the reservoir size was in 2017 299.67 million Sm^3 (standard cubic meter) recoverable oil and 9.13 million Sm^3 recoverable gas.(Oljemuseum, 2019)

Demand Model

Johan Sverdrup field will be operated with power from the mainland with a start-up in 2019 and throughout its lifetime. In first phase it is estimated that the field will need 100 MW to the field centre, this is with 20 % recommended safety margin. In the next construction phase an extra line will be established from the mainland to cover future power need from Johan Sverdrup and the three other fields; Gina Krog, Edvard Grieg and Ivar Aasen. This extra capacity will be installed fastest as possible and latest in 2022. The power demand for a fully operative Johan Sverdrup is dependent on the final production capacity. Indications show that a fully operative Johan Sverdrup will use between 120-170 MW. The three other fields are estimated to use up to 75 MW. Added together with the consideration of transmission losses between 10-12 and with security margins power demand could reach 280 MW from mainland (Equinor, 2014a, Equinor, 2014b)

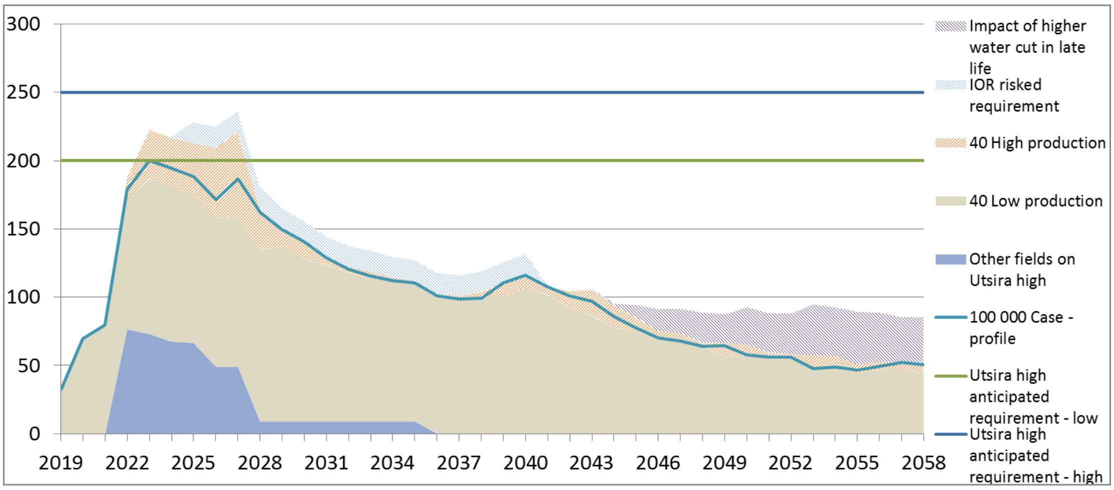

Figure 6: Power demand for full field lifetime (Equinor, 2014b)

Supply Model

Johan Sverdrup has a scheduled start-up in late 2019 with power from shore (PFS). The other three platforms Gina Krog, Edvard Greig and Ivar Aasen will have prepared for installations of PFS when a PFS solution is offered. Gina Krog field is operating with a gas turbine but is pre-invested in equipment to use PFS when it is available. When PFS is implemented the gas turbine will serve as a back-up system. The Edvard Grieg field similarly has pre-invested in equipment to receive PFS, but instead of one gas turbine Edvard Grieg is equipped with two gas turbines. Ivar Aasen is receiving its power from the Edvard Grieg platform with a dedicated AC cable.

In phase one, Johan Sverdrup is to be supplied with PFS. Kårstø grid has been modified for phase 1 and 2. The upgrade includes extension of the building with 300KV switchgear for both phases and an AC cable from Kårstø to Haugsneset, where the HVDC will be placed. This cable has a dimension of 3x630 mm^2. In phase 1 the power delivery from Haugsneset to the Johan Sverdrup riser platform will be 100MW.

Johan Sverdrup riser platform will be connected with 200 km 2x800 mm^2 subsea cables. Similar HVDC system will be installed in Johan Sverdrup as inn Haugsneset. DC power will be converted to AC and transformed down to 33 kV in this station to be distributed to Johan Sverdrup Installations (Equinor, 2014b, Equinor, 2014a)

2.4. Key issues in assessing wind resources

When planning a wind turbine farm, one of the essential parts is the location of the farm site since the wind is the fuel that wind turbines tap into to generate electricity and income. The wind farm has to endure the wind to operate reliably over their planned lifetime since this is one of the environmental forces that will affect the wind farm performance and reliability. Wind resource assessment is the procedure of portraying the atmospheric environment through measurement and modelling to address the many enquiries raised throughout the development, construction, and operational stage of a wind farm. These enquiries relate to site selection, energy production potential, turbine suitability and layout, the balance-of-plant design, site accessibility, and other project elements.

Fundamental for wind resource assessment is air temperature, humidity, precipitation, pressure and other atmospheric variables. They affect both the amount of power obtainable in the wind as well as the efficiency by which wind turbines capture and reform this power. Other factors are ocean waves, surface temperature, currents and other water-related parameters. These factors have a direct influence on the nature of the overlying atmosphere and impose significant loads on the foundations and is a challenge for vessels. Ultimately, the study of the physical and operating design environment of wind farms must be advanced in a combined fashion; meteorological and oceanographic (metocean) factors are interactive. An example of this is that wind farms must be designed after the concurrence of extreme winds and extreme waves from severe storms. Figure 7 demonstrates many of the metocean factors which offshore wind turbines must resist.

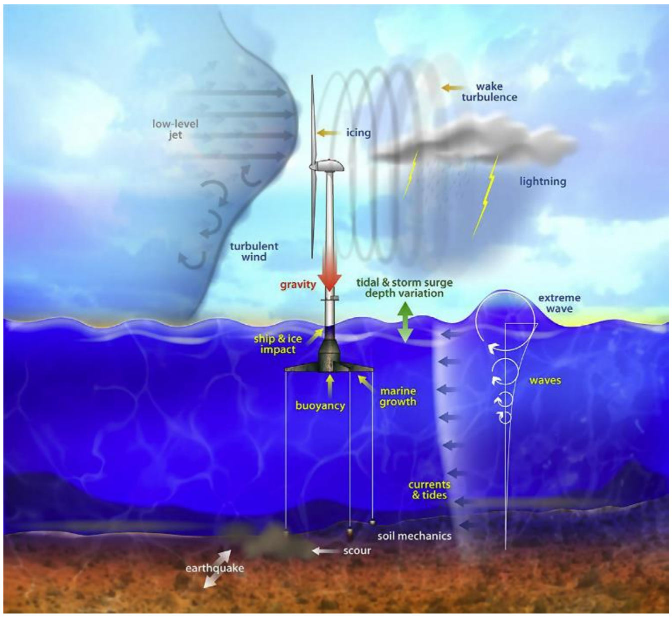

Figure 7: External conditions relevant for an offshore wind turbine system (NREL, 2014)

The marine environment itself is the greatest challenge to characterise offshore resources. Physical measurements are relatively sparse since it is logistically difficult and expensive. To reduce the negative impact of sparse physical measurements, strong emphasis is placed on numeric weather prediction models and weather satellites to characterise the ocean environment for numerous marine activities. Even though they are effective for special purposes, for example commercial fishing and navigation, for wind energy applications their value is more qualitative than quantitative. The reason behind this is that most atmospheric measurements focus on the ocean surface and a few meters above and below it, while large-scale wind turbines extend to at least 150 m above water surface and are not addressed by most measurements. Additional, since wind turbines are mounted to sea bottom-fixed or floating foundations, measurements of the water column, which are mostly absent from observational networks, are essential too.

The expectation from an offshore wind environment nature

Since the wind farm is going to located offshore in the Norwegian Sea, we need to see what differentiates the offshore environment from the land. Amongst the most apparent differences of the exposed ocean environment relative to land is the lack of terrain that contributes to low surface roughness. This leads to winds that are stronger with greater horizontal uniformity, wind speeds with smaller changes with height (ie, wind shear), and less turbulence. Figure 8 is satellite imagery of the low wind conditions over the world's ocean. Sea surface with small waves would have a surface roughness length of approximately 0.001; by comparison surface roughness of length of most vegetated land would be between 0.03-1.0m, height and

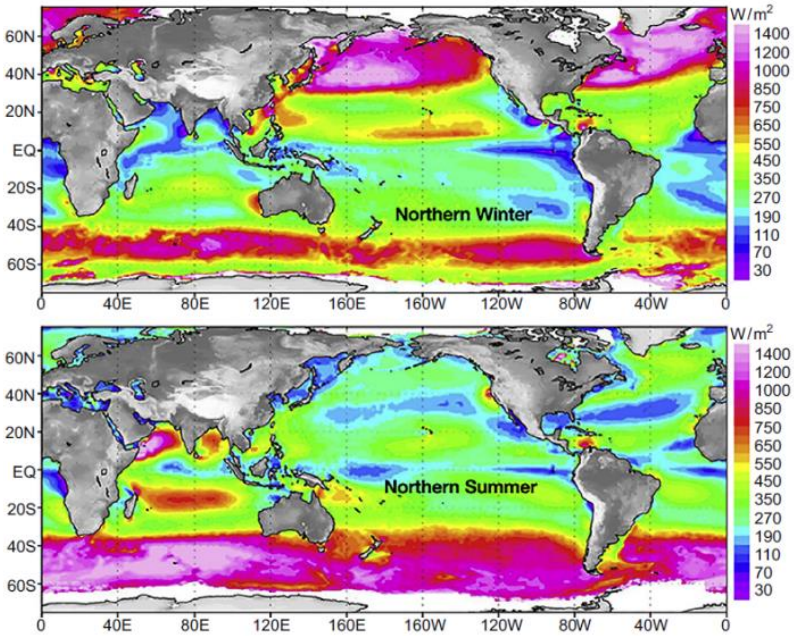

Figure 8: Wind power density over the global oceans in winter and summer(NASA, 2008).

