Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Department of Economics

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Viability Analysis of Proposed Industrial Wind Park Projects

Cost benefit analysis of two proposed industrial wind parks situated at Kårstø and Sjursøya

Master's thesis in Economics
Supervisor: Lars Erik Borge
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Abstract

The implementation of wind projects in industrial areas offers a promising solution for renewable energy development, as it allows for the conservation of "untouched" nature that would otherwise be impacted by traditional wind parks. This thesis compares the potential for wind energy development in two different industrial areas with varying wind speeds. The two potential sites were chosen based on previous proposals by Norwegian politicians and our own internal analysis of the sites. The aim of this thesis is to perform a cost/benefit analysis of the two sites using 2019 wind data, and to identify the factors that make a potential site viable for wind energy development such as wind speeds, location, and vicinity to residential areas. The results indicate that even sites with low wind speeds can be profitable, but that factors such as noise pollution and distance to the electrical grid must also be considered. This study demonstrates the feasibility of wind energy development in industrial areas and highlights the importance of considering a range of factors beyond wind speed when evaluating potential sites for wind projects.

Abstrakt

Ideen om å utvikle vindprosjekter i industriområder tilbyr en lovende løsning for utvikling av fornybar energi, da det åpner for bevaring av "urørt" natur som ellers ville blitt påvirket av tradisjonelle vindparker. Denne oppgaven sammenligner potensialet for vindenergiutvikling i to ulike industriområder med varierende vindhastighet. De to potensielle områdene ble valgt på bakgrunn av tidligere forslag fra norske politikere og våre egne vurderinger av områdene. Målet med denne oppgaven er å utføre en kostnads-/nytteanalyse av de to lokalitetene ved å bruke 2019 vinddata, og å identifisere faktorene som gjør et potensielt område passende for vindenergiutvikling. Herunder vindhastighet, beliggenhet, nærhet til bebyggelse. Resultatene tyder på at også lokaliteter med lave vindhastigheter kan være lønnsomme, men at faktorer som støy og avstand til el-nettet også må vurderes. Denne studien demonstrerer gjennomførbarheten av vindenergiutvikling i industriområder og fremhever viktigheten av å vurdere en rekke faktorer utover vindhastighet når man analyserer potensielle steder for vindprosjekter.

Preface

This thesis concludes our masters' degrees in social economics at the Norwegian University of Science and Technology (NTNU).

The thesis statement concerning wind energy was chosen because we share an interest for sustainable energy and found the subject to be very relevant.

Two different datasets were used to perform the analysis' in the thesis. Hourly wind-data from 2019 gathered from (Pfenninger & Staffell, 2016) (Pfenninger & Staffell, n.d.) (Pfenninger & Staffell, 2016) as well as 2022 data from (Global Wind Atlas, n.d.) was used to perform our analysis and discussion of the two sites.

We want to thank our supervisor Lars Erik Borge for useful guidance, help with developing the thesis statement and various suggestions. Additionally, we extend our thanks to NVE for their invaluable support and guidance. Whenever we contacted them or needed guidance, they provided extensive support and helpfulness.

Trondheim, May, 2023

Hidle, Nils Hadle and Lampe, Herman

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1. Introduction

As modern technology advances and the population increases, demand for energy in the world rises (Norwegian Ministry of Petroleum and Energy, 2018). According to NVE, Norway's need for power is projected to increase from 133 TWh in 2016 to 155 TWh in 2035, which is an increase of 15.7% or 24 TWh (Spilde, et al., 2018). Industries such as petroleum, data centers, and other related industries are cited as the leading causes of the rising energy needs (Spilde, et al., 2018).

The Norwegian government has established ambitious goals for renewable energy production in alignment with EU initiatives for climate policies, including the Paris Agreement. By 2030, a target of 40% reduction in emissions has been set. Wind energy is expected to play a significant role in achieving these goals, as there is a target of 27% of energy consumption to be generated from renewable sources (Erichsen, et al., 2014).

As a significant portion of the potential hydropower production in Norway has been exhausted, the importance of wind power becomes increasingly evident. NVE approximates that an additional 6 - 8 TWh of power can be harvested by upgrading and expanding existing hydropower. However, even if expansion is theoretically possible, its practicality is limited in nature (Norges vassdrags- og energidirektorat, 2020). Figure 1.1 shows the distribution of hydropower potential in Norway as of September 20, 2020.

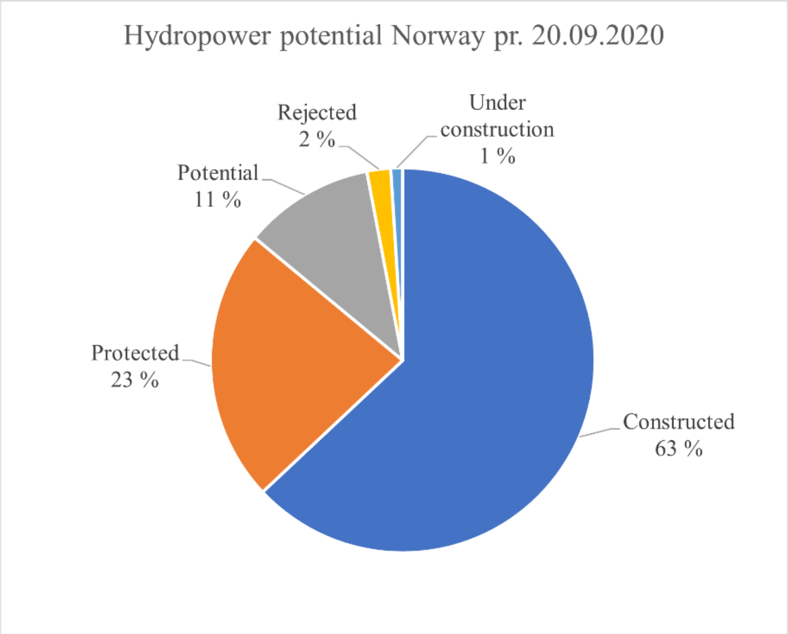

Figure 1.1 *Hydropower potential Norway, Source***:** *(Norges vassdrags- og energidirektorat, 2020).*

In recent years, there has been a growing concern for environmental conservation, and public awareness regarding climate change has significantly increased. Public concern towards nature loss is growing and had risen by 16% in the five years leading up to 2021 (WWF, 2021). This concern is reflected in Norway as the amount of wilderness in the country has significantly decreased from 50% in 1900 to 11.5% in 2018 (Miljødirektoratet, 2018). Areas defined as wilderness are characterized by having no significant human intervention within a 5 km radius. In efforts to preserve nature, 17.6% of Norway is protected through national parks, nature reserves, and landscape conservation areas (Miljødirektoratet, 2021). Debates regarding the trade-off between energy and nature conservation remain controversial. Protests against further intervention in natural areas is not uncommon, as has been made evident by the recent case with Fosen wind (NRK, 2023).

