Norwegian School of Economics
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Assessing Offshore Wind Farm Placements in Norway

Is NVE's current plan optimal – or can we do better?

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Master´s Thesis, MSc In Economics and Business Administration,
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Abstract

Over the last decade, offshore wind has received increased attention due to global warming and the increase in energy demand. Therefore, it is of the highest interest to develop more renewable energy production to satisfy the increase in energy consumption and reduce global pollution. Even though Norway has excellent hydropower opportunities and is self-sufficient and a leading prosecutor in this field, developing offshore wind is now a goal. In 2020, the Norwegian government opened for wind farm development in Sørlige Nordsjø II and Utsira Nord. The government is also planning to delegate licenses for around 30 gigawatts of offshore wind by 2040. Luckily enough, as we will see throughout this thesis, the Norwegian wind conditions are outstanding for wind power production. Additionally, the technologies surrounding offshore wind farms have become drastically better, making them both more affordable and effective.

This paper aims to explore and perform statistical analyses on potential sites for offshore wind farms in Norway. The thesis will have an “investor perspective” and seek optimal locations to maximise production while minimizing variability and costs. As already mentioned, Sørlige Nordsjø II and Utsira Nord are open for production. We want to use these locations as baselines when researching the other areas to see whether one can outperform them. After selecting our locations through a qualitative analysis, we use the dataset NORA3-WP to explore the maximum power production and create portfolios from the selected locations. Objectively, it is hard to determine whether some locations are better than others, but we have overcome some findings. The interpretation from the results is that the South of Lindesnes is stand-alone best in terms of power production and Sharpe ratio. The portfolio evaluation showed that a combination of all the locations except Utsira Nord creates a minimum variance- and a maximum Sharpe ratio–portfolio. We also provide three scenarios with different weights for locations that would satisfy the government’s goal of producing 120 TWh within 2040. Notably, this thesis is heavily influenced by the “investor perspective”, and the calculations are massively simplified. Further and broader research would be necessary before making any final decisions.

Keywords – Offshore wind, Norwegian wind conditions, renewable energy production, portfolio approach, NORA3-WP, Norwegian Water Resources and Energy Directorate.

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1. Introduction

1.1 Motivation and purpose

The global energy market has never been more relevant. Debates are raging nationally and worldwide, focusing on costs and energy sources. Norway, an energy-rich nation because of oil, gas, and hydropower, plays a vital role in these discussions. The energy market is a complex supply-demand market. Countries with valuable energy resources sell their goods to other countries that need more energy. The system is based on cooperation and trust and has worked well for decades. However, the market is facing difficulties like the Paris accords and the heavy dependencies on “energy-rich” countries. 2022 has been a roller coaster with soaring prices and a constant need for better renewable energy sources. The current situation may have several complex solutions, but whether this is through refining the oil industry, nuclear power, or finding new renewable energy sources is hard to say. This master’s thesis does not seek to solve the global energy crisis. Instead, it aims to shed light on offshore wind as a competitive renewable energy source and map out the possibilities for offshore wind farms in Norway. The motivation for developing this thesis is firmly based on the outlook of energy consumption and global warming. Additionally, it is exciting to shed light on a relevant topic that will be highly actual in the next decade.

Energy Shortage

Throughout the last year, the world has experienced an energy shortage. A preference shift for more renewable energy is crucial to the current energy shortage situation. The situation resulted in countries such as Germany stopping their nuclear energy (Reuters, 2022) and Europe becoming more dependent on Russian gas (Statista, 2022). Global energy consumption has experienced steady growth except for 2020 when we had the pandemic (World Energy & Climate Statistics, 2022). In 2019, only 11.4% of the energy consumption came from renewable energy sources (Ritchie, Roser, & Rosado, 2020). Offshore wind power should be strongly considered, as it could meet the increased demand for renewable energy and significantly impact the future energy market.

Paris Accord

In 2015, 194 countries agreed to sign the Paris Accord. The Paris Accord is an international legal treaty on climate change, a global framework to avoid climate change by limiting global warming. To meet the goals in the agreement and cover the increasing energy demand, it is evident that the world needs more renewable energy than today. One of the fastest-growing renewable energy sources is offshore wind energy. However, it is still in an early phase regarding commercial value and research. Today, only 0.3% of the global power generation comes from offshore wind. Even though the potential is vast, the industry and government need to act for it to become a mainstay of clean energy (International Energy Agency, 2019). From the figure below, we can see the energy consumption from each source. The figure shows that only a tiny portion of the total energy consumption comes from renewable energy sources. Tracing back to the Paris Accord, coal, oil, and gas consumption needs to be drastically reduced and replaced by more renewable energy sources.

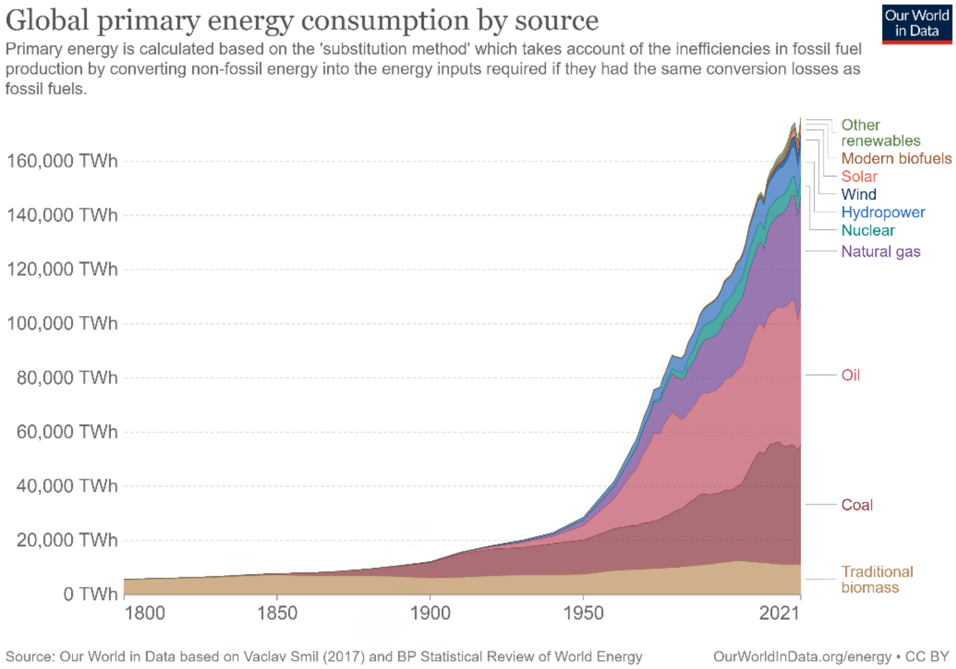


Figure 1.1: Global primary energy consumption by source from 1800 – 2021 (Ritchie, Roser, & Rosado, 2020).

The energy situation in Norway

Traditionally Norway has been an essential oil and gas supplier to the world. However, because of the advantageous coastline and preferred wind conditions, Norway might increase or replace its energy supply with offshore wind. Wind power technology has rapidly developed over the past years and has now possibly become a more reliable energy source than the early developed wind farms (NVE, 2012). After detailed planning, the government decided to develop two wind sites in southern Norway: Utsira Nord and Sørlige Nordsjø II (Regjeringen, 2022).

Although Norway has started to invest heavily in offshore wind energy, its electricity production is still dominated by hydropower (SSB, 2022a). Existing and further offshore wind investments could improve Norway's current energy balance. Sørlige Nordsjø II and Utsira Nord will contribute 4 500 MW (Equals 18 TWh per year given 4000 full operating hours (Hovland, 2022)) to the electricity balance (Norconsult, 2021). New installations secure electricity when the hydropower storages are low and possibly enable higher electricity export. The improvement in offshore wind technology pushes it to become more competitive, and it could reach the same potential as conventional energy sources. The new technologies and preferred wind conditions in Norway make investments in Norwegian offshore wind farms attractive.

It is widely agreed that offshore wind farms have several benefits, but the energy source also has some apparent drawbacks. Because the energy comes from wind, offshore wind farms suffer from the fluxional nature of their source (Milan, Wächter, & Peinke, 2013). These fluctuations are a combination of two elements for wind power production: variability and predictability (Datta & Hansen, 2006). The variability of wind implies that the wind does not blow at a constant speed. Predictability signifies the lack of knowledge about the variability pattern in advance. Together these elements are called intermittency and make implications for the reliability of offshore wind as a consistent energy source.

Although offshore wind as an energy source is heavily debated in the media, more research on possible locations needs to be performed. The energy source has benefits and drawbacks, but the development has come far, and Norway is now on the way to becoming a severe market participant.

1.2 Research question

In 2010, NVE drafted a report on the potential for offshore wind in Norwegian waters (NVE, 2010). Despite being quite old, the report is relevant today. This year (2022), Norway plans on building two offshore wind farms. The NVE report from drafted several areas to explore, but only two were approved for further development. The locations suggested account for several factors, such as wind speeds, ocean depths, environmental impact, commercial fishing impact, and connection to power grids. Sørlige Nordsjø II and Utsira Nord were the two locations selected.

The objective of this master's thesis is to challenge NVE´s choice of locations. The thesis will analyse Sørlige Nordsjø II and Utsira Nord and additionally come up with several alternative locations. The comparison will primarily be based on profitability/production, and by using a financial portfolio approach, the alternative locations seek to minimise intermittency and create a steady energy supply. In addition, the alternative locations also seek to minimise the total costs. We only include a simplified cost analysis of the locations and points out their crucial cost drivers.

The thesis is built on qualitative and quantitative analyses. The qualitative analysis aims to pick out and rank alternative locations based on techno-economic elements, such as wind conditions, ocean depth and grid connection. The quantitative analyses will rank and combine the alternative locations, find optimal combinations or outstanding single sites, and try to provide solutions to the government's goal of 30 GW offshore wind within 2040. As briefly mentioned, the whole thesis will use an investor perspective when finding the optimal locations, and socioeconomic perspectives will be down-prioritised. This brings us to the research question.

Research Question

By having an investor perspective and using financial models, what locations for wind farms will benefit Norway AS the most in terms of stabilising and maximising energy output?

Our work will provide valuable insights into future research and a big-picture overview of the ideal locations for offshore wind farms in Norway. Our thesis is structured as follows. Chapter two provides an overview of earlier research and how this thesis supplements the existing literature. Chapter three deals with the history, present and future outlook of offshore wind, and the physics and cost structures of an offshore wind farm. The data used is presented in chapter four. Here we also touch upon data handling. Chapter five, and the largest chapter, assesses offshore wind farm potential in the Norwegian coastal areas. Here we limit potential locations for the wind farms and choose our final locations. The sixth chapter runs through our methodologies as well as the results we have obtained with them. Chapter seven contains the discussion and interpretation of these results. Finally, chapter eight presents our final remarks and suggestions for further research.

2. Literature review

The following chapter reviews studies and topics of interest and discusses the current thesis' contribution to the existing literature.

Deployment of offshore wind is a topic that has existed for several years but has seen an increase lately. Following the initiative from the government and the assessment from the Norwegian Water Resources and Energy Directorates (NVE, 2010), the interest gained more momentum in Norway. In addition to the domestic interest, large energy agencies have increased the mentioning of "offshore wind"; for example, IEA´s annual energy reports have increased the number of mentions from four in 2009 to 19 in 2022((IEA, 2009): (IEA, 2022)). Aligned with the development of commercial offshore wind farms and the need for optimal decision-making tools, more literature has been published. Ida M. Solbrekke is among many others who analysed offshore wind opportunities along the Norwegian coast. Her PhD ranks the wind power suitability along the Norwegian coast based on interests from different target groups. The study stresses the conflict of interest that exists between the interest group. For example, the wind conditions could be optimal in one place, but at the same time, it could ruin shipping transport and wildlife. Solbrekke´s PhD states different opportunity areas, whether you are an investor, environmentalist, or fisherman. The idea of an investor scenario is used to determine suitable locations in our thesis.

The use of theory regarding wind physics and energy markets is gathered from several reports and websites. The physics behind wind and conditions analyses are mostly from (Letcher, 2017). The information about Norwegian and International power markets is mostly from (Statnett, 2021), SSB, and reports from IEA and GWEC.

The financial calculations performed in the thesis are based on the portfolio theory developed by (Markowitz, 1952) and (Sharpe, 1994). The adaption of financial tools for energy sources has previously been researched. Papers such as (Hu, Crijns-Graus, & Worrell, 2019) and (Thomaidis, Pozo-Vázquez, & Usalo-García, 2016) explore the use of financial tools to optimise energy output and risk. Thomaidias et al. combine solar and wind energy in Southern Spain to create optimal portfolios and Pareto-optimal solutions. Hu et al. identified the efficient frontier by combining portfolios of renewable energy sources in China. Both the mentioned papers differ from ours in terms of location and amount of grid points analysed.

This thesis combines Solbrekke´s PhD, NVE´s reports, and financial tools adapted to energy. We contribute to the existing literature in different ways. Firstly, to our knowledge, this thesis is the only study that uses a financial portfolio approach to analyse the offshore wind power potential along the Norwegian coast. Earlier studies have mainly focused on onshore wind farms. This thesis focuses on the Norwegian coast and a financial approach where we exploit the opportunities embedded with correlation.

Contrary to Hu et al. and Thomaidias et al., this thesis includes a qualitative analysis of the Norwegian coast. The qualitative analysis is utilized to select the alternative locations. Earlier research, together with our motivation to explore the opportunities that offshore wind brings up, led us to investigate the financial potential of the Norwegian coast. Norway has adequate wind conditions throughout its large coastal areas. Solbrekke´s PhD concluded that long distances reduced the correlation between wind sites. This thesis expects to build on Solbrekke´s results and find a similar value of diversification as previous studies.

The following chapter will address the historical and future perspectives on offshore wind and provide details about it.

3. Offshore wind and the nordic power market

This chapter aims to build a shared understanding of offshore wind. We will go through the historical development, future outlooks, the physics of offshore wind, a market analysis, and the cost structure.

3.1 Offshore wind throughout the past, present and future

The first offshore wind farm was deployed in 1991, an 11-turbine farm located 2 km off Denmark´s coast at "Vindeby" (IRENA, 2019). The capacity of the wind farm was 49 MW, which is far less than the potential modern wind turbines. Figure 3.1 illustrates the historical increase in energy output from offshore wind farms.

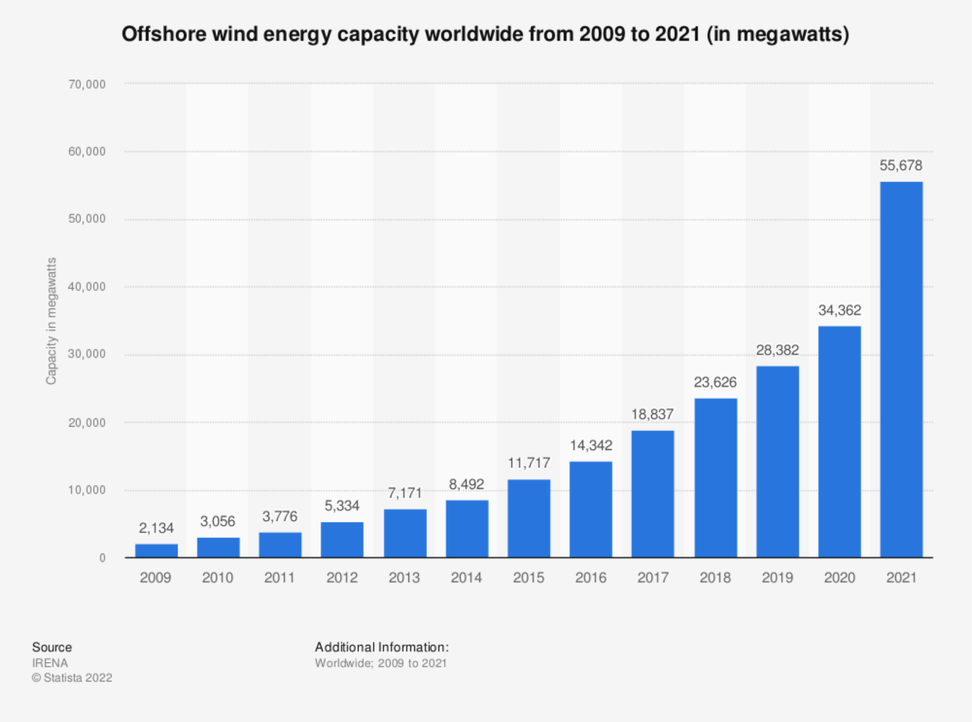


Figure 3.1: Capacity of offshore wind throughout history analysed by International Renewable Energy Agency (IRENA, 2022).

From 2009 to 2021, offshore wind experienced steady capacity additions. Last year's growth was substantial and saw around 60% increase in capacity factor (Global Wind Energy Council) (GWEC, 2022). China was the main contributor to the positive change with 50%, and Europe the remaining (GWEC, 2022). In 2017, the first floating wind farm was established. Equinor´s

Hywind Scotland opened a new landscape by going beyond bottom-fixed solutions and enabling deep-water offshore wind farms (Equinor, 2021).

This section is based on the market from 2021. Today's markets consist of several countries that all contribute to the growth. As already mentioned, China´s installations led the contribution for the third year, with more than 3 GW of total wind grid connected in 2020. The Netherlands led the steady growth in Europe, which installed 1.5 GW. Figure 3.2 below shows the market structure by country from 2020.

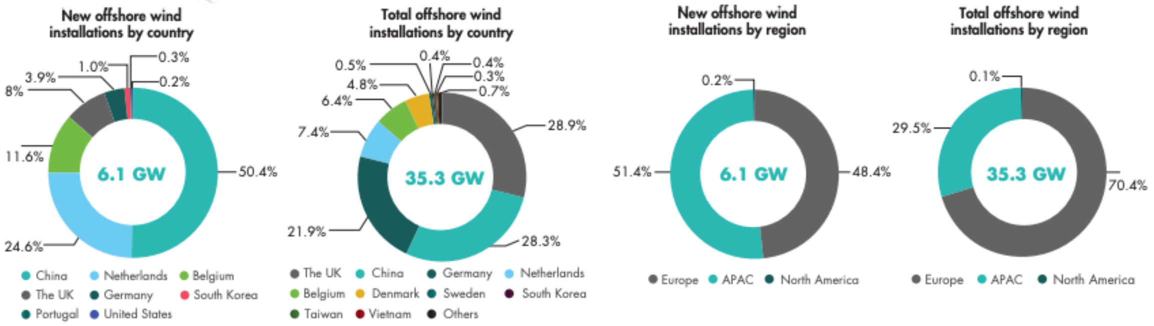
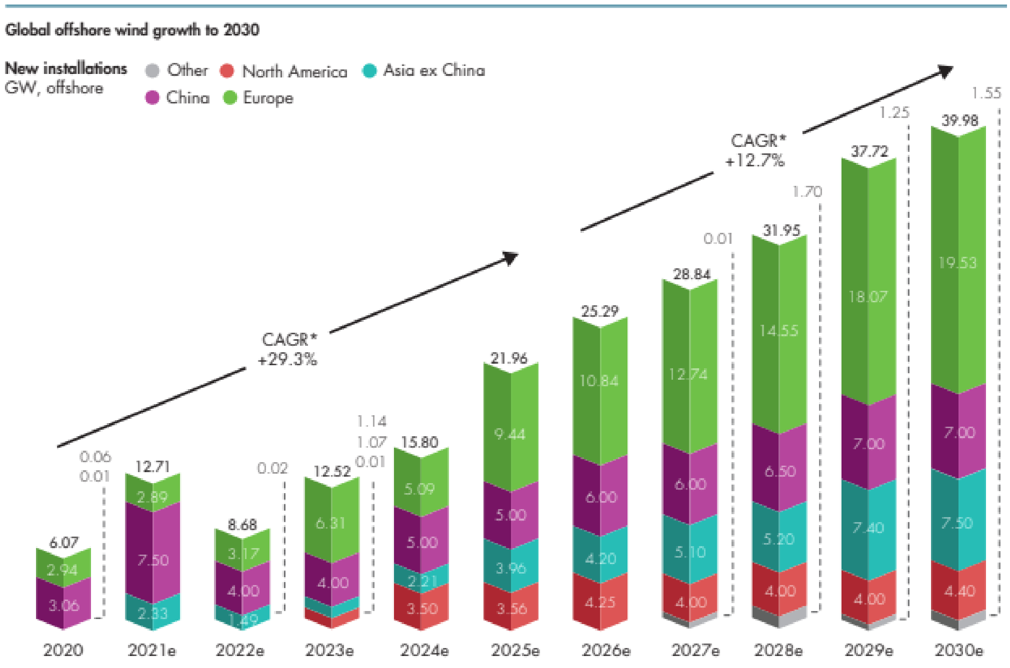


Figure 3.2: Analysis of the offshore wind market 2020 done by Global Wind Energy Council (GWEC, 2021). The left panel shows new installations by country, followed by the total installation by country. The third panel shows new installations by region, and the right panel shows total installations by region.