vegetation type effects this. Bulk effects of surface roughness elements are being represented by surface roughness length and have a value of approximately one-tenth the height of those elements (Stull, 2012, Sutton, 1953)

Offshore wind turbines assume a power law wind shear exponent of 0.14 for IEC-specified operational conditions, 0.11 as a lower value specified for extreme conditions (IEC, 2009). In reality, atmospheric conditions influence wind shear, in the North Sea and western Atlantic average values between 0.06 and 0.16 have been observed (Berge et al., 2009, Brower, 2012). On land wind shear values averages significantly higher with between 0.14-0.30. The standard deviation of wind speed samples relative to the recorded mean is named turbulence intensity (TI), in the offshore environment, it is commonly observed to average in the range of 0.05-0-10. Surface roughness increases with high waves that are produced by strong winds, that leads to increased TI. On land the TI values are double as high then the sea (Bailey, 2016).

Important data parameters

Understanding of the local metocean environment is a key element for sound planning and design of offshore wind plants. This environment varies in time and space and is comprised of a spectrum of atmospheric and oceanographic conditions. Extremes that can be encountered over a plant's lifetime are part of the conditions of this nature, to ensure reliable long-term delivery of energy and storm survivability these extremes have to be addressed in the upfront. Wind and other meteorological variables; water- and sea bed-related variables; and joint variables are data parameters that are grouped into categories, these data parameters are used to define metocean conditions. These parameters are achieved through one or more observations while some are directly measured. The parameters mentioned are obtained through recommendations from a cross-section of leading international standards and guidelines, documents from best practice industry, turbine manufacturer suitability forms, and industry experience from others (IEC, 2005a, IEC, 2005b, IEC, 2009, ABS, 2013a, ABS, 2013b, Atmosphere, 1975, API, 2007, DNV, 2014). Time scales, parameter measurement and modelling approach, analytical methods can have differences between the sources.

2.5. Design of a floating offshore wind turbine

Floating offshore wind turbine (FOWT) development takes learnings from previous development of onshore wind turbine generation (WTG), but we need to be careful about making assumptions about optimal turbine design (one size fits all) from previous learnings from developing onshore wind turbines since many of the design drivers for onshore wind turbines are not present offshore. FOWT components need to be developed to demand minimal with operation and maintenance (O&M) cost. The components that need less change then other parts of a wind turbine are the gearbox, generator, and power electronic components. These components that need changes to demand less maintenance, since getting to the FOWT is challenging, and to perform maintenance becomes costly. The focus in this part will be the blade design and the substructure since these parts are the most crucial and exposed to the challenging environment (Collu and Borg, 2016).

Offshore blade design

When we are designing offshore rotors, we need to be careful about making assumptions about optimal turbine design from previous learnings from developing onshore wind turbines since many of the design drivers for onshore wind turbines are not present offshore. An example of this is the differences between two- and three-bladed turbines are negligible in terms of economics, the reason two-bladed turbine is less preferable than three-bladed turbine is because of it is less noisy and less visually disruptive. However, in terms of transportation and installation, the two-bladed turbine would offer a significant advantage, since these drivers are not present offshore.

Additionally, the cost of energy offshore is less dependent on the cost of the turbine compared to onshore, as shown in Table 1. To reduce the cost of the turbine trade-offs in the annual energy yield have been made (for example, at the expense of aerodynamic performance using more structurally efficient aerofoil shape) something making sense onshore doesn't implicate that it will have the same impact offshore it could even cause a negative effect. On the other hand, reduction on the cost of energy could perhaps be achieved through reducing the loads the foundation experience, since the foundation is cost is far larger offshore. The whole wind turbine system must be taken into consideration, the point is that we cannot consider the rotor in isolated.

In this report, the turbine architecture, which currently dominates the horizontal axis with variable-speed/variable-pitch turbine will be used (Greaves, 2016).

Table 1: Relative contributions to cost of energy, adapted from (Jamieson and Hassan, 2011).

	Onshore (per unit)	Offshore (per units)
Wind turbine	0,57	0,30
Balance of plant	0,25	0,30
Operations and maintenance	0,18	0,33
Decommissioning	0,01	0,07

The support structure of an offshore wind turbine

The tower is part of the support structure, following the IEC 61400-3 classification (Quarton, 2005), for offshore application, includes the actual foundation embedded in the soil and the substructure. Rotor nacelle assembly (RNA) contains the moving parts and is more technically advanced compared to the tower that is relatively simple. Even though approximately nearly 20% of installed cost offshore and 16% on land is the support structure responsible off (Tegen et al., 2010). Optimising the tower and substructure configurations will effectively reduce the overall project costs since there is plenty of margins. Furthermore, tower engineering experience gained in the past is being pushed to the boundaries with more increasingly challenging sitting at sea, example tropical cyclone regions and continuous growth of turbine RNAs. For these reasons, research and development efforts toward a lower levelized cost of energy (LCOE) have put the topic of support structure into more focus. Essentially, the problem of finding an appropriate distribution that ensures safe turbine operation under all prescribed external conditions, along the tower length, of mass and stiffness properties, including actions from the environment and from the interaction with the grid and the control system is left over to the designer. The necessary length of the tower is dictated by the turbine height, the costs of a taller tower would have to consider the gains in energy captured at higher altitudes and ideally strike a balance between these two aspects. Historically, approximately one rotor diameter was set as the tower lengths. This thumb rule is no longer followed on installations at sea and low wind sites. Higher hub heights that take benefit of higher wind speeds and less turbulent atmospheric layers are required, which return open up for wind development to be profitable in less windy, forested areas. At sea, on the other hand, shorter towers are favoured then on land for a given hub height, because of lesser wind shear values and the substructure interface terminating at several meters above the still-water level. However, solving the design problem, in either case, is a difficult challenge. Offshore installations, promote the largest turbines and generally characterised by more significant ultimate thrust values and tower-head masses than on land (eg, typical for a 6-MW offshore machine 1800kN and 350+ t) given the inherent high balance of station costs. These extreme loads are also to be combined with the possible presence of other sources of loading (eg, floating ice), practically corrosive environment, and wave loading and rotor aerodynamics contribute extraordinarily to fatigue loads coming from some 10^8 cycles and 10^9 cycles respectively.

Several structural criteria have to be met by the overall system simultaneously; this is the designer's job to ensure. The system must achieve the prescribed model behaviour, with regards to the response to external and internal stimulation, decreasing the risk of instabilities or resonance. Load distribution and material utilisation throughout the tower and substructure below need to be economically optimised while also strength and deflection limited states must be verified. Transportability and installation loads and processes must be examined and quantified after the verification of the weldable wall thickness of steel cans the rollability of plates; this is for instances manufacturability constraints. Important aspects must be covered even in the detail design such as the flange and weld design, also the interface with the RNA and the transitions piece, hoists and man lifts, the housing of power electronics, access door and manholes, and the needed coating protections. Generally, loads are determined with the use of aeroelastic simulations, the three-dimensional (3D) stress state is assessed through loads applied to finite element models. To confirm modal characteristics the same models are being used. In this case, the soil-structure interaction and the overall stiffness offered by the substructure and pile subsystem contributes to additional difficulties associated with assessment of the effects (Damiani, 2016).

Tower types and their function

Wind turbine towers accomplish two essential functions and have been considered as one of the crucial components, since the start of the wind industry. One, supporting the rotor to reach an adequately high hub height to be able to access advantageous wind resource. Two, provide a load path from the turbine to the foundation that is safe and dependable. Both land and offshore based support structure layout selections are given. The differences in these alternatives are in applied materials, geometric layout and load paths, or both. The towers must assure regardless of the choice that the modal system characteristics are kept away from the turbine excitation frequency bands and inside the acceptable bounds. Fabrication costs and the transportation and installation procedures need to be paid special attention since one of the alternatives could be more or less promising for a specific site and turbine configuration. Many different environments and applications rarely make one particular design, one-size-fits-all even though this model is attractive. Optimising the entire turbine from a system perspective is increasingly becoming more vital, where all project aspects, from the structural performance to the balance of station costs, are evaluated. There are important differences between onshore and offshore wind turbine generators (WTGs) and only some of the vast experience gained from onshore WTG can be applied for offshore wind turbines (OWTs). Extreme corrosive environments, the variety of support structure and foundations, adding of hydrodynamic loads, and the crucial need to diminish maintenance more than on land because of the extremely expensive O&M are only some of these differences. The experience gained from the O&G sector can be used, but wind and O&G have differences in the system that makes engineering of an OWT very unique, such as larger wind loading, structural dynamics and structural nonlinearities. For this reason, analyzing the entire system with ad hoc tools are preferred and most rigorous design method, this is the so-called fully coupled approach where the WTG to the foundation, including effects of aerodynamics, hydrodynamics, servo-mechanics and structural dynamics are analyzed (Damiani, 2016).