Despite concerns, wind energy is considered a cleaner and more sustainable alternative to traditional fossil fuels. It does not emit greenhouse gases, it does not deplete finite resources, and it has the potential to create jobs and boost local economies (U.S. Energy Information Administration, 2022).

The deployment of wind energy in Norway presents a complex issue of balance between the need for energy production and a wish to preserve precious nature. This thesis presents the idea of using wind energy as a potential solution to meet our energy needs while minimizing harm to the natural environment by utilizing previously disturbed areas as wind energy sites.

This thesis will analyze the viability of wind energy production in industrial areas thorough a cost / benefit analysis, using wind data gathered from (Pfenninger & Staffell, n.d.).

2. Technology

2.1 Introduction:

The modern wind turbine emerges as the result of years of innovation and development across multiple fields. In just the last few years there has been significant developments in the size and power output of standard wind turbines (Office of Energy Efficiency & Renewable Energy, 2022). This section of the master thesis aims to provide a general overview of how the modern wind turbine has developed, and the technology that has made it possible.

2.2 History:

We find evidence of wind power being used as an energy source as early as 5000 BC when boats were propelled along the Nile River. In 200 BC the first wind-powered water pumps were used in China as well as windmills with woven-reed blades grinding grain in Persia and the Middle East.

Global adoption of new wind energy applications eventually took place. In the Middle East, windmills and wind pumps were widely used for agricultural purposes already by the 11th century. Europe first encountered wind technology through traders and the Crusaders. To clear the Rhine River Delta's lakes and marshes, the Dutch constructed huge windpumps. The Western Hemisphere finally received wind energy technologies from European immigrants.

Windmills were employed by American colonists at sawmills, to grind grain, and to pump water. Thousands of wind pumps were erected by ranchers and homesteaders when they populated the western United States. Small wind-electric generators (wind turbines) were also commonly utilized in the late 1800s and early 1900s.

As rural electrification efforts in the 1930s expanded electricity connections to the majority of farms and ranches across the nation, the number of wind pumps and turbines decreased. Yet, several ranchers continue to hydrate their livestock with wind pumps. Tiny wind turbines are regaining popularity, primarily as a means of supplying electricity to isolated and rural locations.

(U.S. Energy Information Administration, 2023)

2.3 Wind Power Equation

Accurately determining the amount of power that can be harvested from the wind at a specific site, is a natural part of any wind energy project. This calculation is typically performed by employing a wind power equation. For the purposes of this thesis, we will examine a simplified model to give a basic understanding of the physics behind wind power. The simplified wind power model is presented below:

$$p = \frac{1}{2} C_p \rho A U^3$$

**Note that this is just one of multiple ways this equation can be formulated. For instance, we could include terms for generator efficiency and gear box bearing efficiency. However, for simplicity, these factors were not included and rather accounted for in the* C_p *term.*

(Sharpe, et al., 2011)

The variables are given by:

$p =$ Power output of the wind turbine

$C_p =$ Power coefficient

$\rho =$ Air density in kilograms per meter squared ($1.25\ kg/m^3$)

$A =$ The rotor swept area, given by $m^2 = \pi r^2$, where $r =$ radius or blade length

$U =$ Wind speed in m/s (cubed)

There are underlying intricacies with multiple of these variables that are important to discuss:

The power coefficient given by C_p, describes what fraction of the wind that can be converted into mechanical work by the turbine. It can be interpreted as an efficiency factor for the turbine, given that its theoretically maximum value is 0.593 as this is the Betz’ limit (Sharpe, et al., 2011).

The Betz limit refers to the maximal potential amount of energy that can be harvested from the wind. It was derived by Albert Betz, a German physicist in 1919 (Ragheb & Ragheb, 2011), and describes how no wind turbine will be able to convert more than 16/27 or approx. 59% of the kinetic energy of the wind into mechanical energy rotating the rotor. It is important to note that this limit does not represent a technical constraint, but rather a theoretical limitation.

To illustrate how this limit emerges, envision a scenario where we want to harvest 100% of the potential energy in the wind. This would entail catching all the wind in the rotors' effective area of operation. To do so, the turbine itself would need to effectively become a solid disk, if not, we would let wind escape between the blades. The issue with this being no rotational motion occurring, and conclusively, no power generation. Conversely only having a set number of blades would let some fraction of the wind escape through the gaps in the rotor blades. This dilemma forms the base of what the Betz limit conveys (Danish Wind Industry Association, 2003).

While the Betz limit establishes that the theoretical maximum ratio of harvestable wind power to potential wind power is 0.59, this value is practically unattainable for standard wind turbines. Several factors come into play that cause the ratio of potential energy to harvested energy to fall below this theoretical limit. Limitations in strength, durability, generator efficiency, bearings and power transmission all contribute to losses in the energy conversion process that limits the overall efficiency of the turbine (Ragheb & Ragheb, 2011).

The ρ term in the equation represents air density. This factor is usually not very significant as it only really affects the power output of the wind turbine if it is situated at high altitudes. Typically, one would simply use the standard value of 1.25 for this variable.

The A term in this simplified model represents the swept area of the turbine blades. Unlike ρ, this term has a big effect on generated power. Doubling the swept area of a turbine theoretically increases power output by a factor of 4. Conversely, halving the swept area of a wind turbine will decrease the theoretical power output by a factor of four. However, it is not always practical to increase rotor blade sizes as this poses technical and cost challenges that need to be carefully evaluated.