The offshore wind accounted for 5% of the total wind power capacity in 2020, bringing the total capacity installation to 35.3 GW. Europe remains the most significant market, with a market share of 70%. Asia surpassed 10 GW after substantial contributions from China. North America only had 43 MW of offshore wind operation last year, but the deployment is expected to accelerate from 2023.

It is a joint agreement among Energy Information Administration (EIA, 2021), (IRENA, 2019), and (GWEC, 2021) that installed offshore wind capacity is set to increase in the next decade (GWEC, 2021). Markets intelligence expects that over 235 GW of new offshore wind capacity will be added over the next decade. The industry will get new policy targets, and technology costs are set to decrease in the scenario. The outlook differs between agencies due to uncertainty regarding the fulfilment of deployment targets. The targets rely on goals set by each country and are all according to the plan to reduce CO2 emissions and decarbonise the globe. Figure 3.3 shows GWEC´s (2021) market outlook towards 2030. Their market intelligence expects the capacity to add 235 GW over the next decade.



*CAGR = Compound Annual Growth Rate

Figure 3.3: Expected annual installations (GW) in offshore wind power from 2020 to 2030 (GWEC, 2021).

3.2 Wind Theory

Three elements decide wind power. Firstly, the mass of the air (p); secondly, the area of interest (A); and thirdly, the wind speed (U). Assuming that the air mass is constant, the area and wind speed are the crucial variables. An increase in the area of interest will increase the total power output. Hence this variable has a positive relationship with the outcome. The wind speed does not have a linear relationship with power output but a nonlinear cubic relationship. A doubling in wind speed, c.t., will eightfold the power output.

Equation 3.1: Power production wind turbine (Letcher, 2017).

$$P = \frac{1}{2} * \rho * A * U^3$$

$P = Power$

$A = Area\ (m^2)$

$\rho = Mass\ of\ air\ (Air\ density\ kg/m^3)$

$U = Wind\ speed\ (\frac{m}{s})$

Wind power capture

Despite the rapid technological development, not all wind power is available for utilisation. The amount of energy a wind turbine can produce is defined and limited by Equation 3.2: . The power coefficient (Cp) compares the utilised power extracted and the total wind power from the area. The power coefficient is a measure of the efficiency of the wind turbine. New technology enables higher efficiency rates than earlier, however, as stated by Betz's law, the maximum turbine efficiency is limited to 59% (Letcher, 2017). New technology has enabled an efficiency rate of approximately 50%, which is high compared to other types of renewable energy (BOW, 2020).

Equation 3.2: (Letcher, 2017).

$$C_p = \frac{P_t}{P_{wind}} \rightarrow P_t = \frac{1}{2} * \rho * A * U^3 * C_P$$

$P_t = Power\ extract$

$P_{wind} = Total\ wind\ power$

$A = Area\ (m^2)$

$U = Wind\ speed\ (m/s)$

$C_p = Power\ coefficient$

$\rho = Mass\ of\ air\ (Air\ density\ kg/m^3)$

Power curve

The main factor in energy output for offshore wind farms is wind speed. Wind speed accelerates the wind turbine, and energy is generated. The wind turbine will only generate power when the wind speed is between cut-in and cut-out speeds. The cut-in speed is 4 m/s for most wind turbines, while cut-out speed varies considerably between different wind turbine models. When the wind speed exceeds the cut-out limit, the rotor will shut down to avoid structural damage. Figure 3.4 shows the cut-in and cut-out for the IEA reference turbine.

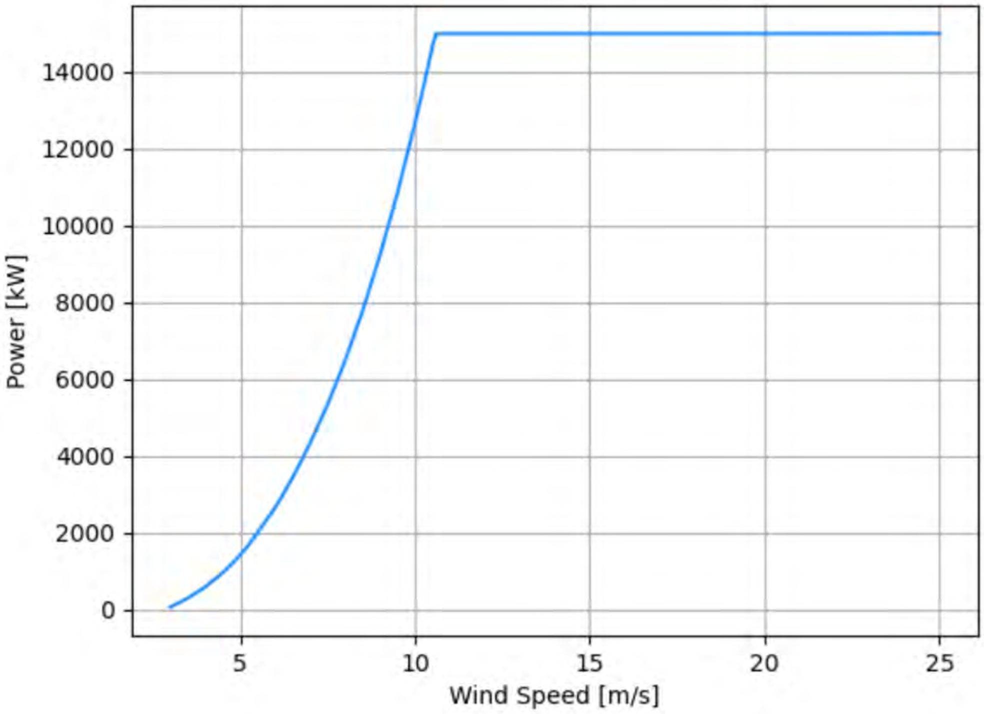


Figure 3.4: Power Curve IEA Wind 15 MW Reference Turbine. Turbine reaches the nominal power production at just over 10 m/s (NREL, 2020).

3.3 Components of offshore wind farm

Offshore wind farms are large constructions that consist of the components shown in Figure 3.5. Energy generated from offshore wind farms goes through a thorough process when generating, transporting, and serving power to the electricity grid.

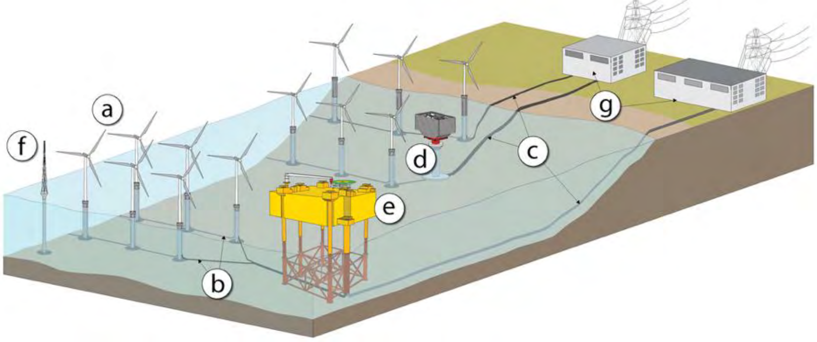


Figure 3.5: Illustration of the main components in an offshore wind farm: (a) wind turbine, (b) collection table, (c) export cables, (d) transformer station, (e) converter station, (f) meteorological mast, (g) onshore stations (Rodigues, et al., 2016).

3.3.1 Wind turbine and foundation

The wind turbine and foundation vary, as they are either vertical- or horizontal-axis wind turbines. The most common one is a horizontal-axis wind turbine. This thesis is based on the use of an IEA 15-MW reference turbine illustrated in Figure 3.6. The choice of the turbine will not significantly impact the results as long as the same turbine is placed at each location. With the same turbine across all locations, we can easily compare and analyse the locations on equal basis.

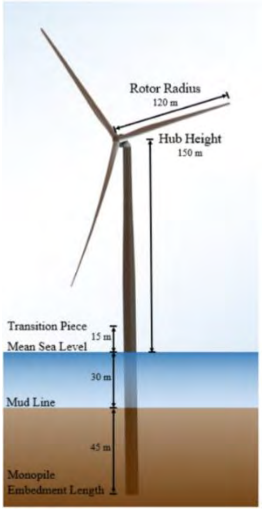


Figure 3.6: IEA – 15 MW Reference Turbine – hub height: 150 meters, rotor diameter: 240 meters, monopile foundation: outer diameter of 10 meters. The wind turbine has a cut-in speed of 3 m/s and cut out of 25 m/s (NREL, 2020).

The current reference turbine cannot fully represent the state of the art in terms of floating foundation design. Therefore, for the sake of research, this thesis assumes that a floating wind turbine will have the same attributes as the reference turbine, while having the same foundation as the Hywind demo developed by Equinor (Equinor, 2021).

3.3.2 Electric power transmission

Array Cables

Offshore wind farms require a connection to an electricity grid to distribute the generated electricity. The cable network consists of both array and export cables. The array cables deliver electricity between the wind turbines, and the export cable connects to the electricity grid. Newer technology and larger wind turbines contribute the same capacity factor with fewer wind turbines. However, larger wind turbines lead to longer distances between offshore wind turbines because of the increasing wake effect. The wake effect is wind speed reduction and the added turbulence that occurs when the wind blows through a wind turbine (Laursen, Sivabalan, Borchersen, & Larsen, 2014). We will also touch upon the wake effects in chapter 7.3. Therefore, offshore wind projects need to consider the trade-off between the costs of long cables and the increased wake effect (Baring-Gould, 2014).

Offshore substation

The offshore substation changes the voltage from offshore wind farms from the inter-array cables to the onshore substation (BVG Associates, 2019). There are two options to change the voltage: High voltage alternating current (HVAC) and High voltage direct current (HVDC). Today, the HVDC is economically preferable at distances greater than 80-100 km from shore. However, if the HVDC is used over longer distances, the electricity distribution relies heavily on electricity cables to minimise electricity loss (BVG Associates, 2019).

European electricity grid

The introduction of floating offshore wind farms utilises the opportunities of European grid connection. Today, each offshore wind farm is connected to one transmission station, but increased activity in multinational seas raises the opportunity of clustering several offshore wind farms in a hub. The hub will be the shared connection grid between several farms, reducing the cost per offshore wind farm because of the shared costs (Zhang, 2021). Furthermore, an electricity hub from offshore wind does not only apply to interconnection, but also domestic offshore wind farms. Therefore, offshore wind farms within reasonable distance should consider investing in a shared transmission system.

3.4 Cost drivers in offshore wind

Offshore wind farms require considerable investment expenses and are embedded with several cost factors, both operational and fixed. The Levelized cost of energy (LCOE) is a composure of both the capital expenditure (CAPEX) and the operational expenditure (OPEX). CAPEX is the fund that the project owner spends to buy, maintain, or improve fixed assets such as wind turbines and foundations. OPEX is the ongoing, day-to-day expenses that keep the business running, such as operating and maintenance (O&M) costs. The purpose of LCOE is to evaluate and compare the cost of electricity from different production facilities, that is, the lifetime average cost of energy produced (BVG Associates, 2022). The cost structure comprises CAPEX (including development expenditure), the cost of finance for CAPEX, OPEX, and the decommissioning expenditure (DECX). An analysis of costs done on UK offshore wind (BVG Associates, 2022) shows the following cost structure:

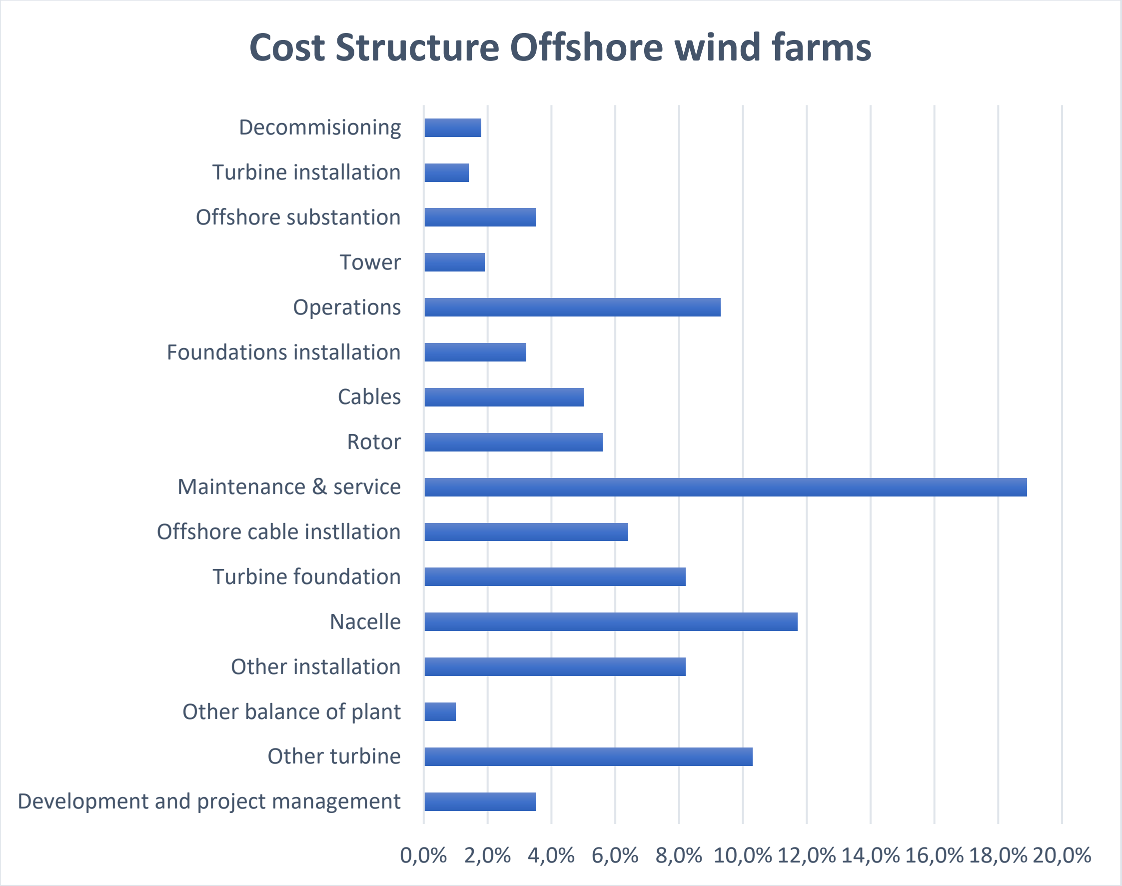


Figure 3.7: Cost structure of an offshore wind farm in percentages. Maintenance & service is by far the largest cost (BVG Associates, 2022).

Maintenance and service account for the highest portion of costs, with almost 20%. In addition, these can grow bigger and impact more in areas where more maintenance is necessary. Most of the costs listed in the figure above are dependent on location. Costs such as cables, rotors, towers, nacelles, and other installations are almost similar, disregarding the location. However, additional costs may differ more in different locations, so it is necessary to analyse timing and critical drivers of cost-increasing variables.

An offshore wind farm project runs for several years, and the costs are connected to the different phases of a project. The investment cost accounts for a considerable portion of the total costs, as most of the costs are presented in Figure 3.7. The most substantial expense is maintenance and service, which occurs every year. Together with operation costs, the total O&M costs account for 30% of the total expenditure. Therefore, almost 70% of the total payments arise before a single watt-hour is produced. This stresses the importance of a long-term plan regarding the placement of offshore wind farms and the investment in infrastructure. The infrastructure should be built to facilitate several wind farms within a reasonable radius. OPEX and CAPEX may vary depending on different techno-economic factors. Other site conditions are beneficial in terms of minimising costs. Techno-economic conditions are the key drivers of investment – and operating costs. Site conditions such as deeper water, distance to the grid, and turbine sizes will all affect the project's total costs. An analysis of the substantial effect will be discussed later.

3.5 Revenues and the nordic power market

The revenues from offshore wind come from energy production, sales and distribution. Since Norway is a part of the Nordic power market, the trading of electricity can happen within Norway and across borders with other countries. Norway introduced market-based power trading in 1991 (Energy Facts Norway, 2019). Power trading allows countries to derive mutual benefits from differences in available natural resources and consumption patterns. The trades result in a lower overall cost than if each country provided energy for itself. Power trading systems also ensure the maximum value for energy. Energy flows from low-price areas to high-price areas. Hence it is revenue maximising for the producers.

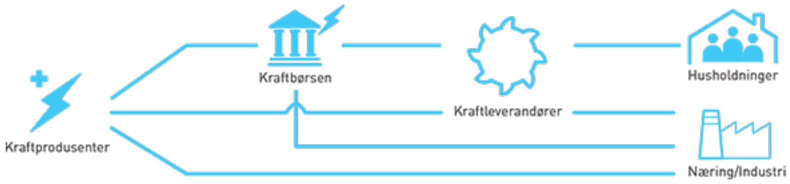


Figure 3.8: Illustration of how the Nordic power market works. The figure illustrates how the consumers get their power, either from a power supplier, the power exchange, or the producer. (Energy Facts Norway, 2022).

Figure 3.8 shows the flows and paths of power supplied in the Nordic power market. The power producer gets paid for the volume they deliver, and the end users pay for their consumption. The grid companies, such as Statnett, keep track of produced and consumed energy.

Energy prices are set through auctioning based on market coupling functions. The auctioning calculates prices and electricity flows simultaneously in the day-ahead market (Energy Facts Norway, 2022). Another price calculation can be done in intraday trading, which is also managed and facilitated by Nord Pool Exchange. The market participants can make offers and do not need extra grid capacity. Lastly, market participants can enter bilateral contracts on purchases and sales of electricity at an agreed price and delivery (Energy Facts Norway, 2022).

4. Data Description

In this chapter, we describe the data used to perform the analyses in this thesis. The qualitative analysis of potential areas for wind power production includes analysing the wind conditions and the possible wind power production. These analyses are based on the dataset NORA3-WP developed by Solbrekke and Sorteberg (Solbrekke & Sorteberg, 2022a). After the qualitative selection of the new areas that will be compared to the existing ones, data from the NORA3-WP dataset will be used to perform several quantitative analyses.

4.1 Introducing NORA3-WP

Much due to the discussion around offshore wind power in the global energy mix, there has been an increase in the request for quality wind data. This has inspired the development of the new high-resolution wind dataset for the offshore areas enclosing Norway called NORA3-WP. This dataset is based on the high-resolution hindcast archive from the Norwegian Meteorological institute, NORA3, using modelled wind data and air temperature, density, and pressure. NORA3-WP contains 43 relevant wind power and wind resource variables and covers the North Sea, the Baltic Sea, and parts of the Norwegian and Barents Seas, visualised in Figure 4.1. The data is available on a 3 x 3 km horizontal grid, covering the Norwegian continental shelf and the surrounding ocean areas (this amounts to 652 grid points in the X-direction (longitude) and 1 149 grid points in Y-direction (latitude)). NORA3-WP covers 1996 – 2019 (Solbrekke & Sorteberg, 2022a).

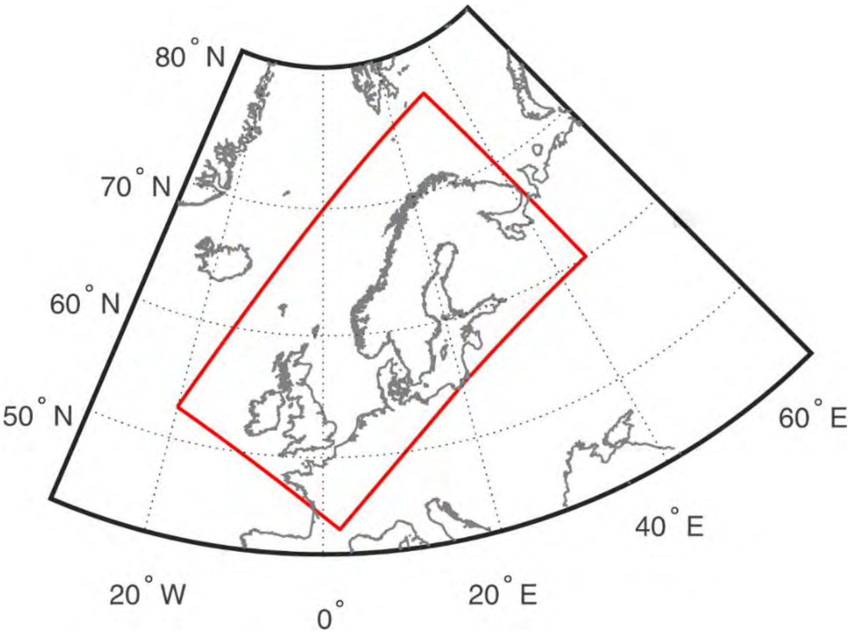


Figure 4.1: The geographical domain covered by NORA3-WP (red rectangle) (Solbrekke & Sorteberg, 2022a).

NORA3-WP contains monthly values for all variables, providing climatological information at each grid cell. It also contains hourly wind speed and generated wind power data providing detailed high-frequency data for more advanced analysis. The wind resource variables included are presented in Table 4.1.