Floating substructure

Floating substructure or platforms, including semisubmersible (where buoyancy and restoring mooring is guaranteeing stability), spars (Gravity is guaranteeing stability), and tension leg platform (TLP) (Excess buoyancy is guaranteeing stability) Figure 9 shows these 3 substructures. Where material and installation price makes fixed-bottom structures economically unfeasible, especially in deeper water, these systems promise economic advantages. Obviously, floating configurations are quite different in terms of dynamic behaviour from the O&G counterparts and again have their own unique challenges. Design procedures of towers that are mounted floating platforms have the same design of those of fixed substructure, but loadings from wave excitation and hydrodynamic becomes even more important. Dangerous oscillations throughout the system and the tower needs to be controlled and is key part of floating OWTs. Examples on floating OWTs include turbines on a spar and a semisubmersible (Equinor's Hywind (Skaare et al., 2015) and Principle Power's WindFloat (Roddier et al.))

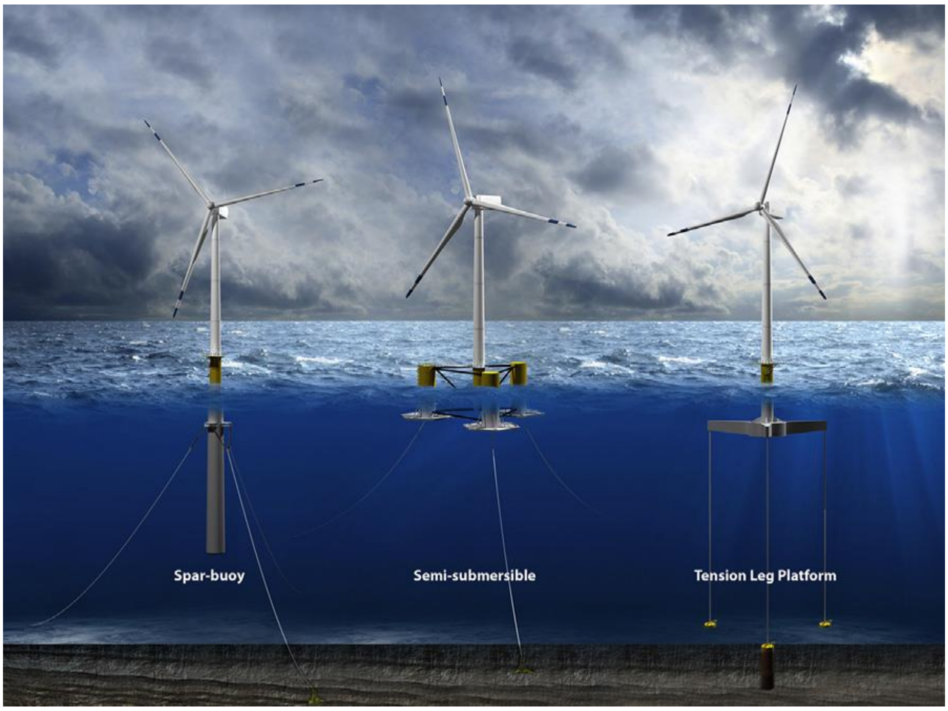

Figure 9: Illustration of types of offshore wind turbine platforms, by Joshua Bauer, (NREL, 2016)

The support structure is site-dependent and is encompassing both tower and substructure, which is an important aspect to underline. The turbine can be deployed at a number of different locations that feature wind conditions within the turbine class specifications since it is designed against the specifications in the standard (eg, class IB from (Quarton, 2005)). Wind statistics, wave and current regimes, bathymetry and modal requirements are the aspects support structure will be optimized after. (Damiani, 2016, Collu and Borg, 2016).

2.6. How HOMER Pro works

U.S. National Renewable Energy Laboratory (NREL) developed the HOMER Micropower Optimization model is a computer model to facilitate the comparison of power generation technologies across a varied range of applications and to assist in the design of micropower systems. A system that generates electricity, and serves a nearby load is a micropower system. Systems serving electric and thermal loads can me modelled with HOMER, grid-connected and off-grid as micropower systems, such a system may employ any combination of electrical generation and storage technologies. A large number of design options and the uncertainty in key parameters, which make analysis and design of micropower systems difficult. Further complexity is added with renewable power sources, since their availability may be uncertain, which can cause the power output to be intermittent, seasonal, and non-dispatchable. To overcome these challenges HOMER got developed.

Homer simulates the operation of a system by making energy calculations in each time step of the year. Electric and thermal demand in every time step is compared to what the system can supply in that time step, and the flow of energy is being calculated for each component in the system. Homer also decides for systems including batteries or fuel-powered generators in each time step how to operate the generators and if to charge or discharge the batteries. In each system configuration that you want to consider energy balance calculations are performed by HOMER. Whether the system can meet the electric demand under the specified conditions, determines whether a configuration is feasible (Lambert et al., 2006)

Wind Turbine

Homer uses a particular power curve, which is graph of power output versus wind speed at hub height, to model a wind turbine as a device that converts the kinetic energy of the wind into ac or dc electricity. Figure 10 is an example of a power curve.

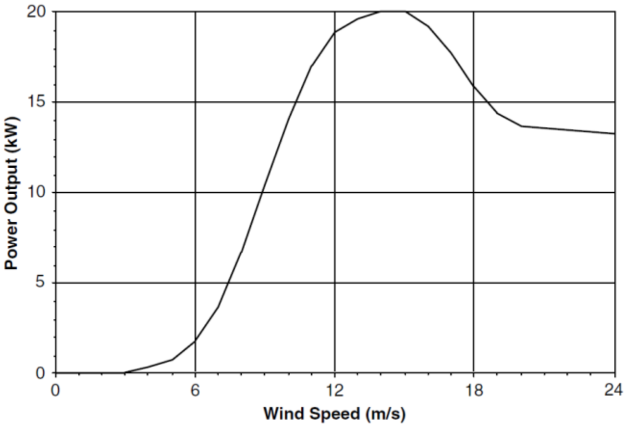

Figure 10: Example of a power curve (Lambert et al., 2006)

A standard air density of 1.225 kg/m^3 is assumed in HOMER, and is applied in the power curve as standard, which corresponds to standard temperature and pressure conditions. Homer uses a four-step process to calculate the power output of the wind turbine, for each hour. First, wind resource data is used to determine the average wind speed for the hour at the anemometer height. Second, with the use of logarithmic law or the power-law, it calculates the corresponding wind speed at the turbine’s height. Third, assuming standard air density it calculates its power output at that wind speed referring to the turbine’s power curve. Fourth, the ratio of the actual air density to the standard air density is the air density ratio, which is used to multiply the power output value. The standard U.S standard atmosphere is used by HOMER to calculate the air density ratio at the site elevation. The air density ratio is assumed to constant throughout the year (Lambert et al., 2006)

2.7. Enercon E-126

Enercon E-126 is a wind turbine with rated power of 7,580 kW, has a rotor diameter of 127 m and a hub height of 135 m. The wind energy converter (WEC) concept: gearless, variable speed, single blade adjustment. Rotor type is upwind rotor with active pitch control, three blades, and rotates clockwise with a variable rotational speed 5-12.1 rpm. Has a cut-in wind speed of 3 m/s, rated wind speed is 16.5 m/s, and cut out wind speed of 25 m/s. (Enercon, 2015)

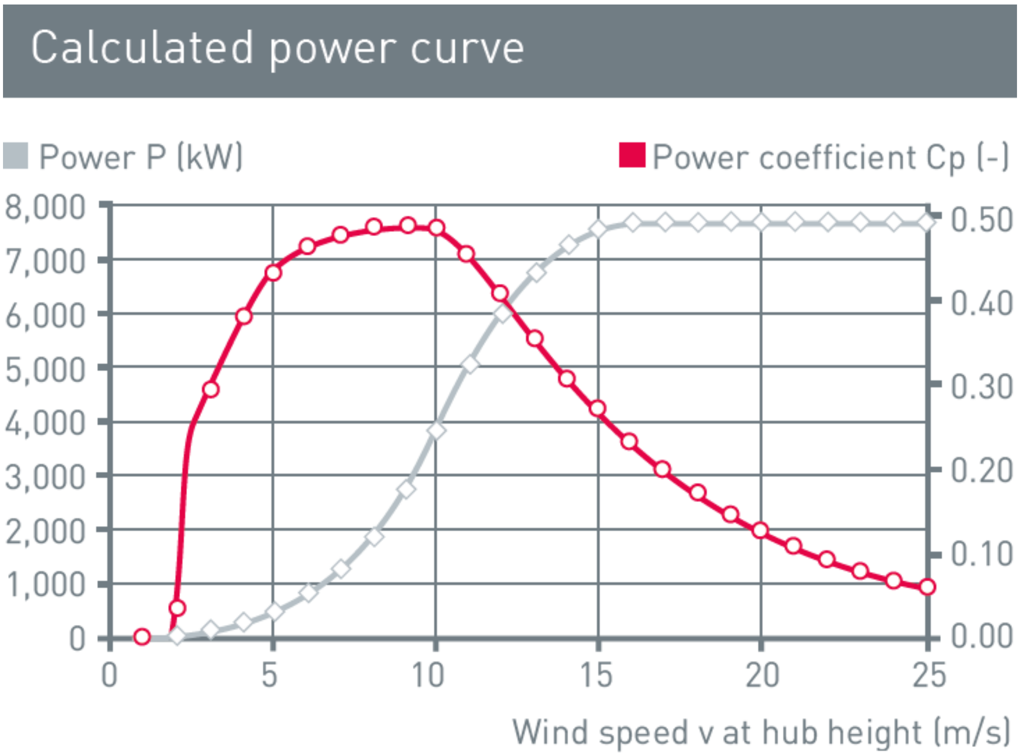

Figure 11: Calculated power curve for Enercon E-126 (Enercon, 2015)

3. Methodology

The objective of this report is to fulfil numerous steps. Initially, in order to gain a better understanding of the subject a throughout literature review was conducted in order to outline the most important literature on the current environmental debate, the Norwegian Oil and Gas industry, wind technology, regulations and the wind turbine market.