The V term is the most significant factor in the equation, representing the wind speed at the specific site. Its significance arises from its direct relationship to the power output, where a doubling of wind speed theoretically increases power output eight-fold. Due to its significant impact, wind speed remains one of the most crucial factors to consider when evaluating potential wind farm locations (Kalmikov, 2017).

Calculating theoretical power output of wind farms provides useful insights. However, when assessing their actual performance, we more commonly refer to capacity factors. The capacity factor quantifies the efficiency of a wind farm by expressing the amount of power generated in a year as a fraction of the time the turbines would have to operate at maximal capacity to produce the same amount. For instance we can assume a wind park with three turbines rated at 2 300 kw each having a capacity factor of 50%, this would mean that if the turbines were operating at maximal capacity for half a year, they would produce the same amount of power that they actually did in the given year. The capacity factor effectively provides a measure of wind farm efficiency by giving an indication of how well the potential power output is being utilized (Albadi & El-Saadany, 2009).

It is important to remember that this section only provides limited insight to the wind power calculations performed by wind energy companies. A vast number of factors have been excluded from this simple approach, which can have a significant impact on the results of these calculations. Given this, there are two main concepts to keep in mind moving forward:

1. The power output of a wind generator is proportional to the area swept by the rotor. One could double the power output of a rotor by doubling the swept area.
2. Wind speed is cubically proportional to the power output of the wind turbine, meaning a doubling of wind speed will lead to increasing power output eightfold.

2.4 Types

When envisioning a wind turbine, the classical three blade design is probably the first that comes to mind. There is however a plethora of other turbine designs that utilize the wind for electrical power generation. The two most prevalent are the HAWT and the VAWT (Horizontal/Vertical Axis Wind Turbines).

Figure 2.1 - A standard HAWT with three blades, Source: (Kratochvil, n.d.).

One of the most popular types of wind turbines utilized for power production is the horizontal axis wind turbine (HAWT). HAWTs are made up of a rotor blade system that is oriented toward the wind and installed vertically on a tower. The energy from the wind is harnessed by the rotating rotor blades, which convert it into rotational motion. This rotational motion is then transmitted to a generator, where it is transformed into electrical energy.

The hub and several blades that make up the HAWT rotor blade system are often built of composite materials like fiberglass, carbon fiber, or wood (Beig & Muyeen, 2016). The rotor blades' aerodynamic shape enables them to transfer the most wind energy possible into rotational energy with the least amount of resistance.

The HAWT rotor blade design is essential to the wind turbine's overall effectiveness. The quantity of energy that may be captured from the wind depends on a number of significant criteria, including blade length, shape, and angle of attack. Moreover, the rotor blade system needs to be built to handle the severe strains and forces produced by the wind, especially during strong gusts of winds.

Wind speed, wind direction, air density, and turbine size are just a few of the variables that must be considered in order to maximize a HAWT's effectiveness. The layout of the wind farm, the orientation of the wind, and the design of the tower are all significant elements that can impact the system's overall efficiency.

In general, HAWTs are a significant and popular technology for producing wind-based renewable energy. As a result, extensive research is being done to enhance the design and functionality of these turbines, especially in terms of improving their efficiency, lowering their cost, and reducing their environmental impact.

Figure 2.2 - A ‘Darrieus’ design VAWT (aarchiba, 2007).

Another popular form of wind turbine used for power generation are the vertical axis wind turbines (VAWT). VAWTs, in contrast to HAWTs, feature rotor blade systems positioned on vertical axis that are vertically oriented, allowing them to gather wind energy from any direction without the need of a sophisticated tracking system.

Typically, a VAWT's rotor blade system consists of several blades connected to a central shaft that is installed atop a tower. Similar to an aviation wing, the rotor blades' airfoil-like form is intended to provide lift as the wind travels over it.

Due to the rotor blade system's ability to be placed close to the ground, where wind conditions are less consistent, VAWTs have the capacity to utilize lower wind speeds for power production. Also, compared to HAWTs, VAWTs often are quieter and have a smaller visual impact, making them better suited for urban and residential environments (Tjiu, et al., 2015).

To sum up, VAWTs have great potential as wind energy technology, especially in areas with low wind speeds and in urban settings. Nevertheless, additional studies and advancements are necessary to enhance their efficiency, dependability, and cost-efficiency, with the aim of increasing their competitiveness compared to other wind turbine options.

There also exists a plethora of unconventional wind turbine designs that have been experimented with. One example is AWES (Airborne Wind Energy Systems), which is a class of energy systems including Airborne Wind Turbines that operate on the kite principle to generate power in high-altitude winds (Diehl, 2013). Another area of experimentation involves turbine designs intended for highway use. These designs aim to leverage the effect of turbulence around highways to generate power from the otherwise “wasted” potential of highway winds (Hu, et al., 2022).

2.5 Design & Construction

The modern wind turbine is made up of many different components that work together to harvest energy from the wind. The inner workings of the turbine might seem complex but the idea behind them is not difficult to grasp. This is an example of how a modern (HAWT) wind turbine can look like on the inside. This part of the thesis will give a brief introduction to the different components.

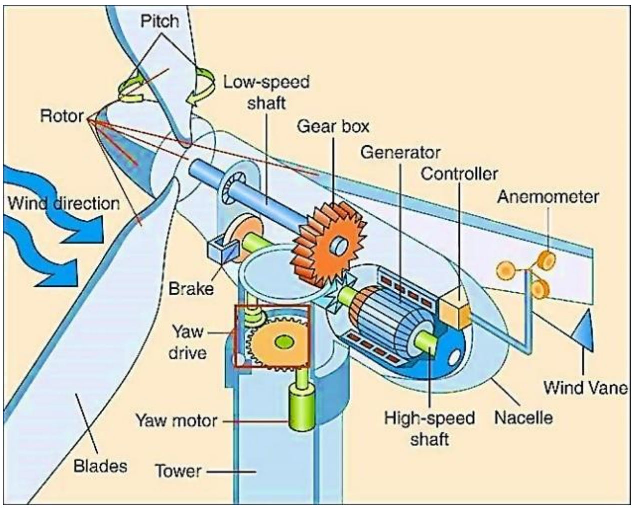

Figure 2.3 – Inside view of the modern wind turbine (Madvar, et al., 2019).