Table 4.1: Wind resource variables included in NORA3-WP (Solbrekke & Sorteberg, 2021).

Wind resource variables in NORA3-WP
Hourly wind speed (m/s)
Monthly wind speed (m/s) (mean, 25-, 50-, 75-, 95-percentile, std, max)
Monthly exponential power law coefficient, alpha (mean)
Monthly Weibull scale and shape parameters
Monthly prevailing wind direction sector (deg) (mean)
Monthly vertical wind shear (m/s) (mean, max)
Monthly absolute ramp-rate (m/s) (mean, max)

NORA3-WP wind power estimates are available for three selected turbines with different rated capacities and hub heights. These three are SWT-6.0-154 from Siemens, a floating three-bladed electricity generator used in Hywind Scotland, DTU-10.0-RWT, the widely used reference wind turbine from the Danish Technological University (DTU), and IEA-15-240-RWT, the new reference turbine from the International Energy Agency (IEA).

Table 4.2: Turbine specifications for the three turbines used to generate the wind power related variables in NORA3-WP (Solbrekke & Sorteberg, 2021).

	SWT-6.0-154	**DTU-10.0-RWT**	**IEA-15-240-RWT**
Rated power, C_r *(W)*	6 000 000	10 000 000	15 000 000
Hub height *(m)*	101	119	150
Rotor diameter *(m)*	154	178.3	240
Specific rated power C_r/A (Wm^{-2})	161.1	200.3	165.8
cut-in *(m/s)*	4.0	4.0	3.0
rated *(m/s)*	13.0	11.4	10.59
cut-out *(m/s)*	25.0	25.0	25.0

We are also provided with a graph illustrating the normalized wind power at different wind speeds for the different turbines and the effect of the storm controls. "SC1": "Storm control 1": Instead of an abrupt shut-down of the power production when the wind speed exceeds the cut-out limit, a smooth shut-down and start-up procedure is practised in SC1. "SC2": "Storm control 2": When the wind speed exceeds the cut-out limit, the SC2 involves termination of wind power generation until the wind speed is below a given wind speed threshold (u_co_new) lower than the cut-out limit (u_co) (Solbrekke & Sorteberg, 2021).

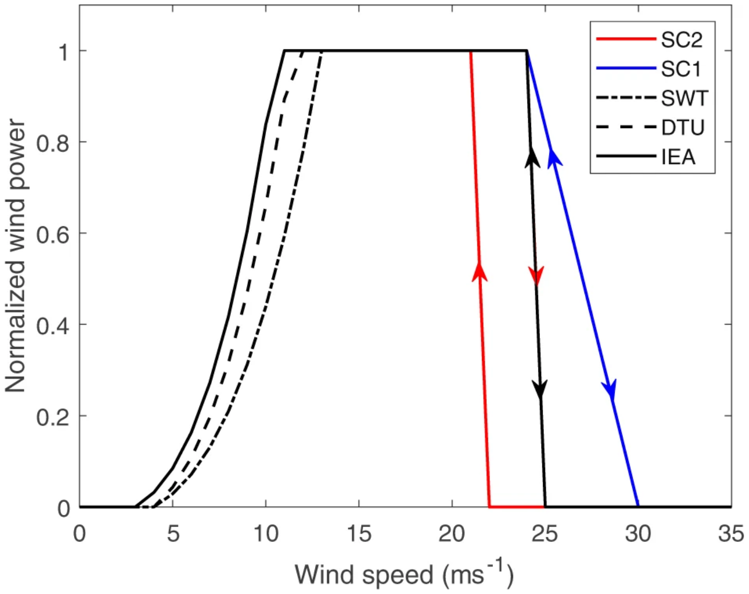


Figure 4.2: Power curves for the three turbines (SWT-6.0-154, DTU-10.0-RWT, IEA-15-240-RWT). In addition, the figure illustrates how the high wind speed end of the power curve changes when storm control 1 (SC1) and storm control 2 (SC2) are included. The arrows indicate how the different power curves shut down (arrow down) and restart (arrow up) at high wind speeds (Solbrekke & Sorteberg, 2022a).

The 17-wind power related variables included in NORA3-WP are:

1. Hourly generated power (W)
2. Monthly wind power density (W/m^2) (mean)
3. Monthly power capture (W/area^2) (mean)
4. Monthly generated power (W) (mean, 25-, 50-, 75-percentile)
5. Monthly generated power, density corrections (W) (mean)
6. Monthly generated power, SC1 and SC2 (W) (mean)
7. Monthly power capture coefficient (%) (mean, max)
8. Monthly generated power absolute ramp-rate (W) (mean, max)
9. Monthly cubed power generation (%)
10. Monthly rated power generation (%)
11. Monthly no generated power, low wind (%)
12. Monthly no generated power, high wind (%)
13. Monthly no generated power, total (%)
14. Monthly no generated power, total, SC1 and SC2 (%)
15. Monthly capacity factor (%)
16. Monthly full load hours (h)
17. Monthly full load hours, SC1 and SC2 (h)

In the following, we will showcase how we have taken advantage of parts of this data source when performing our quantitative analyses.

4.2 Data handling

The complete NORA3-WP dataset amounts to 3.53 TB, an enormous amount of data to analyse. One year of hourly data amounts to 76 GB. In our case, we needed to request an extraction of a sufficient subset of the dataset relevant to our analyses. Sondre Nedreås Hølleland helped us with pulling out our requested data. Luckily, we only needed hourly data for the potential wind power production, and Sondre could exclude many irrelevant variables. Sondre extracted data from “Wind power generation hourly” and created a combined dataset.

The resulting dataset we received from Sondre contained hourly power production data for all our selected locations from 1996 to 2019. This power production is available for all three different turbines – which we enumerate as follows: 1 = SWT-6.0-154, 2 = DTU-10.0-RWT and 3 = IEA-15-240-RWT. The full dataset has 8 204 976 hours of model outputs with nine variables. As already mentioned, we are using the IEA-15-240-RWT as our reference turbine, and the first step in our data handling was to include only data with the turbine variable = 3. After doing this, our new dataset only has 1/3 of the original observations, 2 734 992. The next step is to isolate data for the different locations so that we can perform calculations for the individual locations with the data. The isolation process results in multiple data frames with 210 384 data, i.e., 210 384 model-outputs. This number of model-outputs is also the amount of hours in 24 years, which corresponds with our period (1996 – 2019).

Table 4.3: Finished table for Utsira Nord and turbine = 3 (IEA-15-240-RWT) we use to perform analyses (Solbrekke & Sorteberg, 2021).

turbine	**powerprod (W)**	**year**	**Place**	**Region**	**lon**	**lat**	**locID**	**datetime**
3	6 553 988	1996	Utsira Nord	Southern	4.537266	59.29082	1	1996-01-01 00:00:00
3	10 120 601	1996	Utsira Nord	Southern	4.537266	59.29082	1	1996-01-01 00:00:00
…	…	…	…	…	…	…	…	…

In the following, we will showcase how we have taken advantage of parts of this data source when performing our quantitative analyses.

5. Limiting areas for potential wind farms

In this chapter, we explore and analyse the Norwegian coast to limit the number of suitable locations for offshore wind farms. The Norwegian economic zone extends 200 nautical miles from the coast (Økonomiske Soneloven, 1991, §1). NVE also states that the Norwegian economic zone has a vast offshore wind potential (NVE, 2013). Chapter 5 is divided into three parts, first, an analysis of wind potential, i.e., the revenue and stability parameters. Secondly, an analysis of the techno-economic factors, such as cost-reducing factors and the demand for energy per region. Lastly, we will discuss and conclude different opportunity areas along the Norwegian coast. Before selecting our final locations, we will rank three defined regions: Southern, Middle, and Northern.

Before the analysis begins, it is necessary to repeat the perspective of the study. As mentioned, the analysis has an investor perspective, implying that the study will investigate areas with high-profit potential. Their revenues, variabilities, and costs strongly determine their profit potential. The selected areas have the potential to maximise power production and, at the same time, deliver consistent wind power production. Investment- and operating costs are also a considerable part of the opportunity area selection. The analysis will exclude areas where it is impossible to place offshore wind and favour cost-reducing areas. As for the cost calculations, rather than calculating specific costs for each location, we have done estimations for the conditions that will impact the leveraged cost of energy. Existing analyses done by the government in 2009 (NVE, 2010) and Solbrekke in 2022 (Solbrekke I. M., 2022) have accounted for other parameters, such as environmental and socioeconomic impact. The investor perspective in this thesis ignores these factors to some extent.

5.1 What do the Norwegian wind conditions look like?

When performing our qualitative analysis, it is natural to start by addressing the key and most important factor regarding the decisions around the placement of offshore wind, the wind conditions. No matter how shallow the ocean depth or how close to an oil platform one places the wind turbines, one will never be able to compensate for the lack of wind. Luckily, the Norwegian offshore wind resources are outstanding (Solbrekke I. M., 2022).

We will begin this analysis by looking at the wind speed throughout Norway and its coastal areas. The following section will look at potential power production for different regions in Norway and consider the actual power production one can obtain. We will also touch upon the potential effects of incorporating correlation when placing the wind turbines. Finally, we will conclude this part of the thesis by ranking three pre-defined regions.

5.1.1 Wind speed

A big part of why this thesis was chosen is the development of the already highlighted wind dataset for the offshore areas enclosing Norway called NORA3-WP. Even though we have access to such a comprehensive resource, we will only be able to utilize this after we have chosen the areas we want to compare. The main reasons for this are limitations in time and computational power. To do calculations for many different areas could be highly time-consuming and ineffective. In addition, we might be doing calculations for areas that would be instantly excluded after the qualitative analysis is performed. Therefore, the first step is to start with a rougher wind analysis of Norway's coastal areas. We seek to access resources that provide a better overview of "the big picture" and will start by looking at different wind maps.

Solbrekke and Sorteberg (2022b) provide a map highlighting average wind speeds from 1996-2019 at 150 m based on hourly wind data from NORA3-WP. Below is a snippet of this map, including more detailed visuals for the three regions, Southern, Middle, and Northern.

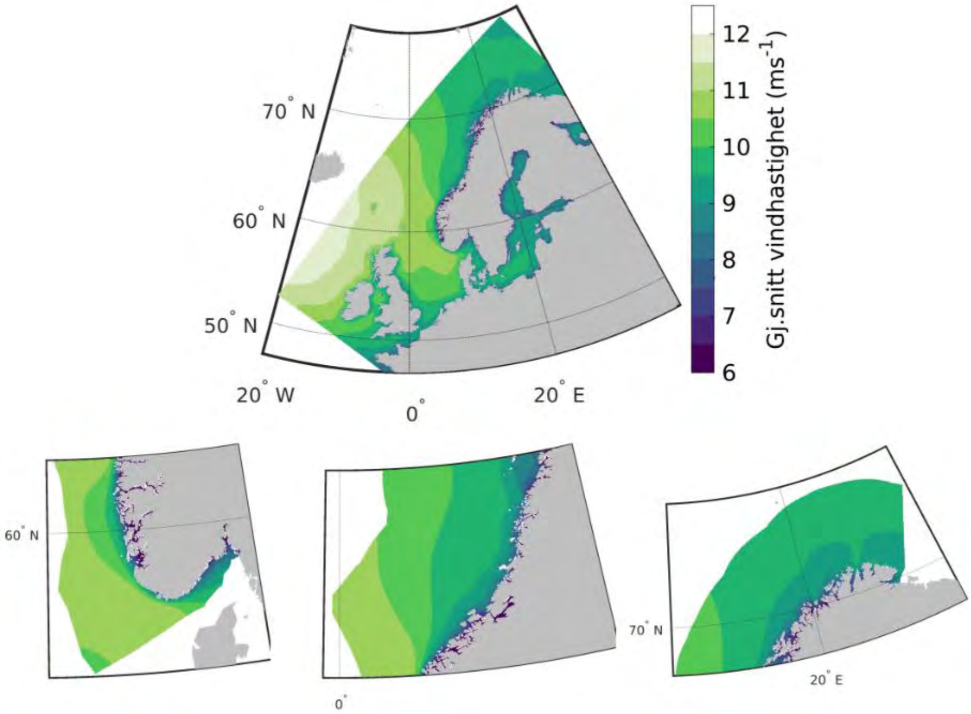


Figure 5.1: Mean wind speed (m/s) from 1996 – 2019 at 150 m. Lower panels highlight the three regions southern (left panel), middle (middle panel), and northern (right panel) (Solbrekke & Sorteberg, 2022b).

Briefly looking at Figure 5.1, there are several trends one can address. The map indicates that yearly average wind speeds for the Norwegian oceans range from around 9.0 ms^{-1} to 11.0 m/s. The figure also indicates that average wind speeds increase when moving further away from the shore and in the southern region. The map from Solbrekke cannot singlehandedly be used when assessing the placement of offshore wind due to its lack of detail and statistics around wind speed, as well as not assessing any other essential factors for wind turbine placement. Nevertheless, it helps achieve a big-picture perspective of the wind situation on the Norwegian coast and backs up the theory that the Norwegian offshore wind resources are outstanding.

Solbrekke and Sorteberg (2022) divided the covered area of NORA3-WP into three smaller regions.

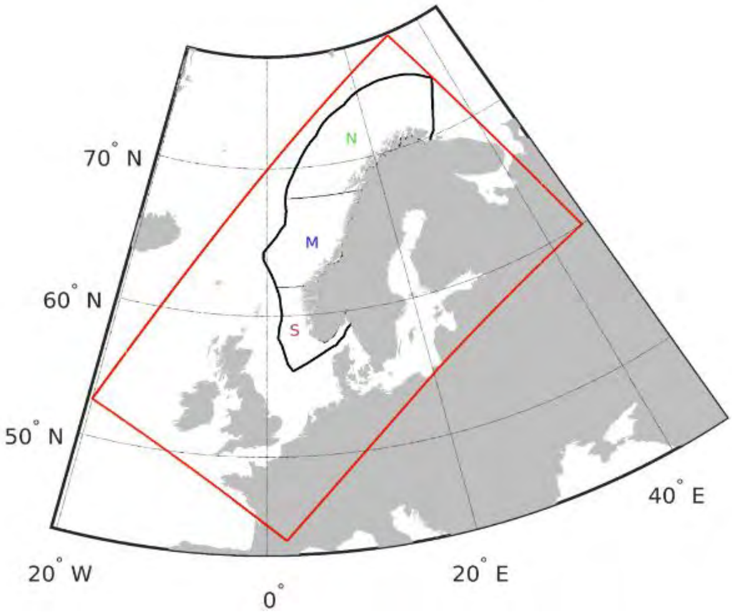


Figure 5.2: The geographical area covered by NORA3-WP, with the different regions S (southern), M (middle), and N (northern) highlighted (Solbrekke & Sorteberg, 2022b).

The three smaller areas show the southern region (pink), the middle region (blue), and the northern region (green). The average wind speed for the area within the red rectangle is 9-11 m/s. The simulated wind speeds in this data set are typically 0.5 m/s too low, resulting in rather conservative estimates. However, this will not matter because we will solely use this dataset to compare different areas, not calculate real-life outputs. We also have some statistics for the three regions with seasonal averages and variances.

Table 5.1: Seasonal variation for wind speeds and hourly change for the three regions (S, M, N). The average wind speed and variance for the year are highlighted in bold, followed by the average for winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November) (Solbrekke & Sorteberg, 2022b).

	Wind speed (m/s)					**Wind variability** (m/s)				
Region	Yearly	Winter	Spring	Summer	Fall	Yearly	Winter	Spring	Summer	Fall
South	**10.2**	11.9	9.7	8.3	10.8	**0.78**	0.9	0.74	0.67	0.80
Middle	**9.9**	11.8	9.6	7.9	10.3	**0.80**	0.99	0.76	0.61	0.82
North	**9.5**	10.8	9.5	7.7	9.7	**0.72**	0.9	0.72	0.53	0.74

In Table 5.1, statistics provide insight into the historical wind speeds throughout the different regions in Norway. As already mentioned, the Norwegian wind conditions are outstanding for wind power production, which is also backed up by (Letcher, 2017), who presents us with Table 5.2.

Table 5.2: Wind power classification based on wind speed (m/s) (Letcher, 2017).

Wind Power Class	Resource Potential	Wind speed (m/s)
1	Poor	0.0 – 5.9
2	Marginal	5.9 – 6.7
3	Fair	6.7 – 7.4
4	Good	7.4 – 7.9
5	Excellent	7.9 – 8.4
6	Outstanding	8.4 – 9.3
7	Superb	> 9.3

This part of the thesis only considers wind speed and some of its metrics. Whereas it is a good starting point to look at wind conditions, wind speed and the following metrics do not necessarily provide us with good insights into the potential power production by wind farms in covered areas. Higher wind speed does not linearly mean higher power production in an offshore wind farm because many factors contribute to the output.

5.1.2 Wind power potential

We have already concluded that the Norwegian coastal areas favour wind power production. The wind power potential contains information about how much kinetic energy is in the wind per square meter per second. In our simplified version of the real-world situation, we do not include any technical limitations regarding turbines. Therefore, the thesis deal with a theoretical picture of the energy in the wind. As we have already touched upon in chapter 3, the wind power potential is proportional to the air density and the wind speed cubed. Because the wind speed in this equation is to the power of three, a slight change in wind speed will result in a much more significant change in the potential power production.

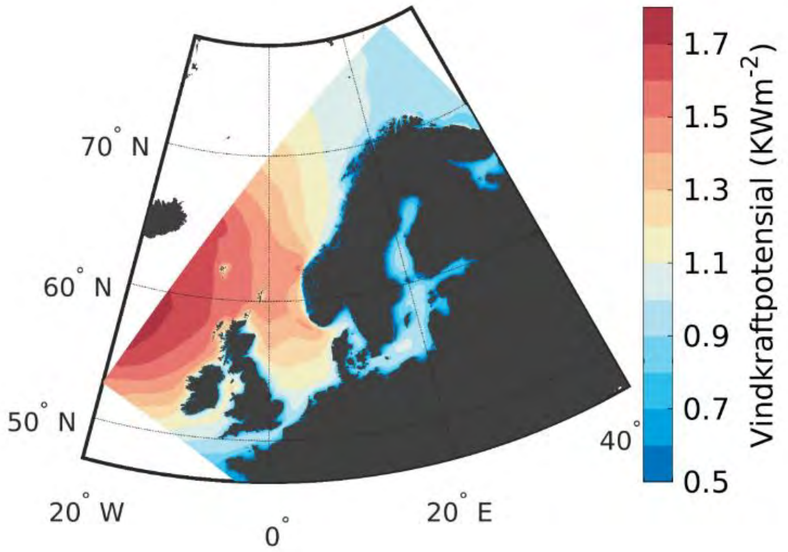


Figure 5.3: Average hourly KWm^{-2} rotor area for the period 1996-2019 (Solbrekke & Sorteberg, 2022b).

Figure 5.3 shows the wind power potential of the Norwegian coast. In this area, we have smaller areas providing between 900-1500 W with wind energy per square meter per second. The highest values are found off the west coast of southern Norway, with a maximum at Stad, and partly along the southwestern coast between Obrestad and Lista. This correlates strongly with the areas experiencing the highest wind speeds (Solbrekke & Sorteberg, 2022b).

The wind power potential of 900-1500 W is a theoretical estimate that only measures how much wind energy pass through a square meter per second. It does not tell us how much power one can produce in the area with a wind turbine. If we were to consider that a wind turbine does not produce power when the wind is too weak (u < cut-in wind speed) or high (u > cut-out wind speed), and in addition that it does not follow the wind speed to the power of three when exceeding the nominal limit, the map of produced wind power will look much different than the map of the wind power potential (Solbrekke & Sorteberg, 2022b). This brings us to the next part, wind power production

5.1.3 Wind power production

We must choose a turbine to gain a better and more realistic picture of how much power we can produce. In the report we have retrieved our data from, “Norsk Havvind del 1: Vindressurs og potensiell kraftproduksjon”, they have chosen to use IEA’s 15 MW reference turbine which is set at the height of 150 meters. IEA’s 15 MW reference turbine is also the turbine we will use for the quantitative analysis in our thesis. The IEA turbine starts producing power at 3 m/s (also known as cut-in speed, u_{ci}). It reaches optimal production of 15 MW at 10.59 m/s but must shut down and stop production at 25 m/s (also known as cut-out speed, u_{co}).