After selecting the offshore platforms for electrification in the Norwegian continental shelf, information about these platforms had to be gathered to understand their current supply and demand of energy.

In order to simulate demand-supply matching a software had to be used and the choice landed on HOMER Pro. HOMER Pro is a microgrid simulation software. The only wind turbine used in the simulations is Enercon E-126 7,5 MW, so we have the same parameters for the wind turbine itself, in order to be able to decide if the different locations will have a different outcome of production and how much.

There will be two simulation scenarios;

Scenario 1:

In this scenario, the wind turbine will be located at the position of Johan Sverdrup, the wind turbine that will be used in the simulation is Enercon e-126 7,5 MW. First, we will simulate only one turbine at the site, at look at the capacity factor we are getting out of the turbine. We will look at the wind speeds and electricity produced. Secondly, we will simulate with multiple turbines to find the optimum setup, that will cover the need of the platforms. The demand will be set to constant 250 MWh, since we do not have a more accurate demand data and that it is close to the platforms, so there is less transfer loss.

Scenario 2:

In the second scenario, the WTG will be located on land, close to the transfer cables that are connecting the platforms to the land. The first step and second step of scenario one will be performed, but with one difference, the demand will be set to 280 MWh to accumulate for the transfer loss that is around 10-12% because of the long distance.

After both scenarios have been completed, they will be compared based on different aspects such as the economy, efficiency and feasibility

4. Case Studies

4.1. Scenario 1

Phase 1

First, we need to select the location we are going to simulate, 02°32'51.381"Ø, 58°49'49.265"N (link), which is the location of Johan Sverdrup, then followed by the import the resources needed in the simulation. We import data for wind, solar and temperature. Afterwards, we need to fill in the demand where we fill in 250 MWh usage for the whole period, thereafter select the type of generation we want for or system, where we select Enercon e-126 7.5 MW wind turbine. We also need to select grid connection to be able to run the simulation, since it will not run if the whole demand is covered.

Then we run the simulation for only one turbine to gain results of the performance of the turbine, and wind speed data. As we see from figure 12 that shows annual max, day avg. max, average, day avg. min and annual min monthly is that the electricity produced is higher in the winter months than in the summer.

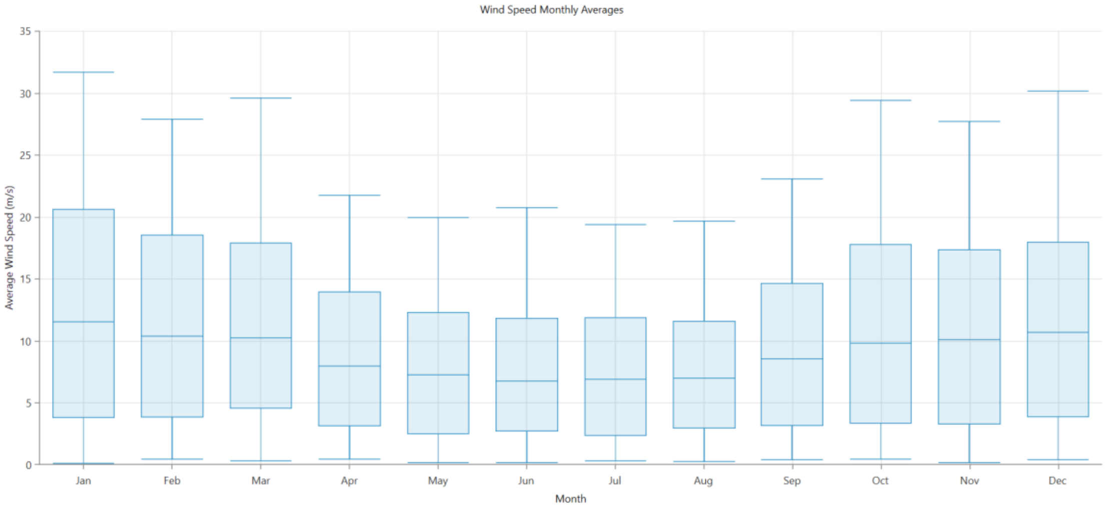

Figure 12: Wind speed monthly averages for, annual max, day avg. max, average, day avg. min and annual min.

Figure 13 shows us the wind speed over 1 year, as we can see that the electricity produced correlate with the wind speed.

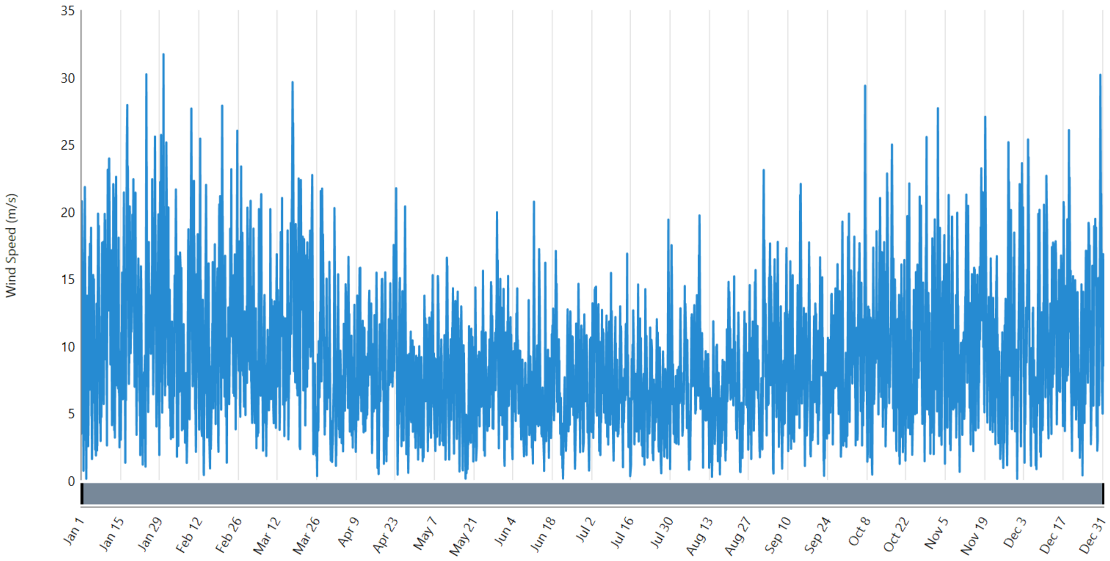

Figure 13: Wind speed offshore over 1 year.

Figur 14 shows that the highest frequency of wind speed in this area is approximately 7 m/s.

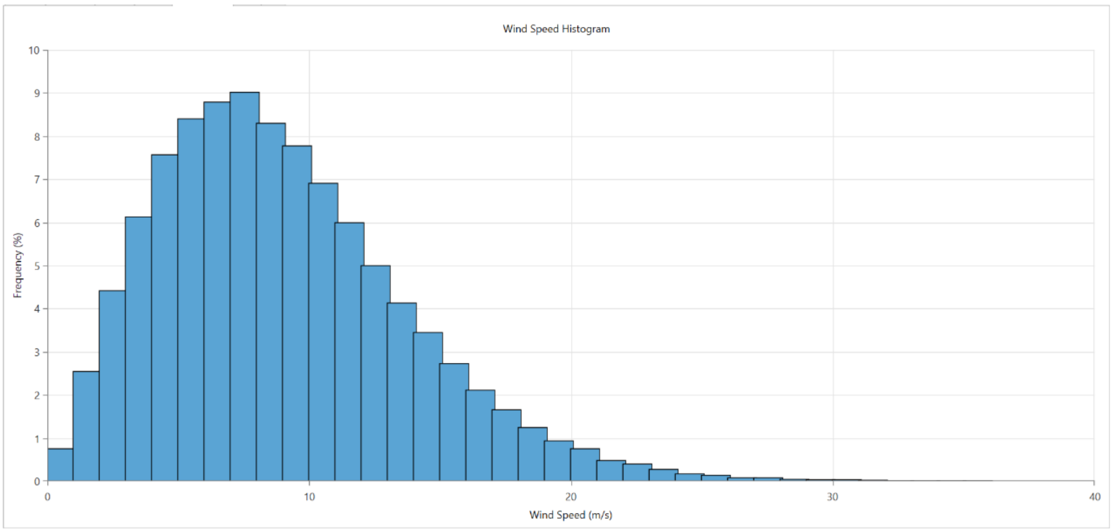

Figure 14: Wind speed histogram offshore.