Pitch is the angle of which the blades face the wind and is highly influential on how much power is being generated by the turbine, dependent on wind speed and direction. It can be adjusted by the controller part which will be discussed in more detail shortly.

The blades and the hub together form the rotor which connects to the nacelle through a low-speed shaft that goes into the gear box. Low rotational motion is then converted to a higher speed through the gear box, into the high-speed shaft which powers the generator. The wind vane and anemometer measure the wind speed and angle, conveying this information to the controller which determines the pitch of the blades as well as the direction of the turbine head. The yaw drive and motor are what determines the direction of the turbine head. A brake is also found inside the turbine whose purpose is to stop the rotor from rotation during high wind speeds or maintenance (Madvar, et al., 2019).

The controller is the brain of the turbine and can be considered a “mini-computer”. They are often microprocessor-based and use software to monitor and adjust the turbines operation. By utilizing different algorithms, the controller can calculate the optimal pitch and direction of the turbine, given the data it gathers from the anemometer and wind vane. Even though the main strategies and principles behind these algorithms are open to the public, small variations and fine tunings are considered confidential trade secrets by multiple wind power companies. This stems from the fact that companies who have better algorithms for operability will gain a competitive advantage in the wind energy market (Danish Wind Industry Association, 2003).

In short, a wind turbine consists of a foundation which anchors the turbine to the ground, a tower which supports the top of the turbine and raises the blades to a more optimal altitude and a turbine head which consists of a rotor (hub and blades) and a nacelle (generator, controller, etc.) which together capture kinetic energy and convert it into electrical energy.

(Office of Energy Efficiency & Renewable Energy, n.d.)

2.5.1 Materials

Wind turbines are made up of a variety of materials, including steel, copper, and aluminum (Fosen Vind, n.d.). One group of materials that has become increasingly important in the construction of modern wind turbines is rare earth metals. These metals, including neodymium and dysprosium are used in the production of powerful magnets (PM – Permanent magnets) that are crucial for the efficient operation of wind turbines.

Neodymium is an essential component of the neodymium-iron-boron (NdFeB) magnet, which is the most common type of magnet used in wind turbines (Vekasi, 2022). These magnets are found in the generator of a wind turbine and are responsible for converting the rotational energy of the turbine blades into electrical energy. They are incredibly strong, able to produce a magnetic field that is ten times stronger than conventional magnets (Monroe Engineering, 2022).

Dysprosium and praseodymium are also used in the production of NdFeB magnets, with dysprosium being added in small quantities to improve the magnetic properties of the magnet at higher temperatures. However, these metals are considered "rare" because they are not commonly found in large quantities, and their mining and processing can have significant environmental impacts (Nayar, 2021).

Despite their importance in wind turbine production, the use of rare earth metals has also raised concerns about their supply and sustainability. Efforts are being made to reduce the reliance on these materials by developing new magnet technologies that use alternative materials, such as iron and cobalt (Pavel, et al., 2017). However, for the time being, rare earth metals remain a critical component of modern wind turbines.

2.6 Operability and maintenance

Operability and maintenance are critical factors to consider when evaluating the cost-effectiveness of wind parks, whether they are built in industrial areas or in nature. Wind turbines are designed to operate efficiently and generate electricity for many years, but regular maintenance and inspections are required to ensure their continued operability.

On average, wind turbines have an uptime of around 97 - 98% (Tallyen, 2015), meaning they are available for generating electricity for about 97 - 98% of the time that they are in operation. This uptime can be affected by several factors, including the quality of the turbine components, the design of the turbine, and the operating environment. Regular maintenance and inspections are necessary to maximize uptime and minimize downtime due to unscheduled maintenance or repairs.

Regular maintenance is particularly crucial for smaller wind parks, as each individual turbine contributes significantly to the total energy production compared to larger traditional wind parks. In a park with only three turbines, the failure of even one turbine due to inadequate maintenance will have catastrophic impact on the overall performance of and cost of energy production of the entire farm.

Some of the maintenance activities that may be required during a wind turbine's lifetime include blade cleaning, gearbox or generator maintenance, oil and filter changes and adjustments of sensors and actuators. Maintenance activities are often divided into two categories; scheduled (preventive) maintenance and unscheduled (failure related) maintenance. The frequency and extent of these maintenance activities can vary depending on several factors, most prominently on the operating environment, as this directly contributes to the load imposed on the components of the turbine (Walford, 2006).

While regular maintenance and inspections are necessary for ensuring the continued operability of wind turbines, they also represent a cost for wind park operators. The cost of maintenance and inspections can vary depending on several factors, including the size and design of the turbine, the type of maintenance required, and the labor and equipment costs associated with the maintenance activities. According to (Walford, 2006), "… ,the cost of replacing a gearbox in a 660 kW turbine on a 65 meter tower, is on the order of $120,000, for a site with local hydraulic crane service" (p. 11).

2.7 Demolition & recycling

At the end of their operational life, wind turbines need to be dismantled and their components either repurposed or disposed of. Approximately 85% of wind turbine materials can be reused or recycled, making wind energy a relatively sustainable form of electricity production. However, the remaining 15% that cannot be recycled poses a challenge for wind turbine recycling efforts (Vestas, n.d.).

One of the main challenges in recycling wind turbines is the composite material used to make the blades. The blades are usually made of a combination of fiberglass and carbon fibers in an epoxy resin, which cannot be remolded to form new composites (Iberdrola, n.d.). This means that blades often end up in landfills or incinerators, where they take up a significant amount of space and contribute to environmental pollution.

Another challenge in wind turbine recycling is the rare earth metals used in the production of wind turbine components. Rare earth metals such as neodymium and dysprosium are critical to the production of the powerful magnets used in wind turbine generators. These metals are not easily recyclable and are often lost during the recycling process (SINTEF, 2022). As a result, the wind industry is exploring ways to reduce its reliance on rare metals and find alternative materials for wind turbine production.

Despite these challenges, there are promising developments in wind turbine recycling. Vestas has developed a technology that can separate the fibers from the resin in the blade, allowing for greater reuse (Vestas, n.d.). In Germany, wind turbine blades are commercially recycled as part of an alternative fuel mix for a cement factory. In the United Kingdom, a project is underway to trial cutting blades into strips for use as rebar in concrete, with the aim of reducing emissions in the construction of High Speed 2, a big new highway project (Mike, 2022). Additionally, used wind turbine blades have been incorporated into pedestrian bridges in Poland and Ireland (Karavida & Peponi, 2023).