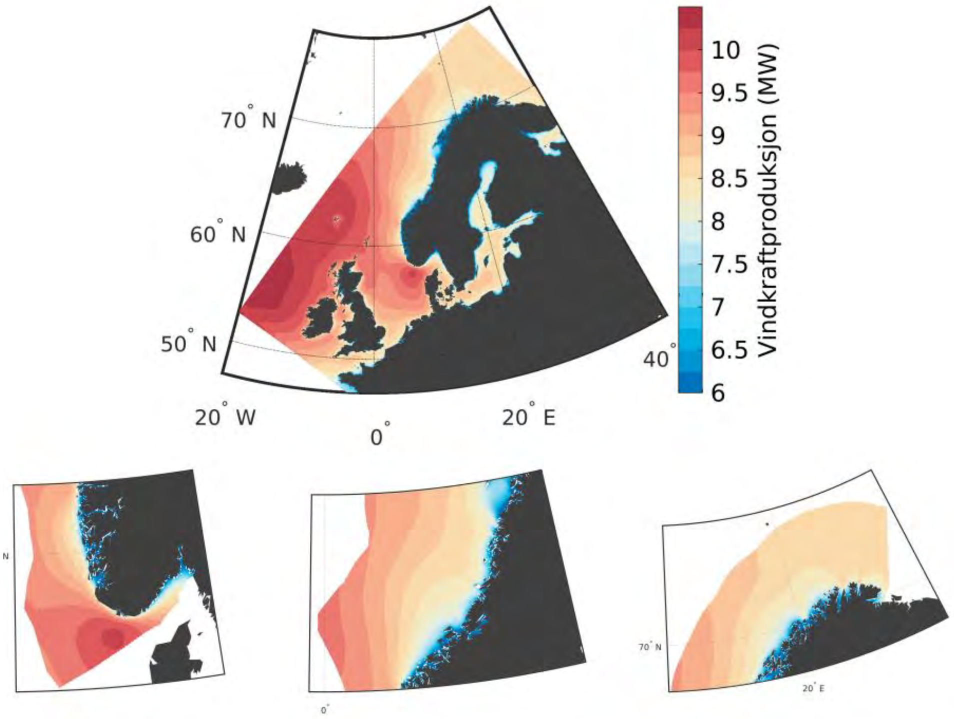


Figure 5.4: Average hourly wind power production (MW) for 1996-2019. Lower panels highlight the three regions southern (left panel), middle (middle panel), and northern (right panel) (Solbrekke & Sorteberg, 2022b).

Figure 5.4 shows the average hourly power production (from 1996-2019) generated using the IEA 15 MW reference turbine. From this chart, the southern areas of Norway generate the most wind power, and the previously mentioned areas around Stad are worse off. The southern areas of Norway have the most wind incidents between cut-in and cut-out and the highest number of incidents between the nominal and cut-out speed limit. The areas around Stad have quite a few incidents where the wind is too strong to produce any power and exceeds the cut-out speed (Solbrekke & Sorteberg, 2022b).

5.1.4 Variation in wind power production

Having a high average power production is beneficial. However, if the interannual power variation and seasonal variation become too big, we have an unfavourable situation in terms of power availability and power security. Figure 5.5 shows the annual variability in average wind power production for the entire NORA3-WP domain and the three pre-defined regions. The southern region is the region that, on average, will produce the highest wind power and which almost always has the highest annual average production. The interannual variation is significant for all the regions and can be up to 1 MW from one year to another. The regions do not produce in phase, meaning one region can experience a relatively high average production while the other regions have lower production than usual (see especially the years 2002 and 2006) (Solbrekke & Sorteberg, 2022b).

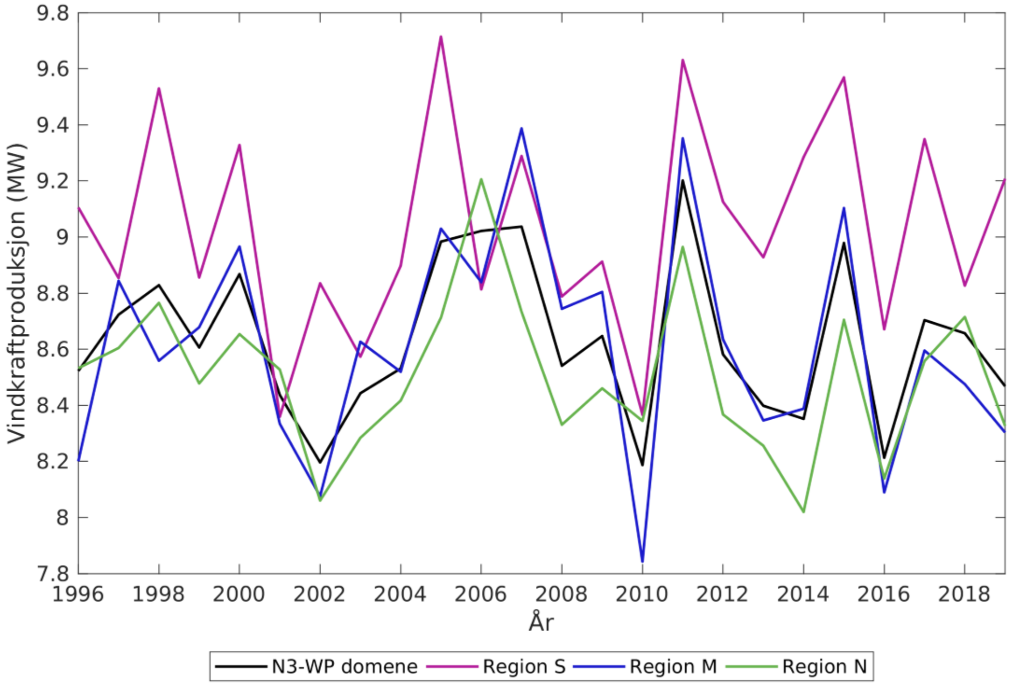


Figure 5.5: Hourly average wind power production for the whole domain and individually for the three regions (Solbrekke & Sorteberg, 2022b).

The seasonal wind power production and hourly change in wind power are listed in Table 5.3 below. The southern region has the highest wind power production throughout all four seasons. The region also has the lowest average power variability from one hour to another. Unlike the middle and northern regions, the southern region has the most significant hourly variance in the summer. This is probably related to the non-linear relation between wind speed and wind power production. If the wind speed changes between the nominal and cut-out wind speed limits, the power production does not change, as it is already optimal. Therefore, a change in the wind speed usually only results in a power production change if it is between the cut-in and the nominal wind speed limit. Because the southern region has high average winds, this region will more regularly experience wind speeds between nominal and cut-out, especially in winter, spring, and autumn. Thus, a change in wind speed from one hour to the next will likely not change the power production in these seasons. Therefore, summer is the season with the highest average power variability for the southern region (Solbrekke & Sorteberg, 2022b).

Both wind power variability and zero production are undesirable. By "zero production", we refer to wind events where the wind is either too weak ($u < u_{ci}$) or too strong ($u \geq u_{co}$) to generate wind power. Figure 5.6 shows wind power variability (left panel) and zero production events (right panel). In addition to variability due to transient weather systems, the areas close to land will be exposed to more friction and turbulence. This will lead to higher wind power variability and zero production. The southern part of the southern region is particularly well suited for optimal wind power production, whereas it has little variability and few zero production events. This area has an average absolute hourly variability of 0.7-0.8 MW, which corresponds to 4.7-5.3% of nominal power (15 MW), and it will only have zero production at 5-7% of the time due to low/high wind speeds (Solbrekke & Sorteberg, 2022b).

Table 5.3: Seasonal variation in wind power production (u) and hourly change in wind power production (variability u) for the three regions (S, M, N) from 1996 – 2019 (Solbrekke & Sorteberg, 2022b).

	Wind power production (MW)					**Hourly wind power variability (MW)**				
Region	Yearly	Winter	Spring	Summer	Fall	Yearly	Winter	Spring	Summer	Fall
South	**9.0**	10.3	8.8	7.3	9.8	**0.81**	0.83	0.80	0.81	0.79
Middle	**8.6**	10.2	8.5	6.7	9.1	**0.84**	0.97	0.83	0.74	0.83
North	**8.5**	9.9	8.6	6.6	8.9	**0.81**	0.93	0.83	0.67	0.82

Table 5.3 shows yearly values highlighted with bold font, followed by seasonal values for December-January-February (winter), March-April-May (spring), June-July-August (summer), and September-October-November (fall). It is also possible to calculate a seasonal ratio for wind power production from 1996 to 2019 for all three regions. This can indicate ranking the regions, whereas we are comparing similar portfolios. From Table 5.3, we see that the southern region is the best yearly and has the highest values for three out of the four seasons. The northern region is the second best on a yearly perspective and beats the middle region in all seasons except in the three fall months. The middle region is the worst yearly and never the best in any of the seasons.

Table 5.4: Wind power production divided by the hourly wind power variability for all three regions for the period 1996 – 2019 (S M N).

	Wind power production (MW) / Hourly wind power variability (MW)				
Region	Yearly	DJF	MAM	JJA	SON
South	**11.11**	12.41	11.00	9.01	12.41
Middle	**10.24**	10.50	10.24	9.05	10.96
North	**10.49**	10.65	10.36	9.85	10.85

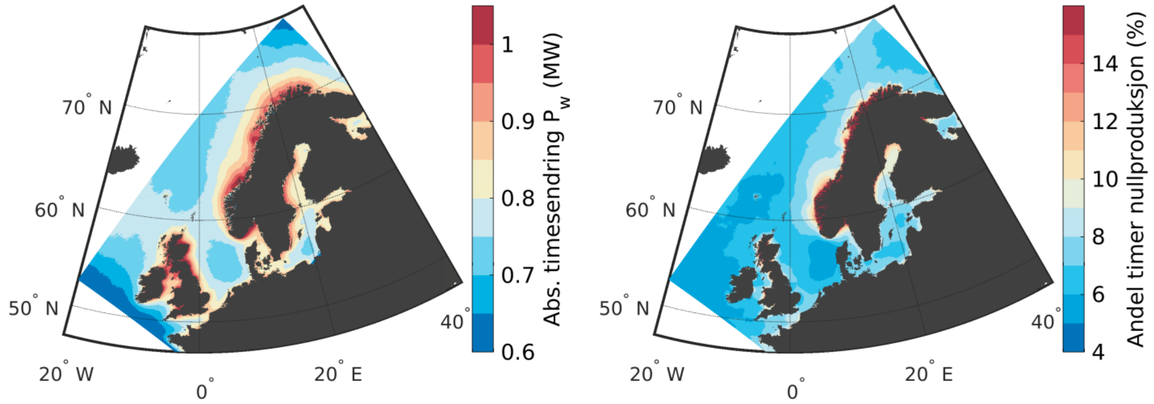


Figure 5.6: Left panel: Average absolute value of hourly change in wind power production (MW). Right panel: Proportion of hours between 1996 – 2019 that do not produce wind power because the wind is too low (u less than cut-in) or too high (u greater than cut-out) (Solbrekke & Sorteberg, 2022b).

5.1.5 Placements based on correlations

As already assessed in our thesis, wind power variability is an issue. The PhD “Assessing the Norwegian Offshore Wind Resources: Climatology, Power Variability and Wind Farm Siting” by Solbrekke enlightens this issue. Solbrekke says that one of the possible solutions to wind power variability might be an interconnection of wind farms. The idea that one can smooth the wind power output by coupling production sites was first studied in 1979 by Kahn (Khan, 1979). His idea behind coupling allocated wind farms is that the interconnected sites will experience different weather at a specific time. Therefore, aggregating the wind farm area could reduce wind power variability (Solbrekke I. M., 2022).

Regarding the ideal reduction of wind power variability, one would want to interconnect two wind farms with a wind power correlation coefficient of r = -1. If this is the case, the combined wind power production would be entirely out of phase, and one would have a constant production of wind power. Figure 5.7 shows the correlation coefficient of hourly wind power production between a hypothetical wind turbine at a point inside the area of Sørlige Nordsjø II (SN2) and all other grid points in the NORA3-WP domain for the year 2004. Figure 5.7, shows that no other sites are entirely anti-correlated (r = -1) with SN2. Some sites have r ≈ 0, meaning that the hourly wind power productions at these sites are completely uncorrelated. We notice that the grid points close to SN2 have a high correlation coefficient, meaning that their hourly wind power productions are synchronized. In other words, when SN2 produces wind power, it is likely that the grid points close to it also produce wind power. Figure 5.7 shows the trend that the further away two grid points are from each other, the less correlated they are. Even though none of the grid points seems to be very anti-correlated, we still need to consider that an increase in distance decreases the correlations (Solbrekke I. M., 2022).

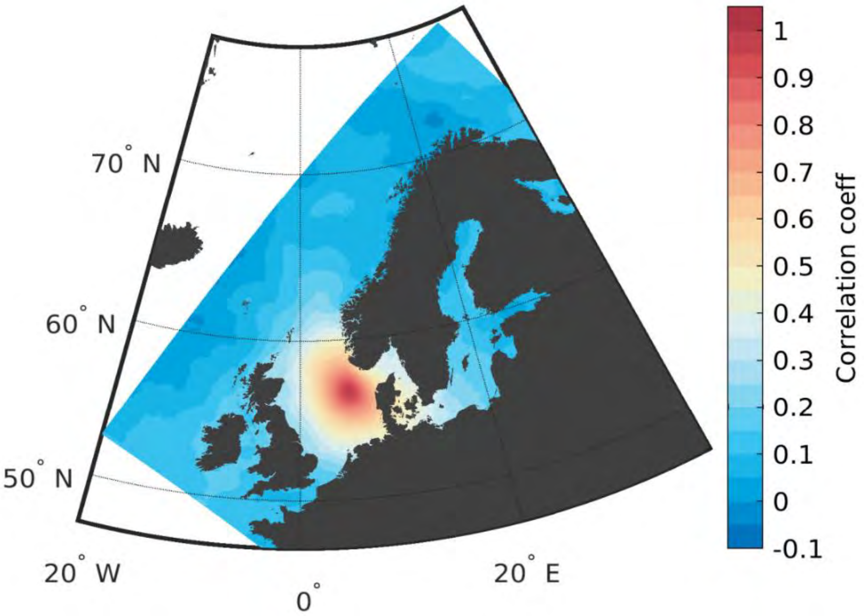


Figure 5.7: The correlation coefficient of hourly wind power production (2004) between a site inside the area of Sørlige Nordsjø II (lat: 56.81, lon: 05.30) and all other grid points covered by NORA3-WP. The power production is calculated using the DTU 10 MW reference turbine using hourly wind power production data from NORA3-WP at 199 m.a.s.l. (Solbrekke I. M., 2022).

5.2 Technoeconomical factors

Moving on from the wind statistics, we found out that the southern region stood out in terms of power production potential, and the middle region was the worst. This part of the analysis will ignore the wind conditions and focus on cost-reducing factors and revenue from market prices.

5.2.1 Transmission grid connection to mainland or petroleum activity

The Norwegian power grid is a monopoly regulated and controlled by the state. The grid is regulated by NVE, a government agency subject to the Ministry of Petroleum and Energy (OED). The electricity grid consists of three levels: The transmission grid, the regional grid, and the distribution grid (Energy Facts Norway, 2019). The purpose of the grids is to connect the energy producers to the consumers. The transmission grid connects them nationwide, and the regional grid connects the transmission and distribution grid or carries direct voltage from producers to consumers. Lastly, the distribution grid carries electricity to smaller end users. Electricity production in Norway is often located away from the consumer. This stresses the importance of a well-developed electricity grid that enables power transit to the consumer. Costs and revenues are crucial factors in an investment decision, and our decision on where to place the wind turbines is based on profits. The revenue will increase if the electricity grid can easily transport energy. On the other hand, if the new offshore wind farms require additional investments in power grids and grid lines, the investment project costs will increase.

One needs to place the wind farm within a reasonable radius of the nearest transmission grid to minimise the costs of gridlines connection. Large energy producers, i.e., offshore wind farms, are connected to the transmission or regional grids (Energy Facts Norway, 2019). The power from the wind farms is transported to the transmission grid. The electricity transport could be through a hybrid cable that enables the power supply to the Norwegian mainland and abroad (Norwegian Offshore Wind, 2022). Offshore wind farms in areas with power surpluses will benefit if they can transport the energy abroad. Sørlige Nordsjø II, for instance, can easily be connected to several markets in addition to the mainland (Nesse, 2022). We will assume that all offshore wind farms along the Norwegian coast are built with hybrid cables. Regarding the cost impact of high distance to the transmission grid, the main concern is the voltage drop. The longer the distance from production to the grid, the more voltage is dropped

(Calculater.net, 2022). The investment and maintenance of long power transmission lines will also be costly. Alternative wind turbine locations should therefore be placed within a relatively short distance of the transmission grid if the goal is to minimise costs.

Since the Norwegian Coast is highly developed with transmission grid stations, the exact location will only make a small impact. The main concern is that the developer should consider placing wind farms as close to the shore as possible. Shorter distance to the transmission grid means a lower voltage drop, hence a lower cost of energy.

In addition to the transmission grid, offshore wind farms could also be placed within a reasonable distance of oil platforms. Today, most platforms generate their electricity from gas turbines (Naturvernforbundet, 2022). Offshore wind farms could replace the gas turbines or contribute to lowering CO2 emissions. Wind power supply to oil platforms is not widespread, but Johan Sverdrup and Utsira High ring demonstrated the possibility of renewable electricity consumption on oil platforms (Cable, 2019). For example, Equinor´s Hywind Tampen floating wind farm project is estimated to provide 35% of Gullfaks and Snorre platform´s power demands.

Figure 5.8 shows an overview of offshore petroleum activity along the Norwegian coast. The Norwegian coast is crowded with petroleum and oil platform activity. The high petroleum activity gives Norway a unique opportunity to easily transport wind energy to consumers other than the mainland. Platforms in the North Sea are often placed far from shore, and offshore wind farms could be placed far from shore and still have a short distance to the consumer. However, a combination of electricity supply to both platforms and the mainland from the North Sea would be expensive because of the total cable length. Therefore, hybrid electricity production to offshore platforms and the mainland is only suited if the offshore activity is located near shores. However, the thesis assumes further that a hybrid supply to both parties would not be conducted. Instead, the wind farms would supply the nearest energy consumer, whether it is oil platforms or the Norwegian mainland.

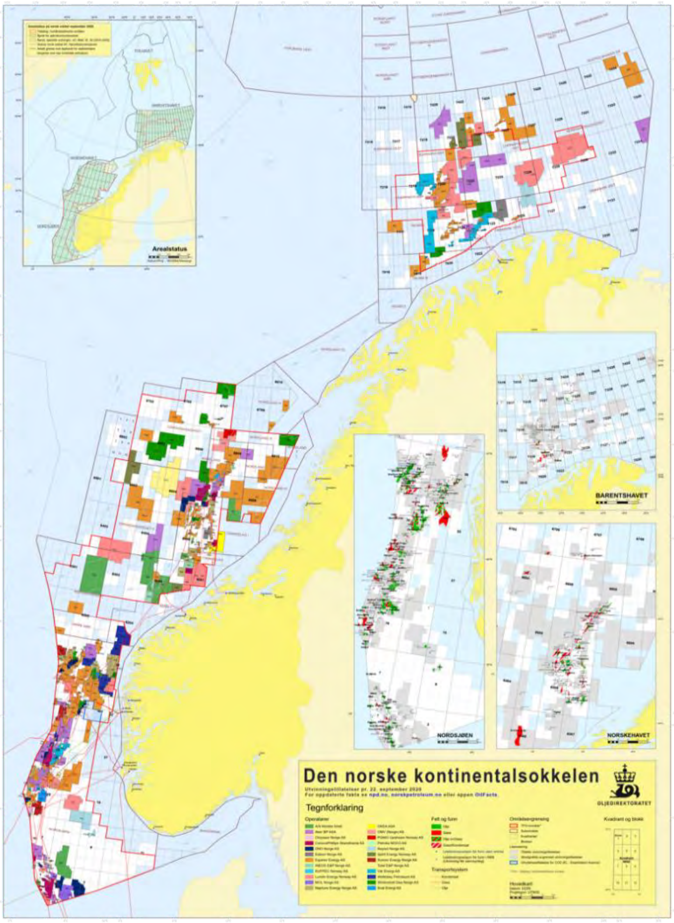


Figure 5.8: Petroleum activity along the Norwegian coast (SNL, 2020).

If the offshore wind farm should be connected to an existing oil platform, it somehow limits the area. The Norwegian coast is assembled with many oil platforms; therefore, most of the ocean is suitable for low-cost offshore wind. In the south, the offshore wind farms need to be far from the shore near Johan Sverdrup. The same conditions apply to the southwest region as well. For the northwest region, it is possible to place it closer to the shore. Platforms in the middle regions are far from the shore; thus, the offshore wind farms should be in the same areas. There are no platforms around Harstad, and connection to platforms is irrelevant. In the north, the platforms are located close to and far from the shore, meaning there are various opportunities to connect power production with an oil platform.

The transmission grids connect the Norwegian power grid. For the system to work, it must balance the power supply and consumption. The Norwegian power supply relies heavily on weather-based power such as hydropower, solar and wind. Therefore, the power supply will vary across time and regions. Today, the capacity of the power grid does not have the capabilities to equalise these differences. Hence the Norwegian power grid consists of five price areas (Statnett, 2021). The different price areas are shown in the figure below.