The capacity factor achieved for this turbine at this location is 45.8 %. The average output is 3,471 kw, total production is 30,407,277 KWh/yr and 8,447 hrs/yr of operation.

Phase 2

In Phase 2, we use the same location and turbine as in phase 1, but instead of 1 turbine we simulate 33 turbines, this is the maximum amount of the Enercon E-126 7.5 MW turbine model we can select without the maximum production bypasses the maximum demand of the platforms (250/7.5=33.33). Since we do not have a dynamic demand, implementing storage without WTG capacity that exceeds the demand would not be functional.

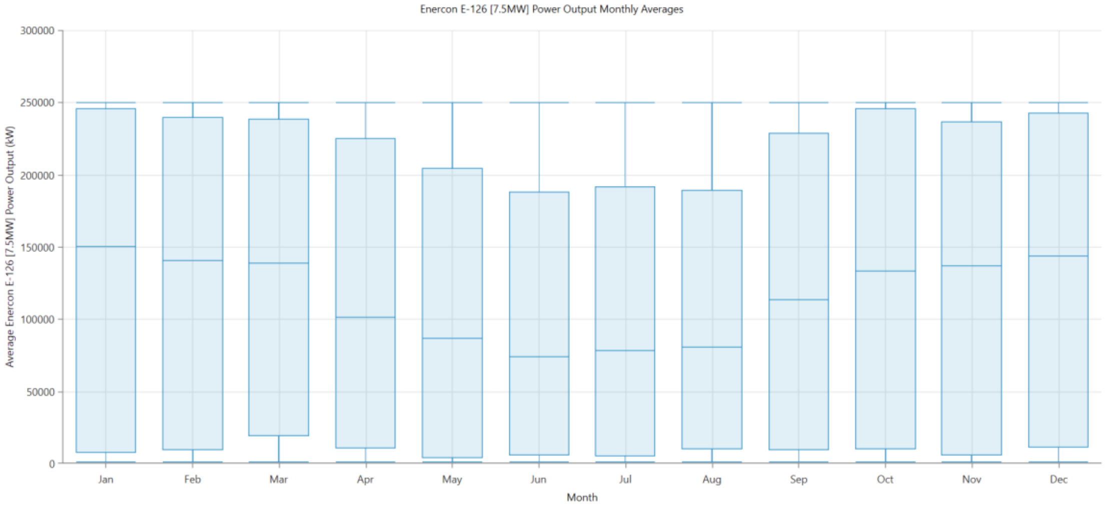

Figure 15: Power output monthly averages for, annual max, day avg. max, average, day avg. min and annual min for 33 turbines offshore.

Figure 15 shows the electricity production over the year in monthly averages. The electricity production of the 33 wind turbines covers 45.8 % of the annual electricity demand. If we inspect figure 16 which shows the power output from the system in kW, we can see that the electricity production is alternating.

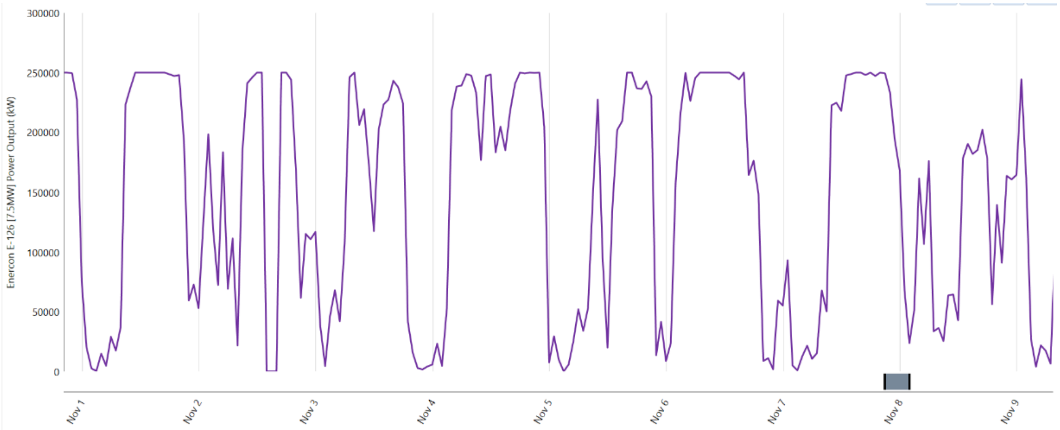

Figure 16: Alternating of power production for 9 days offshore 33 turbines.

The total production is 1,003,440,156 kWh/yr and the average output is 114,548 kW. The capacity factor of 45.8 % and is operative 8,447 hrs/yr.

4.2. Scenario 2

Phase 1

Like scenario 1, first is the selection of the location for wind turbines to be simulated from. We select a location close to Kårstø where the electricity is being transferred from land to Johan Sverdrup, to minimise even more loss in transmission, 04°44'40.99"E, 59°14'05.16"N is the selected site. We then import the resources needed in the simulation. We import data for wind, solar and temperature. This time the demand will be set at 280 MWh because of the length of the transmission cable. The same wind turbine is also used Enercon e-126 7.5 MW. The demand will also be connected to the grid so that the simulation can be done.

The simulation is run with one turbine, so we can gain results on the performance of the turbine, and wind speed data. Figure 17 shows the annual max, day avg. max, average, day avg. min and annual min, as we can see the production is higher in the winter months compared to the summer months.

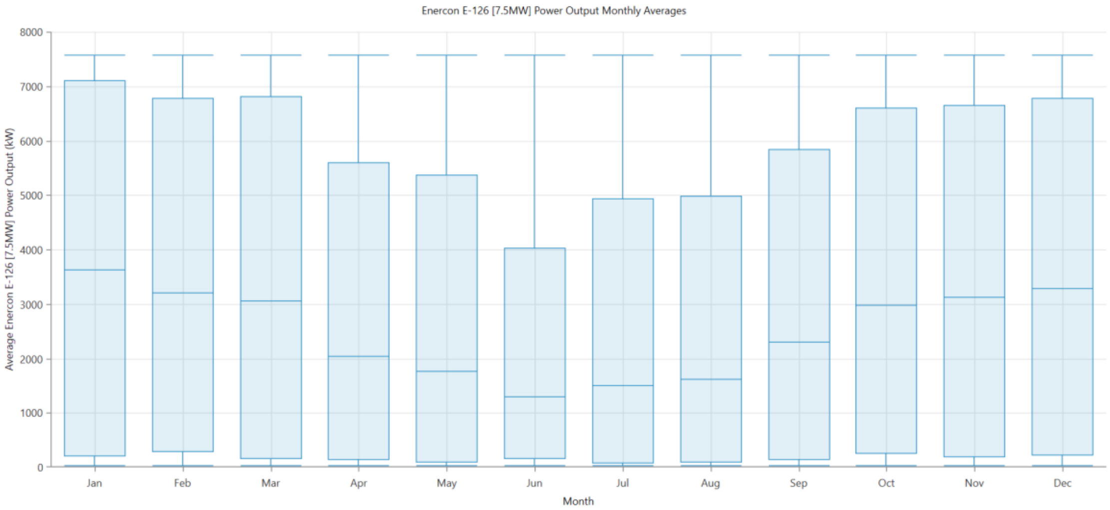

Figure 17: Power output monthly averages for, annual max, day avg. max, average, day avg. min and annual min for 1 turbines on land.

The next graph, figure 18 shows us that electricity production is correlative to the wind speed over a year. Even though the top wind speeds decrease in speed in the summer months, the turbine reaches its maximum production capacity, but fewer times, as we can see the production decreases in the summer.

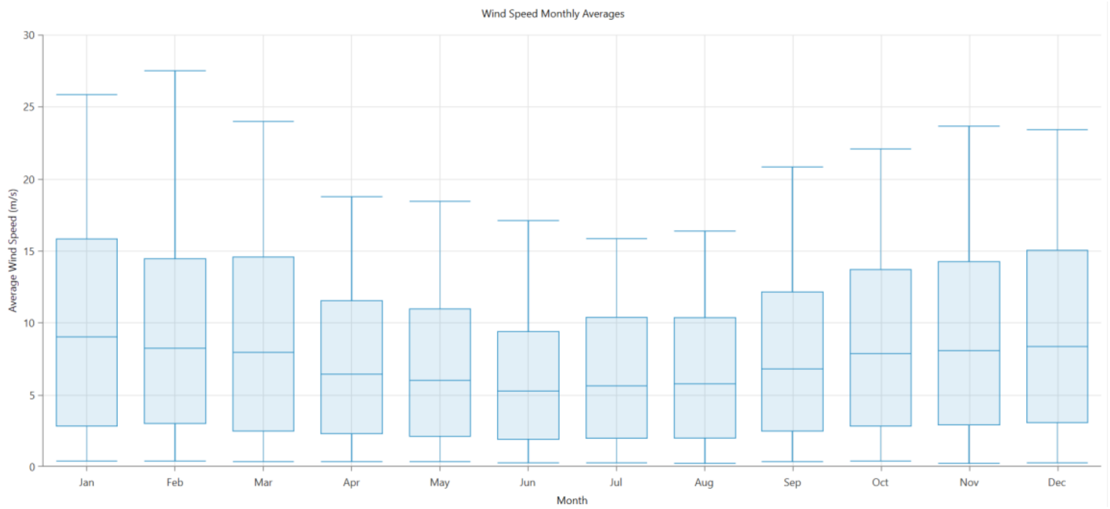

Figure 18: Wind speed monthly averages for, annual max, day avg. max, average, day avg. min and annual min for 1 turbine on land.