Overall, while there are challenges in recycling wind turbines, the industry is actively working to find innovative solutions that promote sustainability and reduce environmental impact.

3. Wind Park Prerequisites

3.1 Natural prerequisites

When considering the prerequisites for wind parks, we need to examine the nature-based factors, such as vegetation and landscape. These elements play a crucial role in determining the feasibility and cost-effectiveness of a wind park.

The landscape is central because of the challenges involved in accessing the wind turbine site. It is estimated that the access road to a wind park varies in size from 1.5 - 15 km, which needs to be wide and robust enough to transport the turbine blades. Rapid altitude change is also a factor, with the road needing to have a low slope (Oslo Economics AS og Sweco Norge AS, 2022). After that the internal roads also need to be accounted for. The cost difference between a flat road and a mountainous road can be significant. NVE has developed a RIX indicator (ruggedness index) to show how much of the terrain slopes at 30% or more. The costs, excluding the wind turbine, tend to increase with rugged terrain (Weir, 2018).

Vegetation, particularly forest, is another critical factor to consider. A wind park located in a forested area needs to consider the impact that trees have on the wind flow. Often, wind turbines need to be taller in such areas to access better wind resources, leading to an estimated 10% increase in wind turbine expenses, according to NVE (Weir, 2018).

In addition to vegetation and landscape, other nature-based factors that can impact wind park development include bird migration patterns. For example, some bird species are at risk of collision with wind turbines, which can be a concern in areas where large numbers of birds migrate. This thesis does not explore this specific issue further, but it is important to note as a factor in the planning of wind parks (Jakobsen, et al., 2019).

3.2 Human made prerequisites

In terms of human-made prerequisites, the net capacity and transformers are crucial components necessary for the operation of a wind farm. One advantage that most industrial wind sites possess is that they typically already have the necessary infrastructure in place, as any industrial site requiring energy would already be equipped with a transformer. We will see that our example sites later in the thesis fulfill this prerequisite. Furthermore, existing industries also tend to have greater net capacity than regular housing and Norwegian districts (Olje- og energidepartementet, 2019).

Net capacity describes the potential wattage that can be transmitted at a given time. In Norway there are three different electricity networks: transmission network, regional network and distribution network. A deciding difference between these is the wattage, as shown in table 3.1.

Transmission net	300 kW – 420 kW
Regional net	33 kW – 132 kW
Distribution net	230 W – 22 kW

Table: 3.1 Networks, Source: (Olje- og energidepartementet, 2019)**.**

In Norway it is normal for power intensive industry to connect to either the transmission network or the regional network (Olje- og energidepartementet, 2019).

However, while these prerequisites do suggest that industrial wind parks may be a good fit, it is important to note that net capacity and transformers may not necessarily be the deciding cost factors. This will be discussed further in the cost section.

3.3 Expropriation

Expropriation is the legal process of having to forcefully surrender your land to the government in exchange for compensation (Falkanger & Reusch, 2022). This can be a time-consuming and costly step in the process of constructing wind farms (NRK, 2023). However, building in areas that have already been developed could potentially reduce the issues associated with expropriation. In fact, we have observed that wind farms in already built areas have been constructed by partners who are supportive of the projects (Greenstat, .d.). In some cases, the erection of wind power in such areas have led the owners to become self-sufficient (Skår & Bierud, 2022).

The prerequisite of having the landowner on your side is substantial. For the obvious reason of not having to buy them out and fight opposition

4. Costs

4.1 Introduction

To determine the viability of constructing wind sites in areas with existing buildings and infrastructure, it is important to have a clear understanding of the cost of producing wind energy in conventional areas. To gain insight into this, we will examine the composition of wind farm costs and the investment costs, variable cost and lastly cost of nature.

4.2 Investment costs

Investment costs are a major component of wind farm expenses, and it is important to identify which areas are the most significant. According to NVE and as shown in table 4.1 and 4.2, there are seven distinct categories of wind farm expenses: Turbines, foundation, roads and buildings, local grid, external grid, land acquisition, and project management (Sidelnikova, et al., 2015).

Land based wind power	**Year**	**2020**
Output represented	MW	474
Full load hours (average)	hours/year	4008
Investment costs (average)		
Turbines	kr/kW	7129
Foundation	kr/kW	396
Buildings/roads/docks/facilities	kr/kW	1471
Intern cables	kr/kW	454
Extern cables	kr/kW	233
Expropriation and one-time costs	kr/kW	42
Project management	kr/kW	347
Sum Investment costs	kr/kW	10071
Variable costs	øre/kWh	10
LCOE 2018 NOK	øre/kWh	30
Prerequisites		
Construction time	year	1,3
Lifespan	year	25
Discount rate	%/year	6 %

Table 4.1: Land based wind power costs 2020, Source: (Wold, 2023).

Turbines are on average the most significant investment cost, comprising 70% of total investment costs. The reason for this is the sheer size of the turbines and the number of materials required to construct such a massive structure. Following turbines; roads and buildings represent the next largest expense at an estimated 12%. Due to the typically remote locations of wind farms in Norway, extensive infrastructure is often necessary to gain access to the sites. Project management costs come in at 4%, with foundation costs following at 5%. Netting and cables account for 8% of investment costs, with the majority of these costs resulting from internal cables within the wind park. As will be examined later, there is little benefit to placing wind farms closer to civilization in this regard. Finally, land acquisition costs make up 1% of investment costs (Sidelnikova, et al., 2015). We note that costs vary from project to project but this is an estimate based on several projects.

These percentages are comprised of NVEs numbers from 2007 - 2020.

4.3 Variable cost

Compared to many other energy sources, wind energy has significantly lower variable costs because the wind itself is a free resource (Sidelnikova, et al., 2015). The only costs beyond this are related to maintenance. However, it is useful to break down these variable costs into six categories.