Name	Location
NO1	East
NO2	South
NO3	Middle
NO4	North
NO5	West

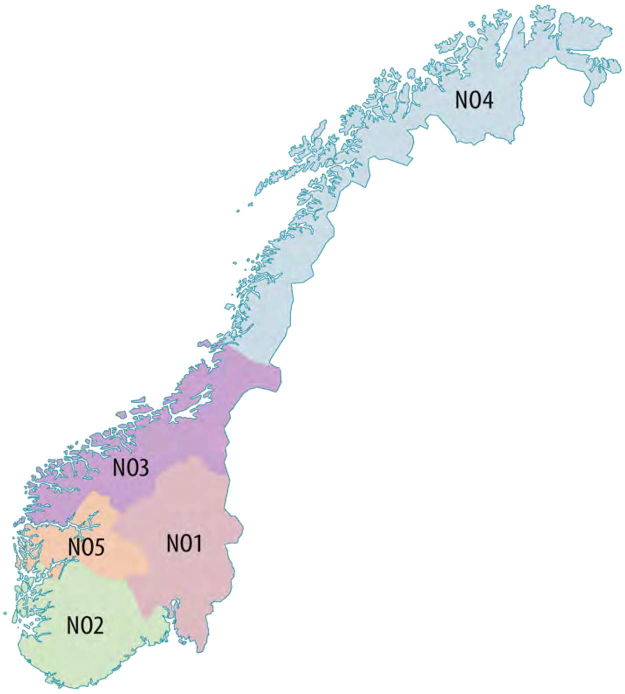


Figure 5.9: Overview of the different price areas in Norway (Oljedirektoratet, 2020).

Historically, Norway has typically had positive net power exportation, even though there have been years of power deficiency (SSB, 2022a). The power generation from offshore wind farms will be sold to either oil platforms, mainland Norway, or internationally. The payment for the power will depend on the spot price within each region. Historically the electricity prices between regions have been close to the same. However, in the last couple of years, some regions have experienced a heavy increase in the electricity spot price. For example, Figure 5.10 illustrates that NO1, NO2, and NO5 have experienced an increased change in spot prices in the last two years. Given that the differences in electricity prices are constant, an offshore wind farm will benefit economically by being linked to either NO – 1,2 or 3.

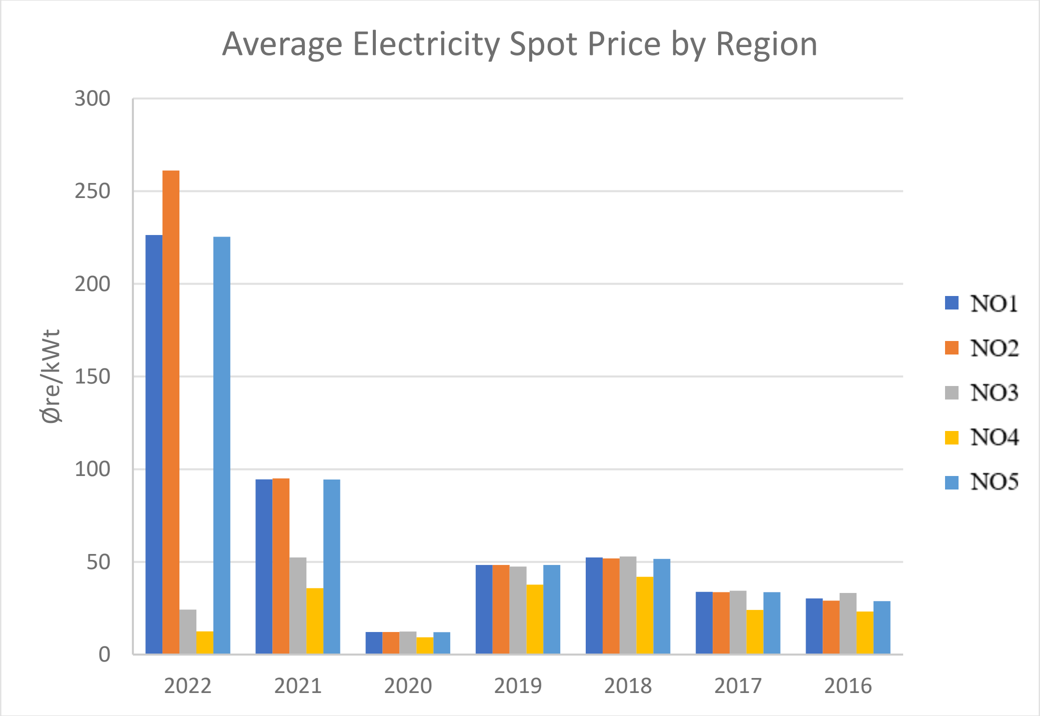


Figure 5.10: Historical electricity prices by region (LOS, 2022).

Norway consists of eleven counties of different sizes. Most Norwegian citizens and industry are located south of Trondheim, and this area will therefore have a higher energy consumption than areas north of Trondheim (SSB, 2022d). Figure 5.11 shows the historical demand for the different counties from 2010 to 2021. We see that total energy consumption has increased over the years. Viken and Vestland have much higher energy consumption than the remaining counties. Viken is the largest county in Norway with 1,2 million citizens. Despite being around 50% of Viken's citizens, Vestland accounts for a large portion of Norway's energy consumption. Vestland´s high energy consumption is primarily due to high energy consumption by the industry.

The regions and counties differ in both electricity prices and consumption. Despite higher energy consumption, the price difference across regions has been nearly irrelevant. Each region will not experience soaring prices if energy production and consumption are equal. The latest soaring in prices is due to other factors such as high gas and coal prices due to the war in Ukraine, little precipitation leading to less water in hydropower plants, and new power cables to Europe.

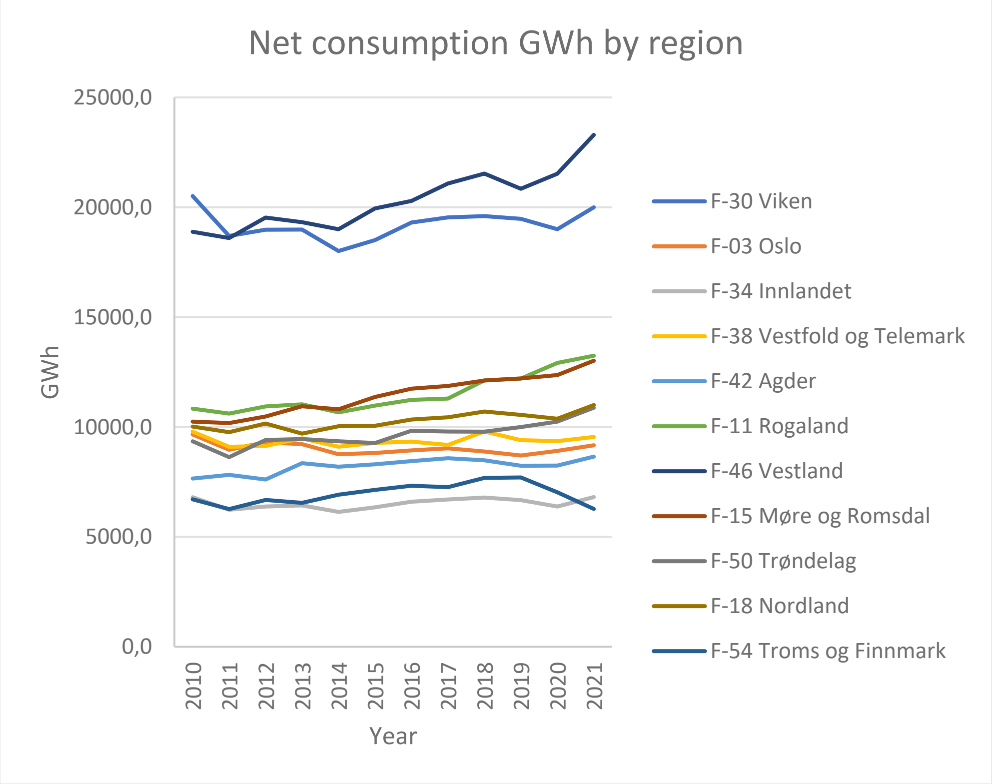


Figure 5.11: Electricity consumption (GWh) by region from 2010 to 2021 (SSB, 2022b).

Despite having a well-established electricity grid, different counties are experiencing higher prices. Historically the prices have been relatively stable, but the regions south of Trondheim have a higher energy consumption than the rest. Additionally, some of these regions connect to the European energy grid. Therefore, an offshore wind farm placement in these regions is beneficial because of the high demand and the connection to Europe.

5.2.2 Location based on ocean depth

The last cost-reducing parameter to account for is ocean depth. Recent technology enables offshore wind farms to be placed in deep waters to 1000 meters below sea level (ESMAP, 2021). Today, most wind turbines are fixed to the seabed (Equinor, 2022). An alternative to bottom fixed wind farms is the newly developed floating structure. Floating structures are more suitable for wind turbines located in water depths greater than 60 m (Matt Shields, 2021). Ocean depths greater than 60 m encompass a large portion of the Norwegian economic zone. There is no direct cost benefit from floating offshore wind compared to fixed. However, the new technology may able better solutions and cost reduction in O&M. If floating offshore wind turbines are a part of the wind farm; deeper water would lead to higher investment and maintenance costs. Lastly, the new floating foundation technology makes high-power production sites doable because the ocean depth constraint is somewhat removed. From Figure 5.12 below, offshore wind farms can be built almost everywhere except the darkest areas.

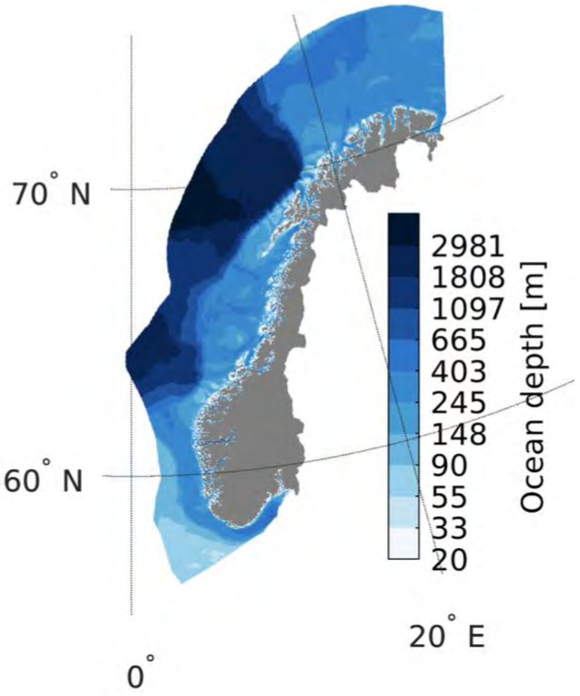


Figure 5.12: Ocean depths (m) for the NORA3-WP covered area (Solbrekke I. M., 2022).

5.2.3 Reference locations

The already approved locations are Sørlige Nordsjø II and Utsira Nord. We will use these as our reference locations when comparing results obtained in our analyses. Some of the analysis will include the locations as well. The information about NVE´s locations is gathered from (NVE, 2013).

Sørlige Nordsjø II (SN2)

One of the two locations the thesis looks to use as a reference point is Sørlige Nordsjø II (SN2). SN2 is located approximately 140 km off the southern coast of the Norwegian mainland. The 2 591 km^2 area is the largest of all considered locations. SN2's wind speed is estimated to be around 10.5 m/s, and it has a grid connection point within 150 km of the mainland. SN2 is more suitable for offshore platform grid connections or electricity transport to Europe. The water depths are between 40 to 70 m, and both floating and bottom-fixed structures would be feasible. SN2 is located between petroleum fields Ekofisk and Tor.

Utsira Nord (UN)

Utsira Nord (UN) is the second reference point. UN is located west of Haugesund, approximately 22 km off the coast. The nearest grid point is the Norwegian mainland. The nearest transmission point discussed is Grismark, but the mainland grid still needs to be updated because of the planned increase in energy supply (Statnett, 2020). The area of 1010 km^2 has an average wind speed of 10.2 m/s. The water depths are between 185 to 280 m, and floating structures are more feasible than bottom fixed structures.

5.3 Selection of potential wind farm locations

5.3.1 Ranking the regions

The qualitative analyses presented in this chapter were supposed to limit areas one can place wind farms and establish beneficial opportunity locations. We have presented several factors that increase revenue and stability and reduce costs. Revenue effects are primarily due to wind speed and production output. Stability effects are linked to reduced intermittency and maximum production hours. Cost effects combine techno-economic factors such as ocean depth and distances to electricity grids. Opportunity areas and locations will be determined on revenues and cost potentials and are concluded as follows.

As already discussed, the Norwegian offshore wind resources are outstanding. We concluded that the southern region of Norway has the best conditions, with the highest average wind power production and the lowest variance. The area within the southern region that sticks out is located directly south of Norway. The middle region comes worst out, with frequent events of too strong winds. Despite this, the overall conclusion on wind power production is that wind conditions are suitable for power production throughout the entire coastline.

Because the qualitative analysis focuses on profit-maximising, areas with relatively high costs compared to other areas should be excluded. The two criteria for exclusions are ocean depths deeper than 1 000 m and the lack of grid connections. It is not possible to place offshore wind farms in ocean depths greater than 1 000 m. Ocean depths greater than 1 000 m are illustrated in Figure 5.12. The dark blue areas are therefore excluded from the opportunity areas. The alternative locations are placed within the ocean depth opportunity area. If the ocean depth exceeds 60 m, the offshore wind farms will have floating foundations. Areas located far from shore will be excluded if there are no oil platforms within a reasonable length to connect the wind farm to the electricity grid. For example, Sørlige Nordsjø II is located far from the shore but 85 km from the nearest electricity grid on an oil platform. Therefore, the locations selected aim to be near shores or within 85 km of the nearest offshore oil platform. Most of the mainland transmission grids need to be upgraded to be able to income the additional energy supply from offshore wind farms. These additional investments will not differ much from location to location and are therefore excluded from the analysis. More power is demanded in the southern region of Norway. The southern region also has operating export opportunities. This is reflected in the spot price for electricity, where the southern region historically has higher prices; and has recently experienced soaring prices. That said, electricity prices will decrease if the supply exceeds the energy demand. This microeconomic problem will not be discussed in this thesis, but more money will be generated, ceterius paribus, by selling electricity to the southern region.

Even though we have performed a comprehensive qualitative analysis of the Norwegian coastal areas, picking out concrete coordinates still seems complicated. To simplify it, we decided to start by ranking the three pre-defined regions, southern, middle, and northern. From our analyses, we conclude that the southern region is the overall best one. The main reasons for this are that the power production conditions are superior, the revenues from the electricity price are the highest, there are good national and international power grid connections, and it is also relatively shallow in some areas. The Northern region is the second-best region. It has good overall power production conditions, low correlation to the other regions, and good mainland and offshore grid connections. However, there are a few cons with potential freezing temperatures, little local demand for electricity, and some wind farms being close to Russia, which at the time has a conflict with the west. Finally, the middle region comes out the worst, primarily because of the volatile power production conditions and low electricity demand compared to the southern regions. Nevertheless, all the regions still have outstanding power production potentials on an international level, and we see it fit that we do not exclude any of the regions yet, but rather distribute locations based on our ranking. Due to this, we picked five locations in the southern region, two in the middle region, and four in the northern region.

Additionally, we have spread out the selected coordinates so that we can experiment with correlations when creating portfolios. It also seems unnecessary to have the locations close to each other, as the wind conditions would likely be similar.

5.3.2 Selecting specific locations

In the report «Norsk havvind del 2: Hvor bør vindparkene plasseres?» Solbrekke provides us with a suitability map from an Investor-perspective. We have decided to take advantage of this when finding our coordinates. The darker the area of the map, the higher the suitability, i.e., we want to place our wind farms in either dark blue or purple areas. Another trend is that we placed the wind turbines as close to a connection grid as possible to reduce operating and maintenance costs and decrease voltage drops. However, we opted to have them at least 20 km from shore to reduce the most intense noise. Black areas on the map are unavailable for different reasons, such as ocean depths, nature reserves, oil platforms, etc.

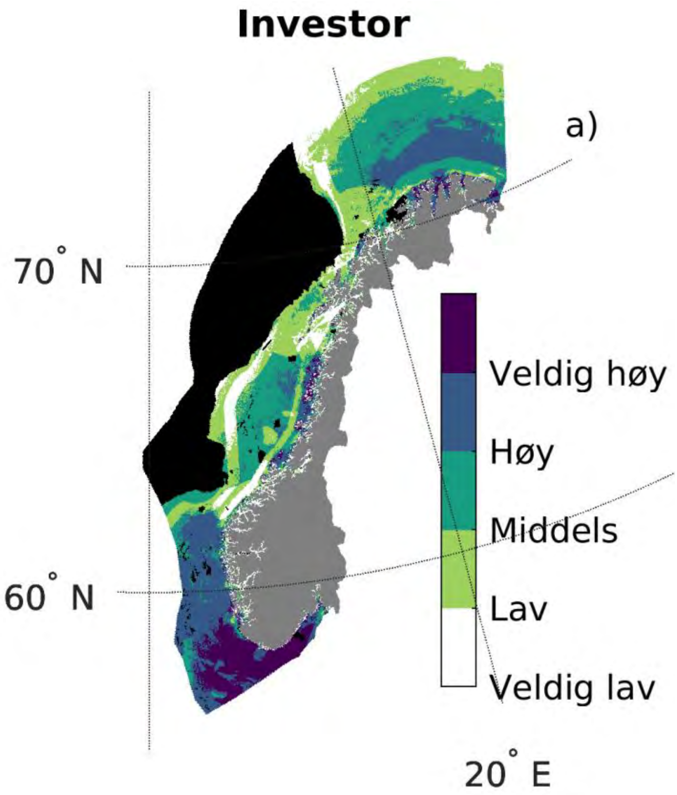


Figure 5.13: Investor suitability map from Norsk havvind del 2. Darker colours imply higher suitability, purple being the most suitable. Black areas on the map are unavailable for wind farms due to different reasons (Solbrekke & Sorteberg, 2022c).

The 11 locations we have decided to compare, including Sørlige Nordsjø II and Utsira Nord, are presented in Table 5.5 with their place names, regions, latitudes, and longitudes.

Table 5.5: Overview of all selected points, Utsira Nord and Sørlige Nordsjø II. Distance is the difference in meters between chosen latitude and longitude and the closest available grid point in NORA3-WP.

Place	Region	Latitude	Longitude
Utsira Nord	Southern	59.29082	4.53727
Sørlige Nordsjø II	Southern	56.72742	4.93766
South of Lindesnes	Southern	57.24191	6.97547
South of Kristiansand	Southern	57.80629	8.55723
West of Flekkefjord	Southern	58.11011	5.45567
West of Fitjar	Southern	59.87581	4.24914
North Sørlige Nordsjø I	Southern	57.97964	3.12901
North of Vega	Middle	65.76118	11.8908
North of Rørvik	Middle	65.05471	11.31994
West of Tromsø	Northern	69.74722	17.2681
North-East of Honningsvåg	Northern	71.17188	26.7257
South-East of Vardø	Northern	70.11969	31.35386
North of Tanafjorden	Northern	72.31211	29.71767

Table 5.6: Techno-economic conditions for the 11 own-selected locations. The grid connections are gathered from (ENTSOE, 2019). Distances are measured using Google Maps.