Figure 19 shows that highest frequency of wind speed in this area is approximately 4 m/s.

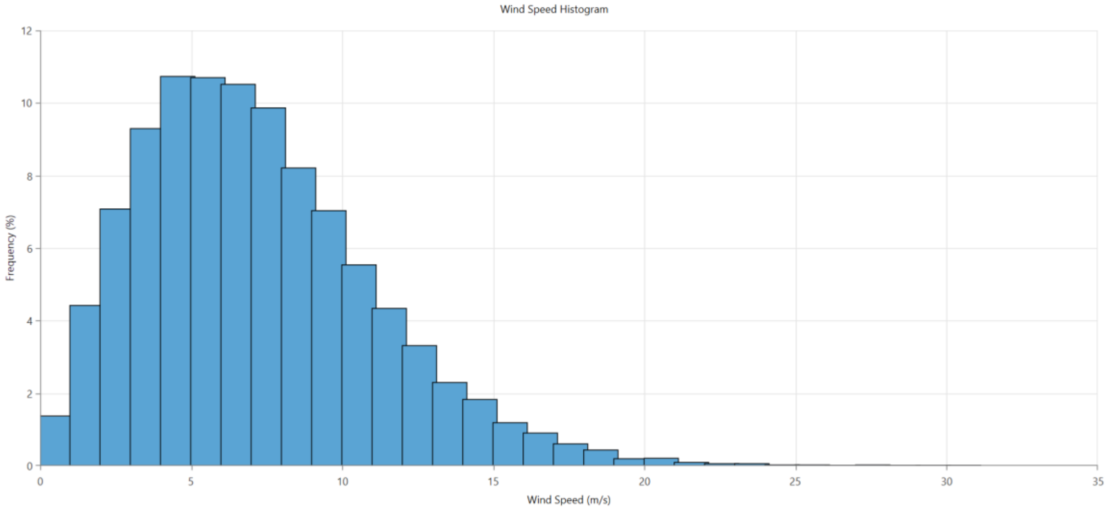

Figure 19: Wind speed histogram on land.

Graph 8

The capacity factor achieved for this turbine at this location is 32.6 %. Mean output is 2,473 kW, total production is 21,660,654 kWh/yr and 8,355 hrs/yr.

Phase 2

The same location on land is used in this phase as in phase 1, but the number of turbines has increased to 37, this is the maximum amount of the Enercon E-126 7.5 MW turbine model we can select without the maximum production bypasses the maximum demand of the platforms (280/7.5=37.33). Since we do not have a dynamic demand, implementing storage without WTG capacity that exceeds the demand would not be functional.

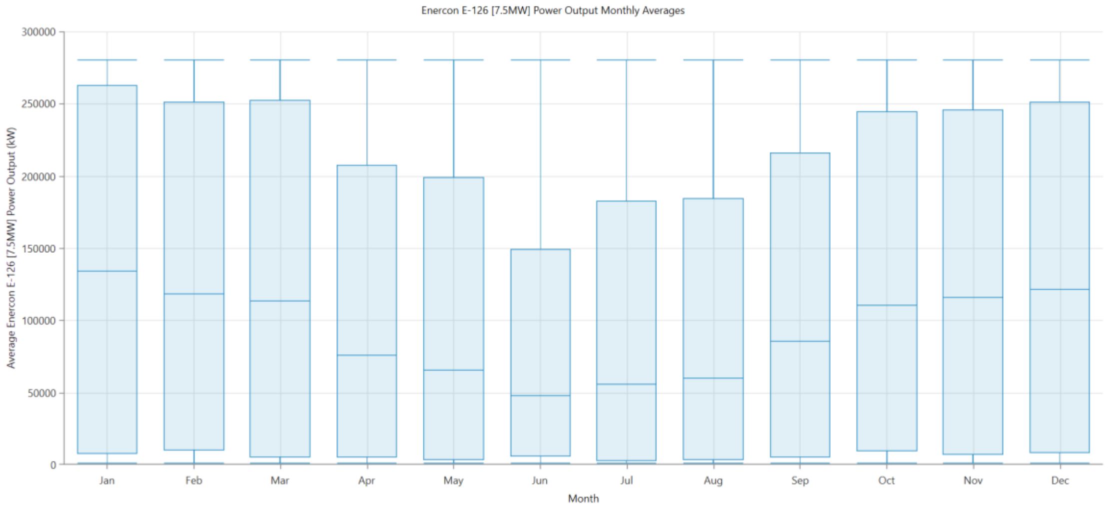

Figure 20: Power output monthly averages for, annual max, day avg. max, average, day avg. min and annual min for 37 turbines on land.

Figure 20 shows the electricity production over the year in monthly averages. The electricity production of the 37 wind turbines covers 36.6 % of the annual electricity demand.

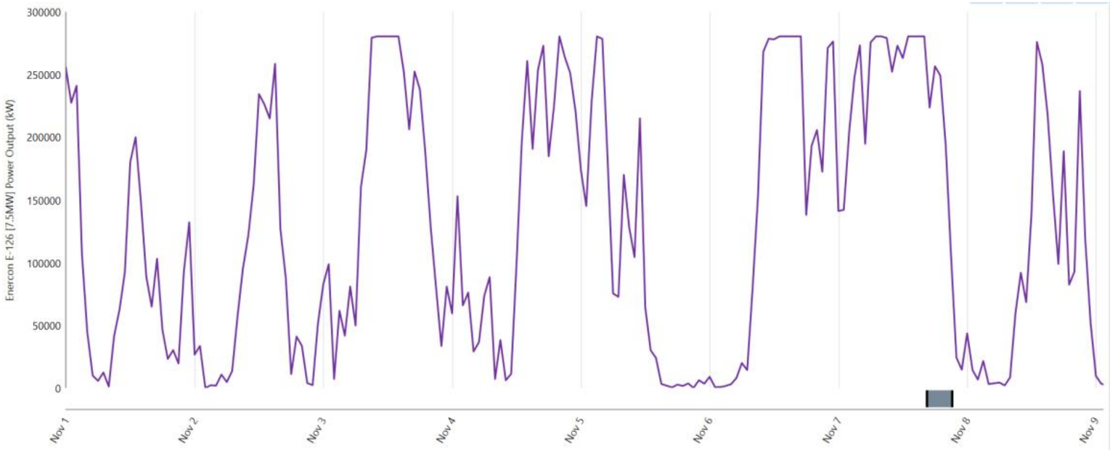

Figure 21: Alternating of power production for 9 days, on land 37 turbines.

Figure 21 visualizes the power output from the system in kW between 1-9 of November, the electricity production is alternating, even hourly. The total production is 801,444,204 kWh/yr, the average output is 91,489 kW, capacity factor 32.6 % and 8,355 hrs/yr operative.

4.3. Results

It is easier to understand the result from the simulation by comparing the result from the different scenarios with each other. The differences in the scenarios compared to each other is the location and the number of turbines used in multiple turbine simulations for offshore and land sites. However, we need to remember that this is the only simulation and guidance for future work.

Table 2: Comparison between Scenario 1 and Scenario 2.

	Scenario 1 (33)	Scenario 2 (37)	Difference	Difference in %
Capacity factor (%)	45,8	32,6	13,2	40,49
Mean output (kW)	114 548	91 489	23 059	25,20
Operative hours (hrs/yr)	8 447	8 355	92	1,10
Total production (kWh/yr)	1 003 440 156	801 444 204	201 995 952	25,20

Capacity factor is one of the main factors when deciding a wind turbine site since it shows how much of its capacity it will use. Wind turbines are intermitted energy source and dependent on the wind speed, and some locations are more suited for WTG then others. The difference between the offshore turbine and the one on land is an increase of 40,49 % in favour of offshore. We can see this difference in the average output as well, where the offshore have higher average production then onshore. The difference is not as prominent as for the capacity factor, as scenario 2 used more wind turbines, so its total rated capacity is 280 460 kW compared to scenario one who has a total rated capacity of 250 140 kW. The difference in working hours between the two scenarios is minor at 1,10 % which implies that the reason for the difference in the capacity factor is that the average wind speeds are higher offshore, |which in turn leads to higher power generation. This can be seen from the total production over a year, where the scenario one has ousted scenario 2 in amount of kWh produced, even though scenario 1 has fewer turbines then scenario 2.

We can see the reason behind the difference in the capacity factors from the average wind speed data. As we can see from the figure 22 that shows the monthly annual max wind speed (the one day with highest wind speed), the offshore site has average higher max wind speed than the land, without 1 month, where they have the same wind speed.