The largest category is service and spare parts, which accounts for 26% of the variable costs. Administration follows closely at 21%, while land rent covers 18%, but only if the land is not purchased outright. Insurance takes up 13%, often provided through long-term agreements with the turbine provider (Sidelnikova, et al., 2015). Finally, power from the grid accounts for 5% and miscellaneous expenses make up 17% (Blanco, 2009).

4.4 LCOE

When looking at energy production costs, the commonly used metric is LCOE, or levelized cost of energy. This takes into account an estimation of the cost of a wind farm over its expected lifespan, usually 25 years (Wold, 2023). It factors in both the investment costs and the variable costs incurred over this period, dividing the total cost by the expected energy production.

This paper adopts the LCOE approach to examine the cost per kilowatt-hour (kWh) of energy production in conventional wind projects and those located in pre-built areas.

4.5 Wind power costs outside of Norway

The energy vs nature crisis is a global problem. A common argument against wind power is that it should be built somewhere else, and that “we” shouldn’t need to sacrifice our land. Therefore, it is interesting to look at wind resources in different places to compare Norway to the rest of the world.

In Norway wind power has a cost of 30 øre/kWh, based of 2020 calculations. This is quite similar to Sweden who NVE lists as having wind energy prices of 32 øre/kWh or 320 kr/MWh (Norges vassdrags- og energidirektorat, 2022).

We have also looked at other sources to see whether Norway is in a special situation and what is average. To compare the thesis looks at three projects in Iran. Results from here show fluctuations in levelized costs from 489.42 - 718.10 kr/MWh (Mirghaed & Roshandel, 2013).

A study from 2009 has made its estimates based on projects all around Europe, based on current technology. They estimate the price of wind power to be between 53 øre and 102 øre per kWh or 530 - 1002 kr/MWh (Blanco, 2009).

We also looked at small wind turbines which is something quite different. It is worth noting that the importance of wind characteristics must be emphasized. The study finds that the kWh price could range from 1.28 kr to 53.48 kr, which is a huge difference. It is also worth noting that in the best-case scenario of 1.28 kr it is still more expensive than all the other examples we have listed (Simic, et al., 2013).

What we want to highlight here is whether wind energy is viable in Norway. Based on costs per kWh it is quite clear that Norway is in a great position to produce wind power. As stated, the main objection is the effect on nature, but if we look at the world as one, Norway must sacrifice less nature to achieve the same goal.

This fact can be further emphasized by observing a picture of the wind quality across Europe. The picture is supplied by Windatlas.info, which is commonly used by NVE.

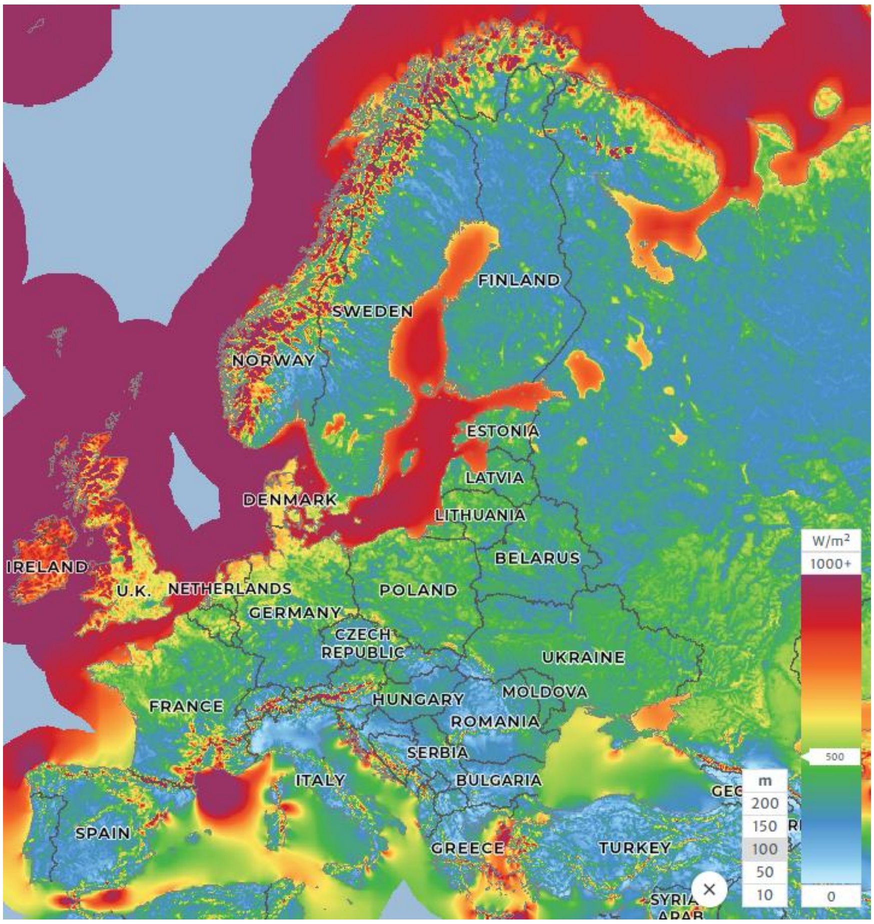

Figure 4.1: Wind quality across Europe. Source: (Global Wind Atlas, n.d.).

Figure 4.1 shows the Mean power density, meaning that the purple and red areas indicate better wind resources (Global Wind Atlas, n.d.). If we look away from the seas it is quite undeniable that Norway has some of the best wind resources in the entire European continent. This is also stated directly by NVE (Jakobsen, et al., 2019).

4.6 Cost trends in Norwegian wind power

In this last section of costs surrounding wind power we will look at notable trends in Norway between 2007 and 2020.

Land based wind power	**Unit**	**2007-2008**	**2011-2013**	**2014-2015**	**2017**
Output represented	MW	108	348	65	324
Full load hours (average)	Hours/year	2841	2872	3813	3556
Turbines	kr/kW	8088	7807	8731	7552
Sum other costs	kr/kW	2679	4025	4249	3156
Foundation	kr/kW	431	612	1074	510
Buildings/roads/docks/facilities	kr/kW	810	1659	1660	998
Intern cables	kr/kW	411	556	447	350
Extern cables	kr/kW	542	374	506	680
Expropriation and one-time costs	kr/kW	-	158	146	203
Project management	kr/kW	485	666	416	415
Sum investment costs	**kr/kW**	**10766**	**11832**	**12979**	**10708**
Variable costs	øre/kWh	15	15	10	10
LCOE 2017 NOK 6% discount rate	øre/kWh	48	51	40	36

Table 4.2: Land based wind power costs 2007-2017, Source: (Sidelnikova, et al., 2015).