Locations	Ocean depth (m)	Nearest grid connection	Distance to grid connection (km)
South of Lindesnes	76	Lindesnes	10
South of Kristiansand	381	Kvareneset	41
West of Flekkefjord	250	Egersund	45
West of Fitjar	263	Svortland or Troll	55 or 90
North of Sørlige Nordsjø I	95	Egersund or YME	20 or 176
North of Vega	88	Brønnøysund	34
North of Rørvik	75	Rørvik	20
West of Tromsø	143	Brensholnen	39
North-East of Honningsvåg	160	Honningsvåg	35
South-East of Vadsø	262	Vadsø	28
North of Tanafjorden	279	Berlefåg or oil field nearby	10 or 473

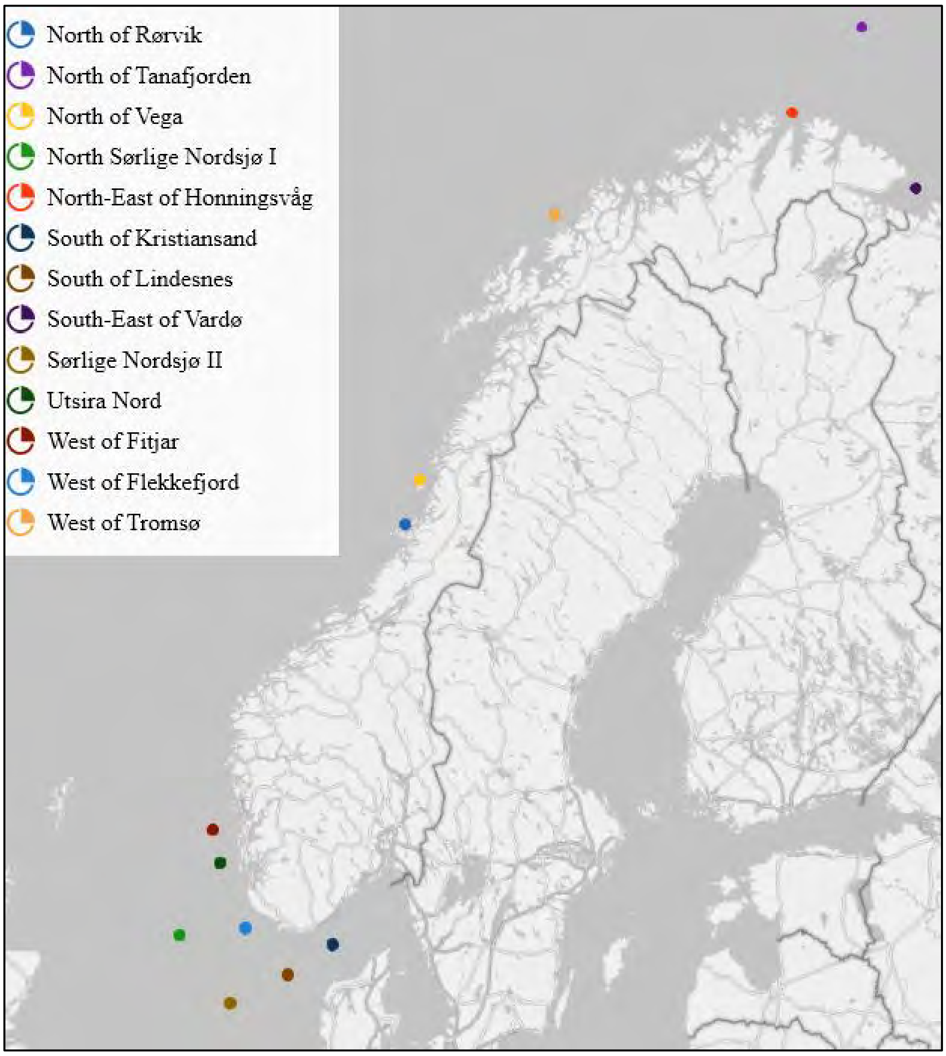


Figure 5.14: The 11 selected, and two reference locations, considered in the analyses. Colours to identify shown in the top left.

We have briefly assessed all the places that could be optimal for wind power production throughout the Norwegian coastal areas. Until now, we have only performed a qualitative analysis, and therefore it is time to proceed with the methodology and the quantitative analyses to gain some real insights.

6. The value of wind farms in Norway

This chapter will present and interpret our obtained results and explain how they are found and calculated. The chapter consists of three main parts. Firstly, an individual assessment of each location is based on a discounted cash flow model (DCF) and a Levelized cost of energy model (LCOE). Secondly, we will treat the locations as combined portfolios, including various locations. Here we compare and evaluate offshore wind farms by treating them as financial assets. This section seeks to shed light on the value of diversification to Norway AS. The optimisation problems are solved using various methods, and this section aims to give a thorough presentation of the methodology and results. Lastly, this section will have a real-life scenario of wind farm potential in Norway.

In the following, we are talking about the average return one IEA-turbine would yield in watts. When calculating total production per year, we multiple the average return with 8 760 hours (number of hours in a year). This differs slightly from methods used in the industry, where often capacity installed and loading hours are used instead.

6.1 Individual assessments of locations

The maximum problem is measured in terms of power production within a time interval. The maximum power production calculates the total energy output from 1996 until 2019. The power production is calculated by summing hourly power production from 1996 to 2019.

The results examine the maximum power production a single IEA-15-240-RWT wind turbine could obtain in our selected areas. The expected power return is measured in watts and is calculated by taking the mean of all model-outputs. In the third column of Table 6.1, we have multiplied every model-output with one hour and summed up all the hours from 1996 – 2019 to get the total production and converted the number to MWh (simply by dividing the total sum by 1 000 000). The best location, when solely looking at the highest average return, is South of Lindesnes, with an expected return of 9 963 633 W. Based on NORA3-WP, this wind turbine would have produced 2 096 189 MWh for the entire period. The worst location is West of Tromsø with an expected power production of 7 520 252 W and a total production of 1 582 141 MWh. We also immediately notice that all 7 locations in the southern regions are the best out of the 13 locations. The column to the far right shows how much worse the other locations perform compared to South of Lindesnes.

Table 6.1: Each location's average and total power production from 1996 – 2019. The "difference to best" column is how much less average hourly production the locations have compared to South of Lindesnes.

Location	Region	Expected return (W)	Zero-Production Hours (1996-2019)	Standard Deviation Return (W)	Sum power production 1996-2019 (MWh)	Difference to best
South of Lindesnes	Southern	9 963 633	5.37%	5 879 456	2 096 189	
Sørlige Nordsjø II	Southern	9 785 289	5.44%	5 885 095	2 058 668	-2%
West of Flekkefjord	Southern	9 710 952	6.41%	6 000 922	2 043 029	-3%
North of Sørlige Nordsjø I	Southern	9 572 173	6.49%	6 003 823	2 013 832	-4%
South of Kristiansand	Southern	9 327 500	7.34%	6 075 692	1 962 357	-6%
Utsira Nord	Southern	8 916 664	8.69%	6 205 880	1 875 923	-11%
West of Fitjar	Southern	8 744 177	9.71%	6 274 087	1 839 635	-12%
North of Tanafjorden	Northern	8 628 533	7.06%	6 031 304	1 815 305	-13%
North-East of Honningsvåg	Northern	8 619 063	7.00%	6 043 130	1 813 313	-13%
South-East of Vadsø	Northern	8 228 320	7.50%	6 038 578	1 731 107	-17%
North of Rørvik	Middle	7 746 896	9.03%	6 076 275	1 629 823	-22%
North of Vega	Middle	7 588 548	11.04%	6 182 446	1 596 509	-24%
West of Tromsø	Northern	7 520 252	10.49%	6 140 392	1 582 141	-25%

The calculations show that if Norway were to invest in one location solely and want to produce the maximum amount of energy, the optimal location would be South of Lindesnes. This is because the southern region dominates the maximum power rating as well. The standard deviation of each location is also visualized in Table 6.1. The two locations with the highest standard deviation are West of Fitjar and Utsira Nord.

The DCF model values an investment based on the net present value of its future free cash flows (Steiger, 2010). The free cash flow is discounted with an appropriate discount rate to find the value of the investment at a specified time. The formula shown below is used for net present value (NPV) determination and is found in numerous business school sources. NPV is commonly used to compare alternatives and can be interpreted as the attractiveness of an investment. Example-wise, a positive NPV indicates a project's attractiveness and vice versa for a negative NPV.

Equation 6.1: NPV Calculation.

$$NPV = \sum_{t=0}^{n} \frac{FCF_t}{(1+r)^t}$$

$NPV = Net\ present\ value\ of\ cash\ flow$

$FCF_t = Future\ Free\ Cash\ Flow\ in\ year\ t$

$r = Discount\ rate$

$t = \ Years$

The free cash flow, which is a part of the numerator, is a measure of the excess cash after accounting for cash outflow to operations and maintenance. The FCF excludes non-cash expenses such as depreciation and amortisation (Investopedia, 2022). This thesis is based on historical data and would not estimate future cash flows. Instead, the FCF method will be used to determine the value of an investment in 1996. We can rank the NPVs from each alternative investment accordingly by comparing them. The FCF for an offshore wind farm consists of the initial investment in year 0, revenues from power generation, and the operating and maintenance costs. The costs need to be predicted despite using historical wind data. The tables below show an offshore wind farm´s baseline scenario at 30 m water depth and 60 km from shore.

Table 6.2: Initial Investment for an offshore wind farm, baseline scenario with ocean depth 30 m and 60 km distance to shore (BVG Associates, 2022).

Costs	Pound Sterling (£/MW)
Turbine	1 000 000
Nacelle	400 000
Rotor	190 000
Tower	70 000
Other Turbine	340 000
Turbine foundation	280 000
Cables	170 000
Offshore substation	120 000
Other balance plant	30 000
Offshore cable installation	650 000
Foundations installation	100 000
Turbine installation	50 000
Other installation	212 000

Table 6.3: Operating and maintenance costs year 1-23 for an offshore wind farm.

Maintenance & service	50 000
Operations	25 000

Table 6.4: Costs year 24, Operating & Maintenance + Decommission.

Maintenance & service	50 000
Operations	25 000
Decommission	330 000

Table 6.5: Net present value of Costs.

NPV sum	4 601 895

LCOE measures the required revenue to earn a rate of return from investments. The calculations from LCOE are done in the following way:

Equation 6.2: LCOE Calculation.

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + M_t)/(1+r)^\wedge t}{\sum_{t=1}^{n}(E_t)/(1+r)^\wedge t}$$

Where:

$I_t = Investment\ expenditure\ in\ year\ t$

$M_t = Operation, maintainance, and\ service\ expenditure\ in\ year\ t$

$E_t = Net\ energy\ generation\ in\ year\ t$

$r = Discounted\ rate\ (WACC)$

$n = Lifetime\ of\ project\ in\ years$

The cost of an investment is a part of the numerator, while revenues are the denominator. Revenues and costs are discounted at the WACC (Weighted Average Cost of Capital). The equation calculates the present value of the total costs of building and operating an offshore wind farm over an assumed lifetime. For offshore wind energy, the two critical drivers of LCOE are initial capital cost and capacity factor.

The calculations of costs are based on the cost estimated for offshore wind farms presented by (BVG Associates, 2022). This includes investment expenditures and operating and maintenance (O&M) costs. However, the LCOE calculations are adjusted accordingly to the techno-economic factors of each location. The cost structure is based on the base case scenario illustrated on the (BVG Associates, 2022) website. The costs are adjusted based on the (Bosch, Staffell, & Hawkes, 2019) report. The report measures changes in cost per MW, but this thesis has decided to break down costs into cost drivers and calculate further. The cost drivers and impact are shown in the appendix, but the adjustment is discussed below.

Firstly, the wind turbines are the same at each site, meaning that the turbine, nacelle, rotor, tower, other turbines, offshore substation, other balance plants, turbine installation and other installations will not differ between the locations. The critical cost drivers are mainly expenses that vary because of distance to the connection grid and shore and the total installation costs because of ocean depth. Additionally, the installation process will cost more further from shore.

Foundation and foundation installations

Offshore wind parks can be both floating- or bottom-fixed. The energy output is not a function of the turbine foundations, but the floating foundations are more expensive than the bottom fixed. We assume that all wind farms located at ocean depth below 70 m are bottom fixed and the rest are floating. With little or no research on today's foundation cost difference between floating and bottom fixed, it was hard to differentiate them. However, (Kausche, Adam, Dahlhaus, & Grossmann, 2018) found a difference in the initial investment between them. Moreover we assumed further that the floating foundation is two times more expensive than the bottom-fixed. The foundation installation also differs, meaning a deeper ocean will lead to higher installation costs. The foundation installation is set to £ 50 000 per meter (BVG Associates, 2022)

Cables and cable installation

Longer distances to the shore will require longer cables, leading to higher installation costs. The increased installation costs include cable material and working hours to build the infrastructure. From the baseline scenario, we found that the cable costs £42 500 per km. The variable cost is used to determine the price of cables for each location. The cable installation costs are found in the same way. By dividing the BVG scenario by the distance to shore, we found that each kilometre of cable installation costs £162 500.

Operating and maintenance

The operating and maintenance costs are variable costs that occur yearly until the decommission date. The variable expenses are dependent on uncontrolled variables such as weather. For example, we know that the northern region suffers from colder weather, damaging the wind turbines more. As a result, the northern region has an estimated £5000 higher operational costs. The maintenance costs are a combination of how each location differs from the baseline scenario regarding ocean depth and distance to grid connection. The maintenance costs change by £100 per difference in distance to the grid and ocean depth from the baseline scenario.

Table 6.6: Cost structure for each location. The costs in the first part of the table occurs at year 0, while maintenance and service occur year 1-24 and decommission occurs year 24. All numbers are in £1 000 000.

Cost structure	**SL[1]**	**SK[2]**	**WF[3]**	**WFI[4]**	**NSN1[5]**	**NV[6]**	**NR[7]**	**WT[8]**	**NEH[9]**	**SEV[10]**	**NT[11]**	**SN2[12]**	**UN[13]**
Turbine	15	15	15	15	15	15	15	15	15	15	15	15	15
Nacelle	6	6	6	6	6	6	6	6	6	6	6	6	6
Rotor	2.85	2. 85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85
Tower	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Other Turbine	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
Turbine foundation	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	4.2	8.4
Cables	0.425	1.743	1.913	3.825	0.850	1.445	8.5	1.658	1.488	1.19	0.425	3.4	0.935
Offshore substation	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Other balance plant	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Offshore cable installation	1.625	6.663	7.313	14.625	3.250	5.525	3.250	6.338	5.688	4.550	1.625	13.0	3.575
Foundations installation	3.8	19.05	12.5	13.15	4.75	4.4	3.75	7.15	8	13.1	13.95	3.45	14
Turbine installation	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Other installation	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18

Maintenance & service	0.76	0.784	0.771	0.767	0.758	0.755	0.756	0.760	0.763	0.773	0.777	0.749	0.776
Operations	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.38	0.38	0.38	0.38	0.38	0.38

Decommission	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95	4.95

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[1] South of Lindesnes
[2] South of Kristiansand
[3] West of Flekkefjord
[4] West of Fitjar
[5] North of Sørlige Nordsjø I
[6] North of Vega
[7] North of Rørvik
[8] West of Tromsø
[9] North-East of Honningsvåg
[10] South-East of Vadsø
[11] North of Tanafjorden
[12] Sørlige Nordsjø II
[13] Utsira Nord

The net energy generation is gathered from the NORA-WP dataset. The lifetime of the project is set to 24 years, the number of years we have data available. The calculation of WACC is very simplified, but an annual WACC between 5.5% and 6.5% is reasonable for offshore wind in the northern region of Europe (PWC, 2020). The NPV of costs, power production, and LCOE from each location are as follows:

Table 6.7: Calculation of total power production, NPV of power production from 1996 to 2019, and Leverage Cost of Energy (LCOE) for each location. The locations are ranked best to worst based on the LCOE.

WACC	**5.50%**

Location	Expected return (W)	NPV Power Prod (MWh)	NPV Costs (£)	LCOE (£/MWh)
South of Lindesnes	9 963 633	1 147 899	66 721’	58
North of Sørlige Nordsjø I	9 572 173	1 102 799	69 694’	63
Sørlige Nordsjø II	9 785 289	1 127 352	76 446’	68
West of Flekkefjord	9 710 952	1 118 788	82 740’	74
North-East of Honningsvåg	8 619 063	992 993	76 150’	77
North of Rørvik	7 746 896	892 511	68 667’	77
Utsira Nord	8 916 664	1 027 279	79 660’	78
North of Tanafjorden	8 628 533	994 084	77 165’	78
South of Kristiansand	9 327 500	1 074 611	88 647’	82
North of Vega	7 588 548	874 268	72 186’	83
South-East of Vadsø	8 228 320	947 976	79 959’	84
West of Tromsø	7 520 252	866 400	76 093’	88
West of Fitjar	8 744 177	1 007 407	92 573’	92

The “best” location in terms of LCOE is South of Lindesnes. This is due to the highest power production and low overall costs. However, the model may favour locations with higher power production because most costs are the same regardless of location. The interpretation of LCOE is that each MWh of energy produced at South of Lindesnes costs £58.

6.2 The value of diversification – a portfolio approach

From the individual assessment, we found that the South of Lindesnes was the single best location. The research question in this thesis seeks to find the locations that can maximise energy output while minimising variability. As touched upon in section 5.1.5, there is a correlation between locations regarding in the hourly power production. The different power production pattern between locations brings value to a portfolio approach, where one can obtain a vast power production and decrease the variability drastically by combining different locations. This section to explores the interaction between the locations and treats them as a combined portfolio.

In finance, a portfolio approach means to evaluate individual investments and add them to a portfolio that can deliver the same return or better for less or the same risk. The portfolio has its own power production and variance, calculated from each location's weighting, its power production and variance, and the correlation between them. This thesis attempts to combine several alternative locations for offshore wind farms to achieve different targets. In this case, the expected return will be monitored and analysed through power production. The volatility is measured through standard deviation with n-1 in the denominator. The following equations need to be calculated to analyse and solve the minimising and maximising problems of the portfolios.

Equation 6.3: Calculations of minimising problem

We minimise the variance of the portfolio:

$$\omega^T * \sum w$$

Subject to the specified expected return.

$$R^T \omega = \mu$$

Solved using the Lagrange multiplier

$$\begin{bmatrix} 2\sum & -R & -1 \\ R^T & 0 & 0 \\ 1^T & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \mu \\ 1 \end{bmatrix}$$

Where:

$\omega\ is\ a\ vector\ of\ portoflio\ weights\ \sum_i \omega_i = 1$

$R\ is\ a\ vector\ of\ expected\ returns$

The calculations are solved with the use of solver add-in package in excel.

We will also utilize the Sharpe ratio to understand the reward-risk relation better. The Sharpe ratio is a measure that calculates the risk-adjusted returns for an asset or portfolio (Sharpe, 1994). The Sharpe ratio measures the performance based on a *reward-to-variability* and is proposed with the following calculation:

Equation 6.4: Sharpe Ratio.

$$Sharpe\ ratio = \frac{E(R_p)}{\sigma_p}$$

6.2.1 Modern Portfolio Theory - Minimum variance portfolio

Modern portfolio theory refers to the idea that investors can assemble a portfolio that maximises expected return for a given level of risk. Minimum variance portfolio (MVP) by Markowitz is a widely used approach for selecting assets in a portfolio to create lower risk (Markowitz, 1952). By combining two or more assets, the investor can create a different risk-return profile depending on the allocation of the product. The minimum variance portfolio is located on the far left of the efficient frontier and is the allocation that accounts for the least amount of risk. The minimum variance portfolio consists of every location, and the correlation between the locations reduces the volatility over time. Table 6.8 and Table 6.9 present the MVP portfolio with only the alternative locations and all the observed locations.

Table 6.8: Weights and calculations for the minimum variance portfolio (MVP) using the only alternative locations.

Location	**Weight**
South of Lindesnes	7%
South of Kristiansand	12%
West of Flekkefjord	6%
West of Fitjar	8%
North of Sørlige Nordsjø I	7%
North of Vega	6%
North of Rørvik	9%
West of Tromsø	15%
North-East of Honningsvåg	6%
South-East of Vadsø	10%
North of Tanafjorden	13%
Sum weights	**100%**

Expected Return (W)	6 073 333.69
Variance	9 949 433 992 438.69
Standard deviation (W)	3 154 272.34

Sharpe Ratio	**1.925**

Table 6.9: Weights and calculations for the minimum variance portfolio (MVP).

Location	Weight
South of Lindesnes	5%
South of Kristiansand	12%
West of Flekkefjord	4%
West of Fitjar	8%
North of Sørlige Nordsjø I	5%
North of Vega	6%
North of Rørvik	9%
West of Tromsø	15%
North-East of Honningsvåg	6%
South-East of Vadsø	10%
North of Tanafjorden	13%
Sørlige Nordsjø II	6%
Utsira Nord	0%
Sum weights	**100%**

Expected Return (W)	8 608 505.54
Variance	9 895 258 653 662.10
Standard deviation (W)	3 145 673.00

Sharpe Ratio	**2.737**

The lowest possible risk and most steady power production portfolio have a standard deviation of 3 154 272.34 and 3 145 673 W, respectively. The weighting in the MVP portfolios is 6-13% for the alternative locations only and 0-15% for all locations.

6.2.2 Mean-variance portfolio – Markowitz

The mean-variance portfolio analysis allows investors to find the least amount of risk for a given return or the highest reward for a given level of risk. The mean-variance portfolio with a given target for expected return is calculated the same way as the mean-variance portfolio above, but it has a target. The model tries to find the least risky portfolio for the given return.

The targets for the calculations are the mean expected return of all locations and the portfolio's expected return consisting of SN2 and UN (SN2 & UN). The average expected return for all locations is 8 796 308 W. The expected return of SN2 & UN is based on weighting, calculated from each location's area. The target portfolio has the following weighting and calculations:

Table 6.10: Weights and calculations for the SN2 & UN Portfolio.

Sørlige Nordsjø II	72%
Utsira Nord	28%
Sum	**100%**

Expected return (W)	9 541 65.11
Variance	28 773 189 294 920.90
Standard deviation (W)	5 364 064.62

Sharpe Ratio	**1.78**

The calculations for the mean-variance portfolio given the different targets are as follows:

Table 6.11: Weights and calculations for Target mean-variance portfolio given the average expected return of 8 759 083 W.

Location	**Weights**
South of Lindesnes	9%
South of Kristiansand	12%
West of Flekkefjord	5%
West of Fitjar	6%
North of Sørlige Nordsjø I	7%
North of Vega	4%
North of Rørvik	7%
West of Tromsø	12%
North-East of Honningsvåg	7%
South-East of Vadsø	9%
North of Tanafjorden	14%
Sørlige Nordsjø II	8%
Utsira Nord	0%
Sum weights	**100.0%**

Expected Return (W)	8 759 083.04
Variance	10 069 104 671 800.50
Standard deviation (W)	3 173 185.26

Sharpe Ratio	**2.76**

Table 6.12: Weights and calculations for Target mean-variance portfolio given the expected return of the SN2 & UN portfolio.