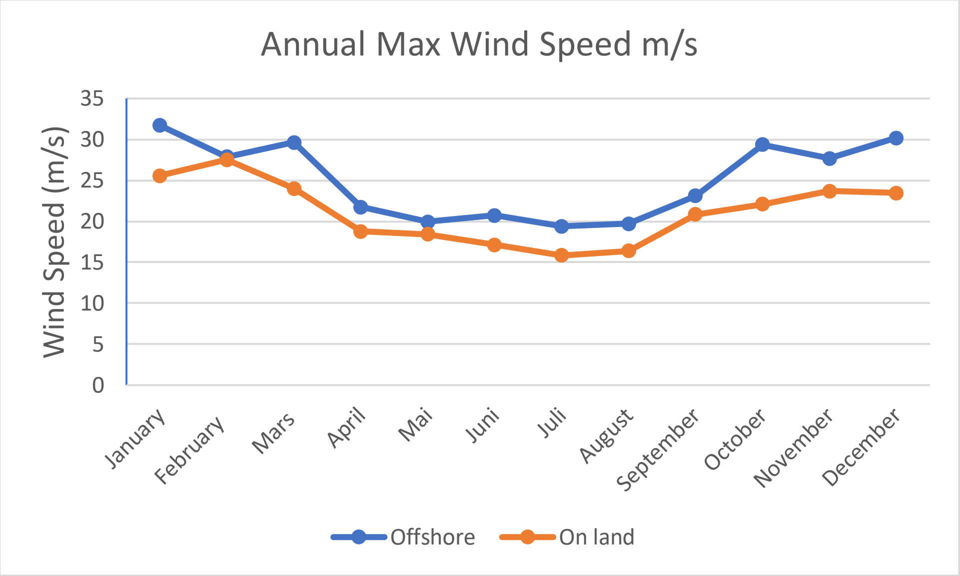

Figure 22: Annual Max Wind Speed comparison.

The daily average max wind speeds are also higher offshore than on land (figure 23); however we can see a decrease in the wind speed compared monthly annual max wind speed. This means that there are fewer days with max wind speed.

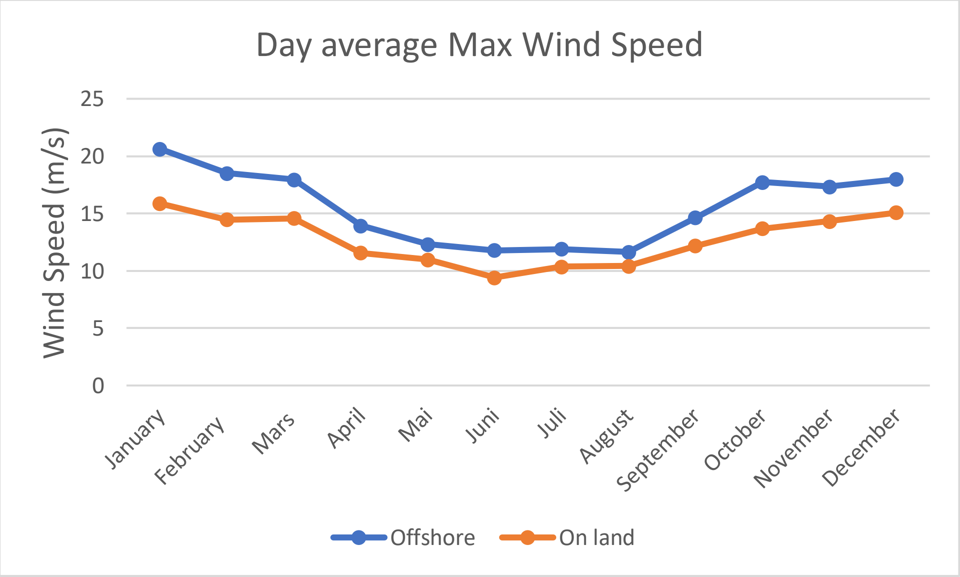

Figure 23: Day average max wind speed comparison.

Figure 24 shows the monthly average wind speeds, and it is following the same monthly trend as the two other graphs for wind speed, where the wind speed is higher in the winter months compared to the summer, which will affect the percentage of wind energy contribution over the year.

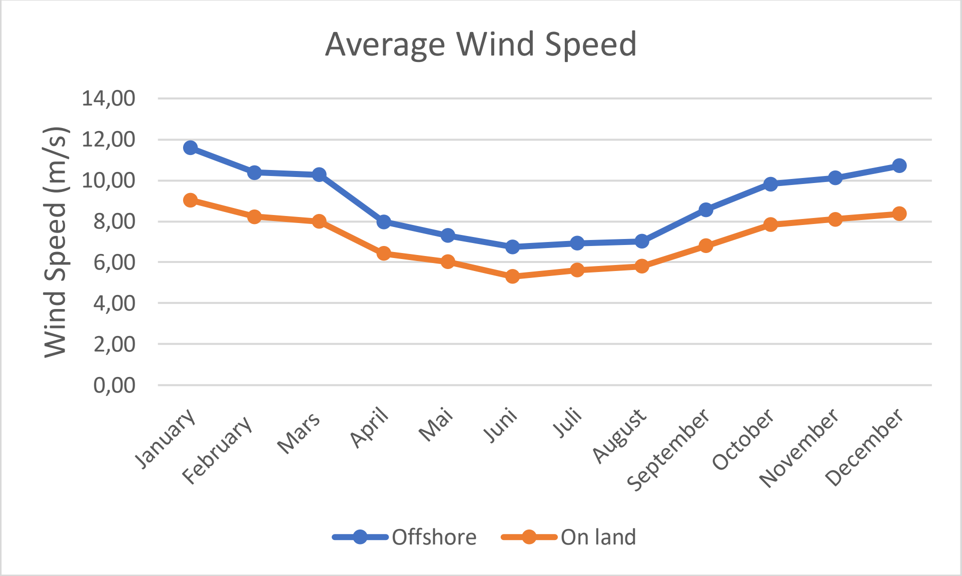

Figure 24: Average wind speed comparison.

As we can see from figure 25 for annual average Max power output is that it correlates with the wind speed. Where we reach the maximum production capacity at least once every month.

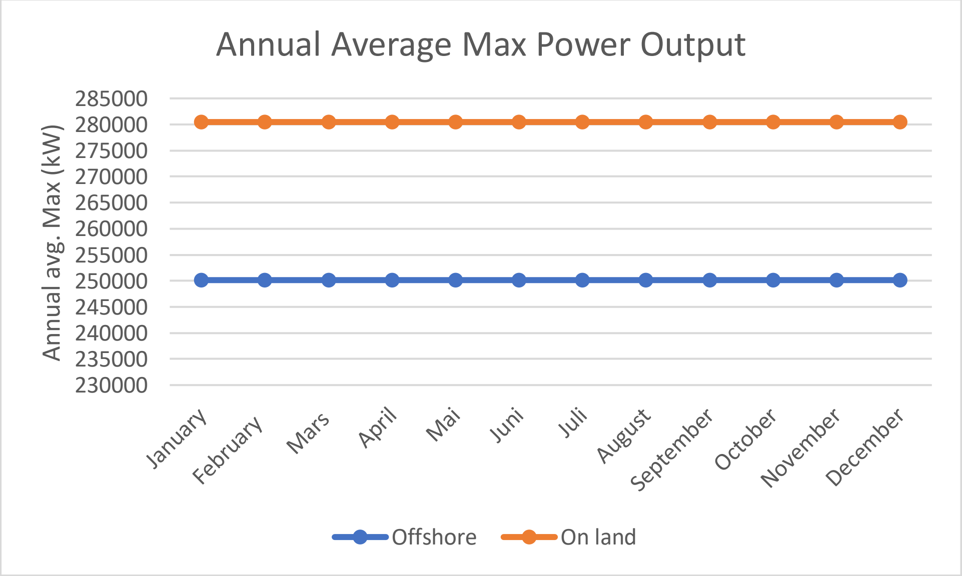

Figure 25: Annual Average Max Power output comparison

Figure 26 shows us that power production output is close to each other on land and offshore in the summer months with the advantage going to the land, the reason behind this is the increased production capacity with the extra wind turbine, while the OWT generation has higher energy output in the winter even though it has less production capacity, the reason behind this is the better win resource at the selected offshore site.

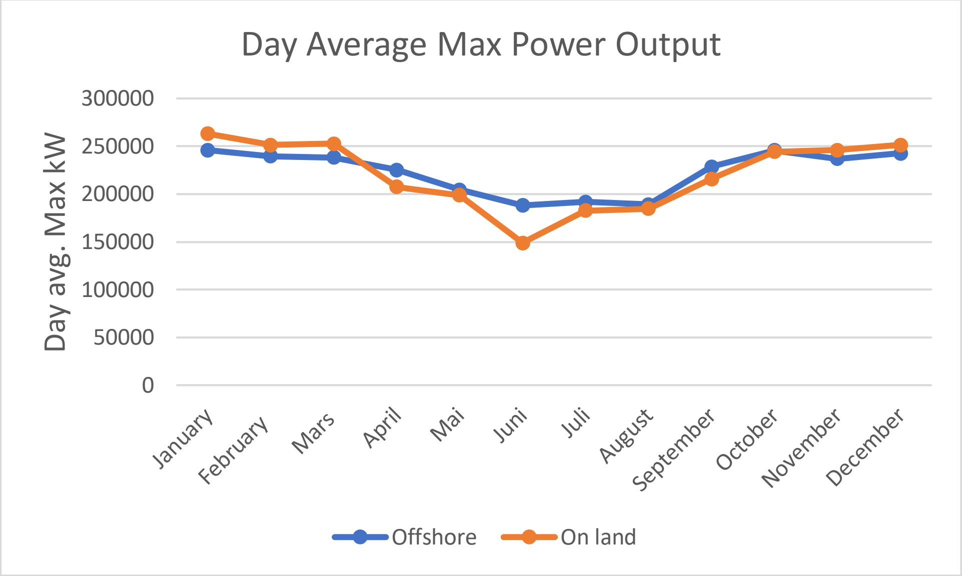

Figure 26: Day average max power output comparison.