Upon analyzing the data provided by NVE in table 4.1 and 4.2, several notable trends become apparent. Firstly, the number of full-load hours has steadily increased from 2841 in 2007 to 4008 in 2020 (Weir, 2018). This can be a sign of increased efficiency in wind turbines but is more likely caused by expanding production. Moreover, variable and service costs have decreased from 15 øre/kWh to 10 øre/kWh, indicating more cost-effective maintenance practices.

Although investment costs exhibit fluctuations, there are a few discernible trends. Turbines remain the dominant investment cost, and their cost has decreased from 8088 kr/kW to 7129 kr/kW from 2007 to 2020 (Weir, 2018). Additionally, roads and buildings continue to be a significant expense every year. Other smaller investment costs exhibit relatively minor fluctuations.

Most significantly, there has been a steady decline in LCOE over the years. LCOE considers both investment and variable costs over the lifespan of the wind farm, divided by the energy produced. From approximately 50 øre/kWh in 2010, LCOE has decreased to 30 øre/kWh in 2020, indicating a substantial drop in the cost of wind energy production (Weir, 2018).

Now that we have a clearer picture of the cost of production, we will take a look at the cost wind power has on nature.

4.7. Costs related to nature and rebuilding**:**

One of the most pressing issues in the energy debate is the cost of nature. This section will look into the actual cost of rebuilding nature and its connected issues. During the construction of a wind park, there are seven primary areas that have an impact on the surroundings. These areas include roads, rig areas, terraforming, turbine areas and foundations, mass excavation and storage, cables, and transformer stations and buildings (Oslo Economics AS og Sweco Norge AS, 2022).

The most extensive area on this list is roads, including both access and internal roads. Access roads vary from 1.5 km to 15 km in length (Oslo Economics AS og Sweco Norge AS, 2022), while internal roads vary based on the number of turbines in the wind park. It is estimated that a wind park requires 125 m to 175 m of internal road per MW installed power (Oslo Economics AS og Sweco Norge AS, 2022). Terraforming is another significant aspect of the construction process; this process is closely linked to the road network. Access roads must be 8 - 12 meters wide to accommodate the large turbine components, leading to extensive terrain modification to ensure no sharp turns or rapid elevation gains (Oslo Economics AS og Sweco Norge AS, 2022).

Turbine foundations and crane areas require 1500 - 2500 square meters of space, while transformer stations and service buildings require 2000 - 8000 square meters of space (Oslo Economics AS og Sweco Norge AS, 2022). These factors must be considered carefully when planning and constructing a wind park to minimize the impact on the surrounding environment.

4.7.1 Rebuilding

Level 1 Revegetation

Element	**Unit**	**Hilly mountain/Coastal terrain**	**Forrest and swamp**	**Blockfield**
Foundation	NOK/pr	100 000 - 200 000	100 000 - 200 000	100 000 - 200 000
Roads	NOK/m	700 - 900	400 - 600	200 - 400
Installation spaces	NOK/m2	110 - 130	20 - 40	20 - 30
Buildings	NOK/m2	110 - 130	20 - 40	20 - 30
Earth cables	NOK/m	200	200	200
overhead cables	NOK/m	-	-	-
Mass withdrawal	NOK/m2	110 - 130	20 - 40	20 - 30

Table 4.3: Cost of rebuilding nature, revegetation, Source: (Oslo Economics AS og Sweco Norge AS, 2022).

Level 2 Revegetation and terraforming

Element	**Unit**	**Hilly mountain/Coastal terrain**	**Forrest and swamp**	**Blockfield**
Foundation	NOK/pr	100 000 - 200 000	100 000 - 200 000	100 000 - 200 000
Roads	NOK/m	1500 - 2000	800 - 1500	600 - 800
Installation spaces	NOK/m2	175 - 225	100 - 140	80 - 120
Buildings	NOK/m2	175 - 225	100 - 140	80 - 120
Earth cables	NOK/m	200	200	200
overhead cables	NOK/m	-	-	-
Mass withdrawal	NOK/m2	175 - 225	100 - 140	80 - 120

Table 4.4: Cost of rebuilding nature, revegetation and terraforming, Source: (Oslo Economics AS og Sweco Norge AS, 2022).

The cost of rebuilding occurs when the wind park is shut down and they are forced to rebuild the nature. In Norway it is put into law that when leaving a wind park site, the nature shall be left as it was found.

> «Det følger av energilovforskriften (1990) § 3-5 at ved nedleggelse av elektriske anlegg, herunder vindkraftverk, plikter konsesjonæren å fjerne det nedlagte anlegget og så langt det er mulig føre landskapet tilbake til naturlig tilstand.» (Oslo Economics AS og Sweco Norge AS, 2022)

Translation:

> «According to the Energy Act Regulation (1990) § 3-5, it is stipulated that upon decommissioning of electrical facilities, including wind power plants, the licensee is obligated to remove the decommissioned facility and, to the extent possible, restore the landscape to its natural state.»

When rebuilding, wind power companies conduct themselves according to three main principles: terraforming, rehabilitating hydrological aspects and revegetation (Oslo Economics AS og Sweco Norge AS, 2022).

Revegetation refers to the process of restoring vegetation to an area that has been impacted by construction, in our case a wind farm. This includes the planting of trees, shrubs, and other vegetation to restore the natural ecosystem. Terraforming, on the other hand, involves modifying the terrain itself to make it more suitable for revegetation. This may include activities like grading, erosion control, and soil improvement. Terraforming is often necessary in areas where the terrain has been severely impacted by construction or where natural soil conditions are not suitable for vegetation growth.

When estimating the cost of rehabilitation, there are two levels to consider: revegetation and terraforming, and just revegetation. Wind power production in Norway is predominantly located in mountainous and challenging terrain, which presents unique challenges for rehabilitation efforts (Oslo Economics AS og Sweco Norge AS, 2022). However, estimates for all terrain types are available.