Location	Weights
South of Lindesnes	44%
South of Kristiansand	3%
West of Flekkefjord	10%
West of Fitjar	0%
North of Sørlige Nordsjø I	21%
North of Vega	0%
North of Rørvik	0%
West of Tromsø	0%
North-East of Honningsvåg	10%
South-East of Vadsø	0%
North of Tanafjorden	12%
Sørlige Nordsjø II	0%
Utsira Nord	0%
Sum weights	**100%**

Expected Return (W)	9 541 659.16
Variance	17 331 526 766 936.50
Standard deviation (W)	4 163 115.03

Sharpe Ratio	**2.29**

Table 6.11 and Table 6.12 show that a portfolio approach gives lower variance and the same power production, i.e., a higher Sharpe ratio than the average location and SN2 & UN portfolio. For example, the average standard deviation for all locations is just above 6 million W, while the portfolio has a standard deviation of 3 173 185 W.

6.2.3 Max Sharpe ratio

Moving on from minimising the variability in wind power production, the reward-to-variability ratio, namely Sharpe Ratio, will be calculated and interpreted in the following section. In addition to calculating the Sharpe ratio, we want to maximise the Sharpe ratio by using the solver function in excel. Table 6.13 and Table 6.14 show the weighting of each wind farm when solving the maximising problem for the Sharpe ratio.

Table 6.13: Weights and calculations for the maximum Sharpe ratio portfolio.

Location	**Weights**
South of Lindesnes	9%
South of Kristiansand	12%
West of Flekkefjord	5%
West of Fitjar	6%
North of Sørlige Nordsjø I	7%
North of Vega	4%
North of Rørvik	7%
West of Tromsø	12%
North-East of Honningsvåg	7%
South-East of Vadsø	9%
North of Tanafjorden	14%
Sørlige Nordsjø II	7%
Utsira Nord	0%
Sum weights	**100%**

Expected Return (W)	8 759 083.04
Variance	10 069 104 671 800.50
Standard deviation (W)	3 173 185.26

Sharpe Ratio	**2.76**

Table 6.14: Weights and calculations for the maximum Sharpe ratio portfolio given 9 000 000 W target.

Location	Weights
South of Lindesnes	14%
South of Kristiansand	11%
West of Flekkefjord	7%
West of Fitjar	4%
North of Sørlige Nordsjø I	10%
North of Vega	2%
North of Rørvik	5%
West of Tromsø	8%
North-East of Honningsvåg	10%
South-East of Vadsø	6%
North of Tanafjorden	14%
Sørlige Nordsjø II	9%
Utsira Nord	0%
Sum weights	**100%**

Expected Return (W)	9 000 000.00
Variance	11 063 830 180 327.00
Standard deviation (W)	3 326 233.63

Sharpe Ratio	**2.71**

The highest Sharpe ratio for a single location was 1.69, while the optimal portfolio obtained a ratio of 2.76. The optimal Sharpe Ratio-portfolio contributes an increase of 2.76 watts for an increase in one unit of risk. When having a target expected return of 9 million watts, the Sharpe ratio was 2.71. Figure 6.1 shows the efficient frontier together with all the calculations. By organising the locations as portfolios, the investor will benefit from a decrease in risk and get the same power production as before.

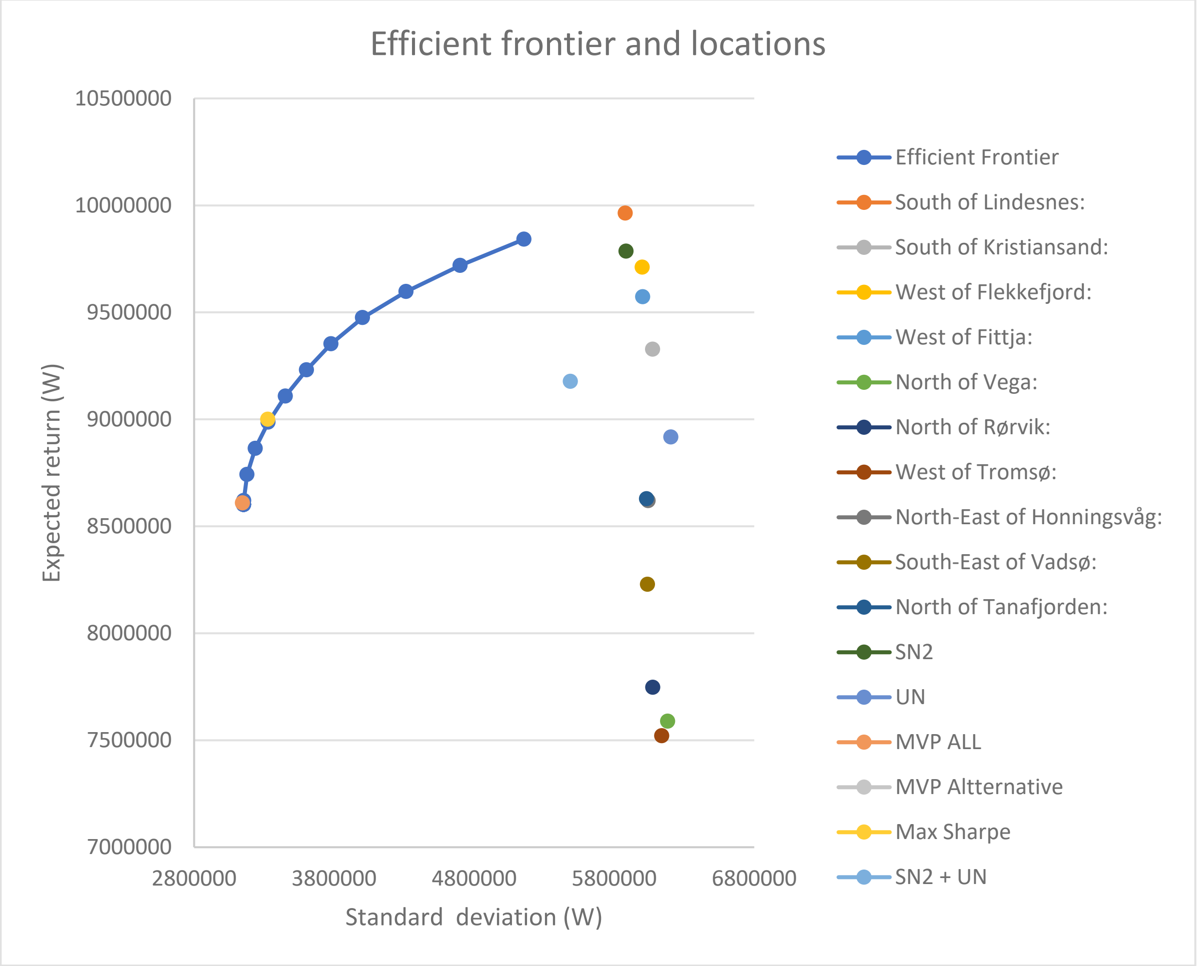

Figure 6.1: Visualization of the efficient frontier, all the calculated portfolios and the single locations.

6.3 Real life scenario

So far, the value of wind farms has only been illustrated using the returns and variances of one IEA 15 MW reference turbine and possible weights in different scenarios. This section seeks to show the real-life application of value from offshore wind farms along the Norwegian shore. The real-life scenario is built on the government's plan to install 30 GW offshore wind within 2040. The installation goal equals approximately 1500 20 MW or 2000 15 MW wind turbines (Teknisk Ukeblad, 2022) (Hovland, 2022). The total energy output of 30 GW is the same as 120 TWh, assuming the baseline scenario of 4 000 operating hours. To reach the government's target, we have shown alternative solutions using some of the portfolios calculated previously in the chapter. The weights illustrate the portion of wind turbines at each location. Since expected return accounts for hours with zero production, the yearly power production is found by multiplying the hourly expected return by 8 760 (number of hours in a year). The results are as follows.

Table 6.15: Overview of hourly and yearly power production using one and 2000 wind turbines, and the number of wind turbines needed to reach 120 TWh. The weights are gathered from the MVP-portfolio, Sharpe-portfolio and MVP-portfolio without SN2+UN with SN2+UN as a target.

	MVP	**Max Sharpe-Portfolio**	**Mean-Variance, Target SN2 + UN**
Location	**Weights**	**Weights**	**Weights**
South of Lindesnes	5.0%	8.7%	44.0%
South of Kristiansand	12.0%	12.0%	3.0%
West of Flekkefjord	4.0%	5.3%	10.0%
West of Fitjar	8.0%	6.5%	0.0%
North of Sørlige Nordsjø I	5.0%	6.7%	21.0%
North of Vega	6.0%	4.4%	0.0%
North of Rørvik	9.0%	7.3%	0.0%
West of Tromsø	15.0%	12.4%	0.0%
North-East of Honningsvåg	6.0%	7.2%	10.0%
South-East of Vadsø	10.0%	8.5%	0.0%
North of Tanafjorden	13.0%	13.6%	12.0%
Sørlige Nordsjø II	6.0%	7.4%	0.0%
Utsira Nord	0.0%	0.0%	0.0%
Sum weights	100.0%	100.0%	100.0%

Expected Return (W)	8 608 505.54	8 759 083.04	9 541 659.16
Standard Deviation (W)	3 145 673.00	3 173 185.26	4 163 115.03
Sharpe Ratio	2.737	2.76	2.29

Single Wind Turbine per Year			
Expected Return GW	75.41	76.73	83.58
Expected Return TW	0.08	0.08	0.08

2000 Wind Turbine per year			
Expected Return GW	150 821	153 459	167 169
Expected Return TW	150.82	153.46	167.17

Wind Turbines to produce 120 TWh	1 591	1 564	1 436

7. What do the results tell us?

In chapter 6, we presented the findings of our quantitative analysis. In this chapter, we will interpret these numbers' meanings and highlight some potential usage fields. This chapter will assess the analysis conducted in this thesis and enlighten issues and limitations common to all the analyses.

7.1 Individual results

The maximum power production is the simplest of all the analyses we performed. We ran a mean and a sum function for all 13 locations and gathered the data in Table 6.1. All the locations in the southern region outperform the sites in the northern and middle regions, which is something we also anticipated from the qualitative analysis. All the other locations are less than 25% worse than the best location, South of Lindesnes. Because the South of Lindesnes is exceptionally good, this also substantiates that the Norwegian offshore wind conditions are overall good. South of Lindesnes has a Sharpe ratio of 1.69, which we will compare with our portfolios.

The calculations in Table 6.1 could be used in a perfect scenario as guidance when assessing offshore wind farm placement. However, it has obvious flaws and lacks. First and foremost, the method ignores variability. Zero incorporation of variance in the power production means that the locations could produce only every other day, week, or month. Ignoring the variability in power production is unfavourable, as we require a constant supply of energy, and we need to consider the time value of energy. It is also difficult to store huge amount of wind power for long periods. Another limitation with choosing a location solely based on maximum power production is the ignoration of power transportation. For example, if we only place wind farms in the southern region, it would be merely impossible to transport the power produced up to the middle and northern parts of Norway.

The calculations done for the FCF and LCOE parts are also not directly applicable to the real world, mainly due to oversimplifying the cost structure. That said, the power production and revenues are based on historical data and could be a good indicator of future energy production. However, the costs stated in Table 6.5 do not represent the actual investment due to several assumptions and limitations. Firstly, the project lifetime is set to 24 years and is not an absolute lifespan for a wind farm. Secondly, each location's financial structure should have been a more comprehensive individual assessment based on the critical cost drivers listed in section 3.4. One of the main concerns when calculating NPV is the need for a pre-defined rate of return. The estimates for interest rates are solely based on theory, which could differ in the real world. If the FCF is discounted at a lower rate, the investment will show false profitability, and the decision-making could be wrong. The cost estimates of FCF are also subject to uncertainty. However, the marginal impact on the total NPV is relatively tiny compared to the rate of return. Another problem is that the LCOE ignores the risk of the project when projecting future power production. This thesis will calculate historical LCOE and, therefore, not be subject to unexpected risks. Lastly, the estimates for interest rates are solely based on theory, which could differ in the real world.

Contrary to the maximum power production, the FCF analysis considers the time value of energy and money. The FCF is a part of the LCOE calculations where the costs and power production are discounted back to year 0. As mentioned, the calculations of the LCOE are quite simplified. The LCOE is also relatively high compared to the market data, which shows an average LCOE of USD 0.033/kWh (IRENA, 2022). The difference between the South of Lindesnes and the average market is approximately 50% (given 1.22 USD = 1 Sterling Pound). This significant difference is mainly because the calculations only account for the costs of one wind turbine at each place and do not elaborate on the actual financial decision that should be made. A "normal" wind farm will consist of several wind turbines at each location, and the marginal cost will decrease because of shared cables, substations, and parts of the maintenance costs. Lastly, the cost estimation of each wind farm does not account for the additional investment that needs to be done in the transmission grid.

7.2 Portfolio results

The portfolio approach created combinations of alternative locations to satisfy different criteria. As mentioned earlier, a portfolio approach brings value to the table where one can maintain a vast power production while reducing variability. In this case, a portfolio would also increase the power availability, as the wind farms are located throughout the whole coast of Norway.

We created two minimum variance portfolios (MVP), one allowing Sørlige Nordsjø II and Utsira Nord, and one without them. Because this portfolio aims to minimise the variance, we see that almost all the locations are included with relatively small weights. As a result, we obtain a lower variance due to the correlation between locations. The standard deviation for the full MVP is 3 145 673 W, which is approximately 2 700 000 W lower than the lowest standard deviation obtained from a single location. We also see that the full MVP includes Sørlige Nordsjø II, which increases the Sharpe ratio from 1.925 to 2.737. Utsira Nord is not a part of the full MVP portfolio because it has a relatively high standard deviation compared to the highly correlated places in the southern region.

Further, we created mean-variance portfolios to illustrate risk against reward. We started by creating a portfolio consisting of only Sørlige Nordsjø II and Utsira Nord with weights representing their size. The portfolio obtained an expected return of 9 541 659 W and a Sharpe ratio of 1.78. The SN2 & UN portfolio acted as a benchmark for the following portfolios. Firstly, we created a portfolio with a target equal to the average return of all the locations, which is 8 759 083 W. The portfolio was made up of 12 out of the 13 locations, but again we see that Utsira Nord is excluded. This portfolio had a Sharpe ratio of 2.76. Lastly, we created a portfolio with all locations except Sørlige Nordsjø II and Utsira Nord, which required to match the latter´s return. This portfolio only utilized six of the eleven available locations, with 44% on the South of Lindesnes. The Sharpe ratio comes out at 2.29, which is 0.51 higher than the portfolio with only Sørlige Nordsjø II and Utsira Nord. By combining six locations in the southern and northern regions, Norway can reduce the total power variability by 22.4% compared to the already approved locations. The key takeaway from the mean-variance portfolios is that weight distribution lowers the risk substantially. We also see the trend that the higher the required return, the more risk comes along, resulting in a decrease in the Sharpe ratio. This will also be highlighted in the discussion around the efficient frontier.

Lastly, we created two portfolios intending to maximise the Sharpe ratio. The first portfolio had zero restrictions and ended with a Sharpe ratio of 2.76 with an expected production of 8 759 083 W. We also created a portfolio with a minimum 9 000 000 W target. The weights for the locations are slightly altered, but the biggest difference is the decrease in the Sharpe ratio from 2.76 to 2.71 due to the increased standard deviation. Again, we see that Utsira Nord is excluded from the portfolios.

We have also created Figure 6.1 to illustrate the efficient frontier. We see that the maximum power production is only available if the investor invests 100% of its funds in the South of Lindesnes wind farm. It is also worth mentioning that the investor also benefits from the SN2 + UN portfolio in terms of risk reduction. The portfolios illustrated in this chapter are not perfect, but it stresses the importance of including a diversification parameter when deciding offshore wind farm locations.

Despite visualising a steady energy source combination, the portfolio approach could be more realistic. For example, the model has no restrictions in terms of the sizes of wind farms. The lack of size constraint enables the creation of the “perfect” portfolio with the least subject to risks. A more realistic approach could be to have at least 10% or 20% weighting in each placement.

In addition to applying Markowitz´s theories, the analysis seeks to maximise the Sharpe ratio. As mentioned earlier, the Sharpe ratio is primarily applicable to financial securities but works as a measure for other assets as well. The main concern using the Sharpe ratio is the lack of risk-free return from offshore wind. Therefore, the calculation ignores the risk-free rate and only visualises the return divided by the risk.

It is essential to point to the assumptions behind the model and its limitations. The assumptions behind the portfolio theory are already touched upon in section 6.2, but the results and impact will be discussed more in the following section. The creator of modern portfolio theory, Markowitz, lists several assumptions and how to interpret the results correctly. The first assumption to be discussed is that the data should be normally distributed. The power production data is not normally distributed because of the cut-in and cut-out of power production, and the non-linear relationship between speed and wind power. Secondly, the model assumes that the correlation between wind farms is constant over time. The analysis is based on historical data, but future diversification is not the same as historical. Thirdly, the investor needs to be rational, meaning they avoid unnecessary risks, want to maximise returns, share the same information, and process it like others.

7.3 Real-life Scenario

Finally, we move on to the part of the thesis where we apply our findings to the real world. Until now, we have only compared the locations with a single fictive wind turbine, which is a highly unrealistic. There are many reasons for not building single wind turbines, but most importantly, the project holder reduces the marginal cost by placing more wind turbines at each location. The project holder also benefits from wind farms close to each other, which can benefit from the already built infrastructure.

The Norwegian government’s ambition is to install 30 GW within 2040. To reach this target, they need to open more areas for offshore wind activity. Only two areas are open today, and the full-scale activity from Sørlige Nordsjø II and Utsira Nord amounts to 4.5 GW. If the goal was to place 2 000 wind turbines along the coast and without an energy target, the wind turbines should be placed based on the government's risk aversion. However, the target is 30 GW (120 TWh per year), and we must therefore utilize locations with vast power production. Table 6.15 provides an overview of how the portfolios discussed in section 7.2 can satisfy the yearly target of 120 TWh. A key finding is that the portfolios can reach the target energy output with less than the budgeted 2 000 wind turbines, as they only need between 1 436 and 1 591 wind turbines to produce 120 TWh per year.

As we have already touched upon the returns and variances for the portfolios, we will now only focus on the weight distributions. The weights illustrate the portion of wind turbines that should be placed at each location. Investigating other alternatives with fever locations could also be interesting, as installing infrastructure and maintaining 11 locations is ineffective and costly. However, we will leave that for later research. With the use of the presented portfolios, the MVP will have as many as 240 wind turbines in the location West of Tromsø, the max Sharpe portfolio will have just over 210 wind turbines North of Tanafjorden, and the mean-variance target portfolio has 44% weight in the South of Lindesnes, resulting in 630 wind turbines there. One will have to look at whether this sounds realistic or not. From Hywind

Scotland, we know that they have five 6 MW turbines placed on four square kilometres, meaning each wind turbine uses 0.8 km^2. The IEA turbine we used for our calculations has a rotor diameter 55% longer than Hywind Scotland's (Equinor, 2022) (IEA, 2022). Assuming this would increase the area demand by 55%, we find that the IEA turbines need 1.24 km^2 each. According to Bergen Offshore Wind Centre (BOW), one can place wind turbines in a quadratic shape with seven times their diameter. This approach implies that each turbine would need 2.82 km^2 each (Universitetet i Bergen, 2020).

Even though we believe BOW's approach would be more realistic due to the small size of Hywind Scotland, it is hard for us to decide which of the approaches is more appropriate. We, therefore, proceed with calculating a range of sizes the areas need instead of a singular size. For the mean-variance – portfolio, one would need between 800-1 800 km2 South of Lindesnes. For MVP, the largest area will occupy 300-676 km^2 West of Tromsø, while the max Sharpe portfolio would occupy 260-590 km^2 North of Tanafjorden. Whether this is realistic or not is hard to say. For reference, the size of Oslo is 454 km^2 (Wikipedia, 2021), and the size of the approved Sørlige Nordsjø II is 2 591 km^2 (NVE, 2013). Hywind Scotland only has five wind turbines, and the project was a massive operation. Hywind´s size of scale implies that having wind farms with the number of turbines we have just discussed might be unrealistic due to the scale of the operations. However, the results are precise; the selected locations can solve the proposed offshore wind opportunity and reduce the total costs given a smaller number of wind turbines and cost-saving locations.

7.4 Limitations

The thesis has dozens of limitations, challenges, and assumptions. Due to the limited time, and lack of resources, we have had to simplify the real-world situation and delineate our goals. Therefore, even though we have already mentioned some of the challenges and limitations earlier, we have created paragraph 7.4 to provide a more structured overview of said limitations and simplifications.