As shown in graph X the average power output is higher offshore, this is simple because the superior quality of the wind resource compared to land, where the wind speeds averagely are higher than on land. Moreover, there is a close correlation between offshore and onshore.

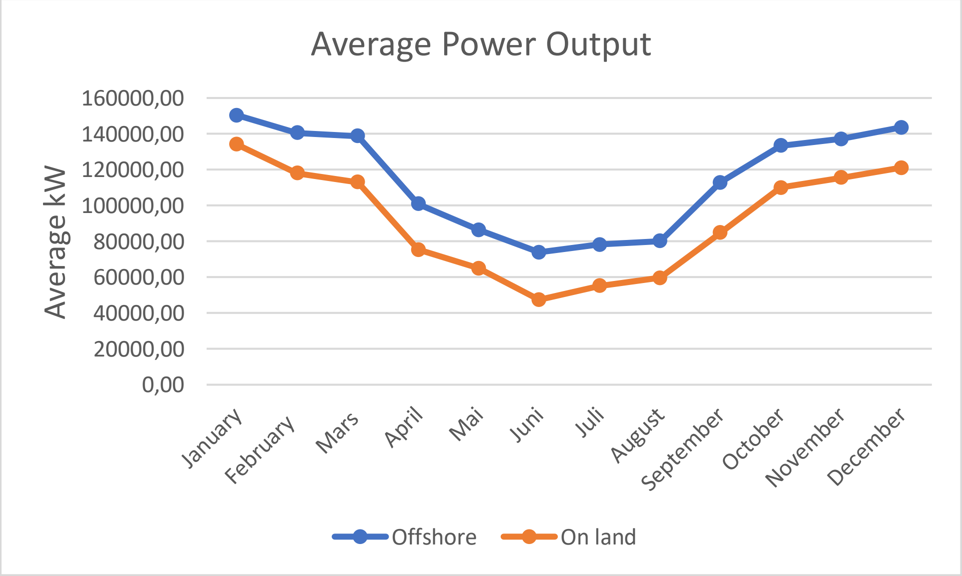

Figure 27: Average power output comparison.

We got high renewable penetration for both scenarios, but the average coverage depends on the wind speed, this means that the wind energy penetration is higher in the winter then summer. Seen from figure 28 and 29.

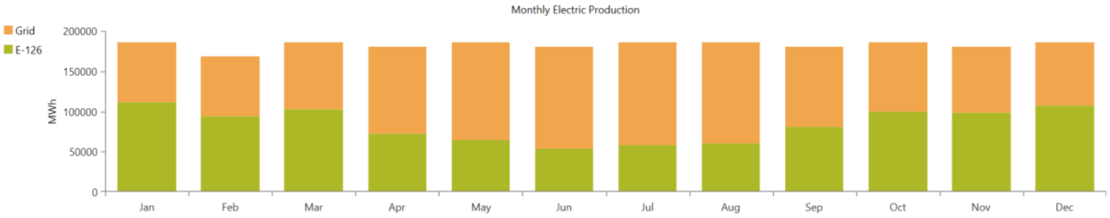

Figure 28: Offshore monthly electric production.

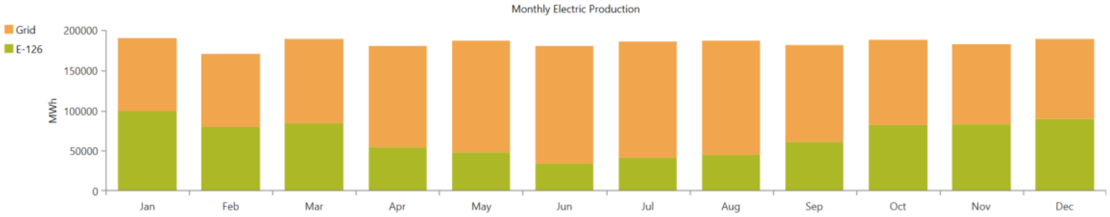

Figure 29: On land monthly electric production.

The penetration of renewable energy sources can be increased with more wind turbines. However, renewable energy sources will not be able to fully replace the grid connection to the extent that the entire amount of energy demand is supposed to be met by wind turbines, mainly as storage would be needed in order to reflect fluctuations in demand and supply throughout the year. This brings new challenges since weight and space is a challenge in the offshore environment because of the cost increase.

There are advantages with both offshore and on land sites. In this case, offshore is more favourable, but in other cases it could go on favor of the land site, for example when the offshore site is close to the demand, which minimizes the transmission losses. But the negative with FOWT is that it is still in development phase, where tests are being conducted. The price of FOWT are higher than their land opponent, where the price is estimated to be around 70 % more for the FOWT (Laura and Vicente, 2014) because FOWT brings new challenges in design and development, innovation is needed to bring down the cost, as seen highlighted in the literature review. However, in return have higher capacity factor, and real test shows that the capacity factor can reach up to 60 % (Hersleth, 2018).

If the electricity that is produced by the wind turbines replaces the grid electricity, with European CO_2 mix in the electricity delivered by the grid. We could reduce the emissions of $CO_{2;}$ the European electricity production had an average of 295,8 g of CO_2/kWh ((2016), (Agency, 2018)).

Table 3: CO_2 emissions.

Location	Energy production kWh	Gram CO2/kWh	Gram CO2 emission reduced
Offshore	1 003 440 156	295,8	296 817 598 144
On land	801 444 204	295,8	237 067 195 543

As we can see from table 3 is that the amount of emission reductions received by implementing wind turbines are quite high, for the offshore the cuts can reach 296 billion grams of CO_2, for the on-land version the cuts can reach 237 billion grams of CO_2 savings. However, it is essential to note that is other factors also affect this calculation.

From the power demand for full-field lifetime figure 6, it is clear that the demand will decrease over the platform's lifetime. Wind turbines have a lifetime of around 20-25 years if we estimate 20 years. Since we planned the scenarios after maximum demand, the turbines will produce more electricity than demanded. Implementing storage options this excess energy can be exploited to increase the percentage of electricity delivered from the wind turbines. Storage options have to get better to be cost-efficient when it comes to offshore environment where weight and space are sparse.

The revenue for these scenarios will mainly be few expenses in form smaller electricity bills and less CO_2 tax to pay (this will also be the case with buying electricity from the grid), this option will be more available for platforms operative with gas turbines today and not economical with connection to the shore, where the gas turbines will operate as backup. This could also have a marketing effect on the company that implements this. Equinor is the main operator of the Johan Sverdrup field and the hywind project, which could allow them to be a frontrunner in terms of providing more eco-friendly solutions.

There is also a political aspect that is important to consider when discussing floating offshore wind turbines. Costs is an immediate drawback for many companies considering such solutions, however, with the increasing pressure on politicians to alter the increasing CO_2 emissions, taxes could be imposed on CO_2 increases, or that the resistance against WTG on land gets tougher, which could open up the way of floating offshore wind turbine generator as the solution would become relatively more economically competitive. Again, with the Paris agreement and the aim of being in the forefront of the environmental debate, tax could be an efficient way to limit the emissions. On the other hand, another solution could be to offer subsidies for companies willing to take on the risk and cost of setting up a floating offshore wind turbine. This would allow the government to set a precedent in the market, increasing the knowledge base around the solutions and in turn limit the future costs and risks related to choosing the more environmentally friendly solution.

Future work

The next steps of planning floating offshore wind turbine generation to support oil fields would firstly be the collection of weather data at the areas this could be interesting to implement. Moreover, demand profiles are to match up the system in most effective way possible and to minimise both the risk and cost of implementation. However, the most critical factor is the floating offshore technology must become more mature and verified, since failure on offshore installations results in significant cost because of the difficult access. Furthermore, the cost of deploying and O&M have also to go down.

Sub technologies for the connection between the different systems are already in place, together with the need to stabilise the alternating wind energy. Then, of course, detailed planning of the whole from subsystems to the final product.

Conclusion

In conclusion, there is a demand for more renewable energy solutions in order to decrease the effects of climate change by reducing global CO_2 emissions. Norway has agreed with the Paris Agreement to reduce its CO_2 emissions, and one of the key sectors they must address is the North Sea O&G sector. One of the solutions is electrifying the offshore sector with power from shore. However, if the electricity from shore has European carbon emission values, then we still have CO_2 emissions. On the other hand, if we count on that the power comes from the renewable energy sources from the mainland Norway, it will decrease the amount of electricity that can be sold to rest of Europe, which will slow down the removal of CO_2 in the European electric marked or increase it since the Norwegian hydropower is being used to stabilize the renewable output from the European market (Denmark). However, the need for stable energy sources and often the cheapest solutions are the fossil fuel-based ones. With increasing resistance against wind turbines on land it is also a problem to increase the renewable share in the electricity market. By implementing floating offshore wind turbines to the supply change of energy to offshore platforms, we will meet the demand locally, reducing the pressure on the established network, in the case of connected platforms. In the case of platforms that are not economically feasible to connect from shore, FOWT will be option to decrease the emissions and possible operational cost for the platform by decreasing the CO_2 taxation and free up the gas for sale to be burned more efficient with fewer emissions.

Better data both for the demand and weather to be able to design a more targeted FOWT to be more efficient. The cost reduction of developing and O&M cost have to be reduced also. Overall FOWT is a viable solution to the electrification of the platforms in the North Sea.

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