The first and most apparent limitation is that all the analyses made in our thesis are based on historical data. We cannot know with certainty that the future wind conditions will be the same as from 1996-2019. Therefore, if our insights will be used for future decisions, one must assume that the future wind conditions will be somewhat equal to the historical ones and that the recorded data is suited to make decisions for the future. As already mentioned, the portfolios created are unrealistic because we have not examined if there is room for X numbers of offshore wind turbines nearby. That assumption is discussed later. However, the sizes of the wind farms are expected to exceed today's largest wind farm. The locations are not meant to conclude where to place the offshore wind turbines. Still, if the plan is to install 30 GW of offshore wind energy, the alternative location combined can do so and, at the same time, fit the project holders' preferences in terms of risk and return. The portfolio approach should also be used to plan the building of the infrastructure regarding the future 30 GW installed wind power. The government should consider the correlation between location and build a shared infrastructure in the southern, middle, and northern regions to facilitate the portfolio reaching the 30 GW energy output target.

Wake effects

As wind turbines extract energy from the wind to generate electricity, the wind that passes the turbines is severely disturbed, lowering the amount of available energy in the wind. The change in the wind also contributes to an increase in turbulence and a decrease in wind speeds. The wake effects mainly depend on two factors. Firstly, the wake effects will be greater the more interaction there is between the turbine and the wind. This typically occurs shortly before the turbines begin feathering (or pitching out) their blades and operating at maximum thrust. The wake effect is less noticeable as turbines reach their nominal power. Secondly, the turbine's up-wind atmospheric conditions will affect them. For example, suppose the wind flow is already turbulent due to complex terrain. In this case, the wake effect will be less significant. In our case, we are dealing with stable conditions, due to no terrain, and the wake effects will therefore be more significant (Sereema, 2021). In this thesis, we have not accounted for any wake effects within the wind farms or the impact they may induce on each other.

Temperature and extreme weather

The air temperature will influence the air density, which will affect the power density and production. According to UiB, the power from a wind turbine will increase by almost 16% as the temperature drops from +20° C to -20° C for any given wind speed. Colder air is denser and increases the power output (Universitetet i Bergen, 2022). A variable in NORA3-WP called "Wind power generation, density correction" accounts for this effect, but it only provides monthly data, not hourly. Therefore, we have chosen to ignore this effect when performing our analyses. We have also not accounted for the full effect of the extreme weather that might damage parts of the turbines, such as storms or extreme cold events. The northern parts of Norway are more exposed to extreme temperatures, the coldest being Karasjok, experiencing -51.4° C (Lippestad, 2009).

Fishing

Another thing to consider when placing the wind farms is their interaction with the fishing industry. According to SINTEF, the fishing industry in Norway contributes to 4% of the Norwegian GDP (SINTEF, 2018). Placing wind farms in areas with much commercial fishing could be sub-optimal and bring economic consequences to the fishermen. An offshore wind farm could increase travelling distances and make fishing locations unavailable. Additionally, one could accidentally damage ships, fishing gear, and also the cables for the turbines if these interfere. Even though this should be considered, we have not mapped out the popular fishing routes in Norway and have not considered this when choosing our location.

Wildlife

The coastal wildlife, with birds and fish being the primary considerations, is also something one should consider when placing wind farms. Birds might be disturbed in their nesting and breeding, as well as in their annual long-distance migrations. In addition, they might also collide with the turbines causing casualties (Piggott, 2021). It has also been speculated that the vibration and noise from wind farms can disturb fish spawning and alter their behaviours. However, this was disproved by research done in Rhode Island over seven years, showing signs of the turbines increasing the biodiversity in the areas (Wilber, May 2022). If this would be the case in Norway is impossible to say. Nevertheless, this thesis has not considered the effects on wildlife the placement of wind farms in these locations could have.

Others

Other things one might consider when building the wind farms could be shipping routes (especially South of Lindesnes and Kristiansand), tourism routes along the western and northern parts (Hurtigruten, etc.) and military activities. We have also not considered legally inaccessible areas, such as nature reserves.

8. Conclusion and reccomendations

As the global energy demand is rapidly increasing, and we are facing the difficult task of increasing energy production while decreasing our emissions - Norwegian offshore wind power production might be a small part of the solution. So let us start the conclusion by circling back on the initial research question:

By having an investor perspective and using financial models, what locations for offshore wind farms will be most beneficial for Norway AS in terms of stabilising and maximising energy output?

To answer the research question, we have performed analyses with 13 different offshore wind farm locations. These locations were selected based on wind power potential, cost-reducing site conditions and their intercorrelation. The data used is sampled from the new high-resolution wind resource and wind power dataset NORA3-WP. The thesis contains an individual assessment of the 13 locations and several analyses of portfolios with different weighting. We also have a part relevant to the real-world situation where the Norwegian government aims to open areas to host 30 GW of installed wind power before 2040, showcasing different alternatives that could satisfy this goal.

The interpretation from the results shows that "South of Lindesnes" is the stand-alone best in terms of maximum power production and the best Sharpe ratio. The portfolio evaluation showed that a combination of all the locations except for Utsira Nord was a part of the minimum variance- and maximum Sharpe ratio–portfolio. A combination of locations across the Norwegian coast created value in terms of variability to return ratio suited for every risk aversion. With the IEA-15-240-RWT, we can reach the goal of 120 TWh with a range of 1 436-1 591 wind turbines distributed in 6-12 of the chosen locations. The three illustrated scenarios satisfy the TWh criteria with differences in expected power production and standard deviations. The trend is that the more locations, the lower the standard deviation due to spatial wind dependency and correlations between the locations.

Further research should include thorough cost evaluations for each location, providing a more realistic scenario of LCOE. A combination of a well-established LCOE model and a portfolio approach could shed more light on the value of diversification of offshore wind along the

Norwegian coast. With more time on hand, analyses like the ones we performed in this thesis should also be applied to more locations than just the ones we selected for this thesis. One should also account for the limitations listed in the thesis, especially the ones related to wind farm size and wake effects, as these will affect the total production. We suggest a more detailed investigation into how much area one will need per wind turbine and for each farm.

We encourage further research in the field, and based on our findings in this thesis; offshore wind farms could and should be placed in Norwegian coastal areas.

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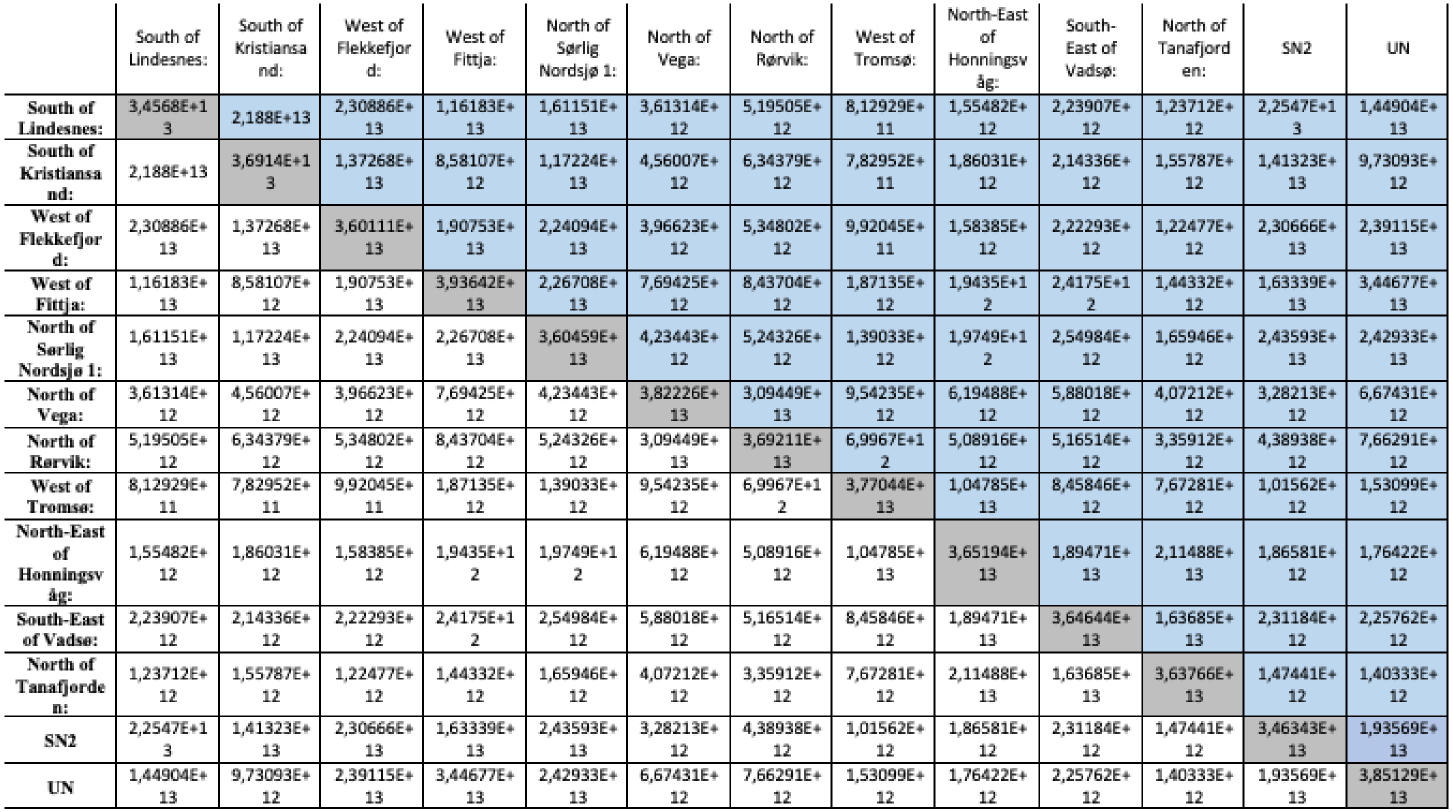
10. Appendix

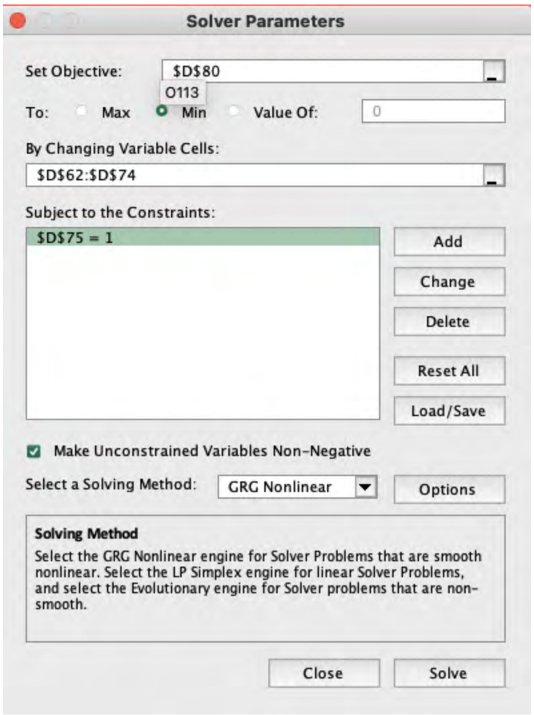
10.1 Covariance table



	South of Lindesnes:	South of Kristiansand:	West of Flekkefjord:	West of Fittja:	North of Sørlig Nordsjø 1:	North of Vega:	North of Rørvik:	West of Tromsø:	North-East of Honningsvåg:	South-East of Vadsø:	North of Tanafjorden:	SN2	UN
South of Lindesnes:	3,4568E+13	2,188E+13	2,30886E+13	1,16183E+13	1,61151E+13	3,61314E+12	5,19505E+12	8,12929E+11	1,55482E+12	2,23907E+12	1,23712E+12	2,2547E+13	1,44904E+13
South of Kristiansand:	2,188E+13	3,6914E+13	1,37268E+13	8,58107E+12	1,17224E+13	4,56007E+12	6,34379E+12	7,82952E+11	1,86031E+12	2,14336E+12	1,55787E+12	1,41323E+13	9,73093E+12
West of Flekkefjord:	2,30886E+13	1,37268E+13	3,60111E+13	1,90753E+13	2,24094E+13	3,96623E+12	5,34802E+12	9,92045E+11	1,58385E+12	2,22293E+12	1,22477E+12	2,30666E+13	2,39115E+13
West of Fittja:	1,16183E+13	8,58107E+12	1,90753E+13	3,93642E+13	2,26708E+13	7,69425E+12	8,43704E+12	1,87135E+12	1,9435E+12	2,4175E+12	1,44332E+12	1,63339E+13	3,44677E+13
North of Sørlig Nordsjø 1:	1,61151E+13	1,17224E+13	2,24094E+13	2,26708E+13	3,60459E+13	4,23443E+12	5,24326E+12	1,39033E+12	1,9749E+12	2,54984E+12	1,65946E+12	2,43593E+13	2,42933E+13
North of Vega:	3,61314E+12	4,56007E+12	3,96623E+12	7,69425E+12	4,23443E+12	3,82226E+13	3,09449E+13	9,54235E+12	6,19488E+12	5,88018E+12	4,07212E+12	3,28213E+12	6,67431E+12
North of Rørvik:	5,19505E+12	6,34379E+12	5,34802E+12	8,43704E+12	5,24326E+12	3,09449E+13	3,69211E+13	6,9967E+12	5,08916E+12	5,16514E+12	3,35912E+12	4,38938E+12	7,66291E+12
West of Tromsø:	8,12929E+11	7,82952E+11	9,92045E+11	1,87135E+12	1,39033E+12	9,54235E+12	6,9967E+12	3,77044E+13	1,04785E+13	8,45846E+12	7,67281E+12	1,01562E+12	1,53099E+12
North-East of Honningsvåg:	1,55482E+12	1,86031E+12	1,58385E+12	1,9435E+12	1,9749E+12	6,19488E+12	5,08916E+12	1,04785E+13	3,65194E+13	1,89471E+13	2,11488E+13	1,86581E+12	1,76422E+12
South-East of Vadsø:	2,23907E+12	2,14336E+12	2,22293E+12	2,4175E+12	2,54984E+12	5,88018E+12	5,16514E+12	8,45846E+12	1,89471E+13	3,64644E+13	1,63685E+13	2,31184E+12	2,25762E+12
North of Tanafjorden:	1,23712E+12	1,55787E+12	1,22477E+12	1,44332E+12	1,65946E+12	4,07212E+12	3,35912E+12	7,67281E+12	2,11488E+13	1,63685E+13	3,63766E+13	1,47441E+12	1,40333E+12
SN2	2,2547E+13	1,41323E+13	2,30666E+13	1,63339E+13	2,43593E+13	3,28213E+12	4,38938E+12	1,01562E+12	1,86581E+12	2,31184E+12	1,47441E+12	3,46343E+13	1,93569E+13
UN	1,44904E+13	9,73093E+12	2,39115E+13	3,44677E+13	2,42933E+13	6,67431E+12	7,66291E+12	1,53099E+12	1,76422E+12	2,25762E+12	1,40333E+12	1,93569E+13	3,85129E+13

10.2 Solver functions

MVP portfolio:



Set Objective: $D$80

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells:
$D$62:$D$74

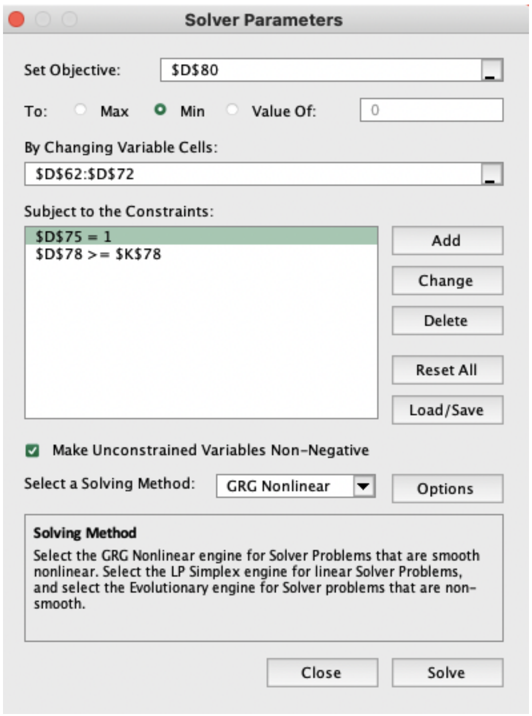
Subject to the Constraints:
$D$75 = 1

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method
Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

MVP Target:



Set Objective: $D$80

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells:
$D$62:$D$72

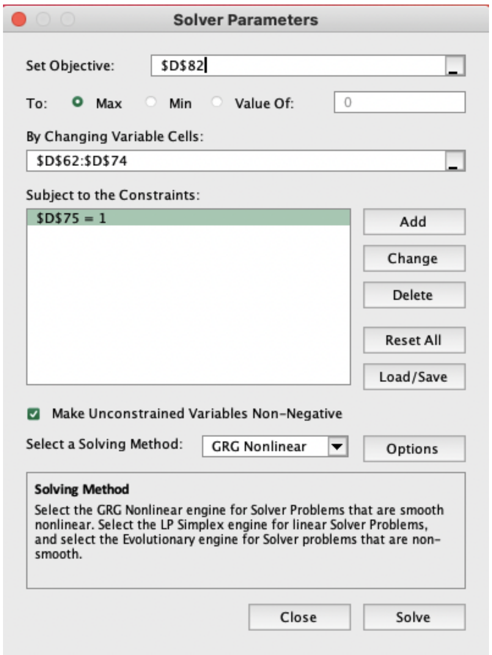
Subject to the Constraints:
$D$75 = 1
$D$78 >= $K$78

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method
Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Sharpe ratio max:



Set Objective: $D$82

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells:
$D$62:$D$74

Subject to the Constraints:
$D$75 = 1

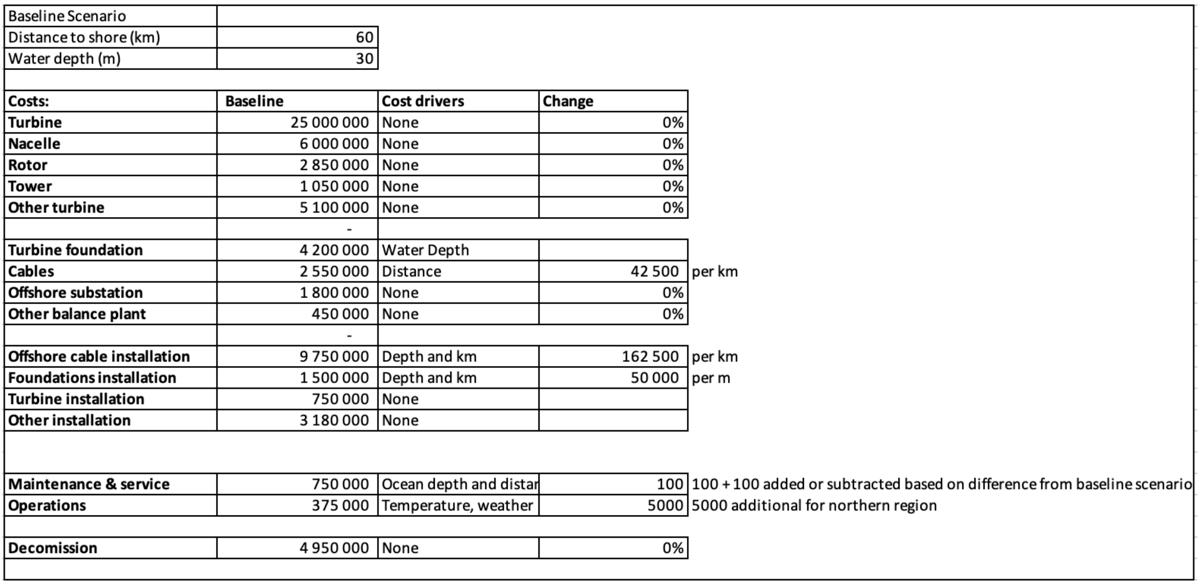
☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method
Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

10.3 LCOE Calculations

Cost drivers and calculations



Baseline Scenario				
Distance to shore (km)	60			
Water depth (m)	30			
Costs:	**Baseline**	**Cost drivers**	**Change**	
Turbine	25 000 000	None	0%	
Nacelle	6 000 000	None	0%	
Rotor	2 850 000	None	0%	
Tower	1 050 000	None	0%	
Other turbine	5 100 000	None	0%	
	-			
Turbine foundation	4 200 000	Water Depth		
Cables	2 550 000	Distance	42 500	per km
Offshore substation	1 800 000	None	0%	
Other balance plant	450 000	None	0%	
	-			
Offshore cable installation	9 750 000	Depth and km	162 500	per km
Foundations installation	1 500 000	Depth and km	50 000	per m
Turbine installation	750 000	None		
Other installation	3 180 000	None		
Maintenance & service	750 000	Ocean depth and distar	100	100 + 100 added or subtracted based on difference from baseline scenario
Operations	375 000	Temperature, weather	5000	5000 additional for northern region
Decomission	4 950 000	None	0%	