It is important to note that transportation and equipment costs are a significant part of the overall rehabilitation costs. Moving large quantities of mass is expensive, and the removal of asphalt and natural mass can be costly. Additionally, it is worth noting that rehabilitation costs tend to be higher in mountainous areas, both for revegetation and terraforming efforts.

As seen the cost difference between terrain types can be quite significant. Mountainous areas, for example, often require more extensive terraforming and revegetation efforts than flat or gently sloping terrain. Mountainous areas may also have rockier soil, which can be more difficult to work with and may require additional soil improvement efforts. Lastly, mountainous areas may be more remote and difficult to access, which can increase transportation costs for equipment and materials. All of these factors lead to higher rehabilitation costs in mountainous areas (Oslo Economics AS og Sweco Norge AS, 2022).

4.7.2 Potential nature preservation

The next point we want to look at is how much nature we could be saving by building our wind parks outside of nature. NVE estimates that wind power in Norway has caused the loss of 385 square kilometers of untouched nature (Norges vassdrags- og energidirektorat., 2023). A more applicable number is the square kilometers needed to produce energy. NVE estimates a need of 35 square kilometers per TWh (Norges vassdrags- og energidirektorat, 2022). The potential to save nature by building wind power in industrialized areas is present. A big foundation of this thesis is the potential for increasing energy production to be combined with preservation of nature. These numbers show that there is room for improvement.

4.7.3 Visually affected areas

Wind turbines, standing as tall as 100 meters, are often visible from large distances, with estimates from NVE suggesting they can be seen up to 50 km away, although the conservative estimate is around 30 km (Norges vassdrags- og energidirektorat, 2022). However, these figures are based on a landscape without topography and vegetation, meaning the numbers may differ significantly in reality. Nevertheless, the size of wind turbines is an important factor in the debate surrounding wind power.

In Norway, it is estimated that approximately 20 000 square kilometers of land has visibility to a wind turbine within a 10 km visibility range. This figure increases to 107 000 square kilometers when the radius is increased to 30 km. However, it is important to note that these calculations do not include terrain and vegetation, which can reduce the actual figures to 13 000 and 54 000 square kilometers, respectively (Norges vassdrags- og energidirektorat, 2022).

4.7.4 Money saved from not building down nature

An important advantage of industrial wind is the money saved on not having to rebuild nature. Based on our chart from NVE, we can calculate roughly how much industrial parks would save.

For the rebuilding costs we are looking at an expected range in each section, based on numbers from table 4.3 and 4.4. We will look at the worst- and best-case scenario and discuss them both.

The first post to look at is foundation and crane areas, these need 1500 - 2500 square meters per turbine. Depending on the level of restoration the price per square meters range from 110 kr - 225 kr. This means that restoring nature for one turbine can cost from: 165 000 kr - 562 500 kr (Oslo Economics AS og Sweco Norge AS, 2022).

Next on the list is transformer stations and buildings. These are estimated to take up 2 000 - 8 000 square meters per wind park. The rebuilding cost here is the same as with the foundations. The cost here per wind park can then range from 220 000 kr - 1 800 000 kr (Oslo Economics AS og Sweco Norge AS, 2022).

Roads leading to and from the wind park are ranging from 1.5 - 15 km and range from 700 kr - 2000 kr per meter in restoration costs. Our cost range then becomes 1 050 000 kr - 30 000 000 kr (Oslo Economics AS og Sweco Norge AS, 2022).

We are then left with the internal roads and internal cables, which varies in cost depending on the amount of installed effect. It is estimated to need 125 m - 175 m per MW. The road length needed for each turbine in our case is 287.5 m - 402.5 m. The potential rebuilding cost of this would then be 700 kr/m - 2000 kr/m for roads plus 200 kr/m for the internal cables. The cost range is 258 750 kr - 885 500 kr .

The last point NVE estimates cost for is mass deposits, this is a very difficult factor to estimate so it has been excluded from our calculations.

We will apply these numbers to evaluate a low and high-cost scenario for our potential wind parks. This section will come later in the thesis.

5. Comparison of Industrial Wind Park Sites: Analysis of Potential Locations in Oslo and Rogaland

5.1 Introduction

This thesis compares two theoretical industrial wind farms located at Kårstø and Sjursøya, analyzing their wind potential, costs, benefits, and impact on the environment and local communities. In the selection of these two sites, we conducted research and took inspiration from a previous politician's proposal, Petter Eide (Gjerde, 2020). After consideration, we chose Kårstø as a promising site and Sjursøya as a site that presents certain challenges.

Determining the optimal locations and number of wind turbines is critical to the success of any wind farm. We based our calculations on wind data and other parameters such as noise levels, industrial movements, and wake regulation. In this section, we discuss the spacing between turbines, turbine specifications, and the recommended minimum distance between turbines and housing.

Spacing and placement of the turbines was performed using the optimal distance between turbines based on the need for 5 - 9 rotor lengths in the prevailing wind direction and 3 - 5 rotor diameters in the direction perpendicular to the prevailing winds (Danish Wind Industry Association, 2003).

Our calculations are based on the use of Enercon GmbH turbines with a rated output of 2 300 kW, a tower height of 71 meters, and a rotor diameter of 71 meters, which are the same turbine specifications employed at Valsneset, one of the only industrial wind parks currently operational in Norway (Norges vassdrags- og energidirektorat, .d.).

> «Den anbefalte grenseverdien på L_{den} 45 dB opptrer normalt på en avstand på 600 - 800 meter fra turbinene. I konsesjonssaker legger NVE til grunn en anbefalt minsteavstand på minimum 800 meter mellom vindkraftverk og bebyggelse.» (Norges vassdrags- og energidirektorat, 2023).

English translation:

> “The recommended limit for L_{den} at 45 dB usually occurs at a distance of 600 - 800 meters from the turbines. In concessions, the NVE applies a recommended minimum distance of at least 800 meters between wind power plants and residential areas.”

In our example parks we try to adhere to or address this recommended limit when necessary.

In the following sections, we will discuss the economic, environmental, and social impacts of wind farms at Kårstø and Sjursøya and provide a comparative analysis of these two sites.

5.1.1 Research goals

An important aim of this thesis is to assess the factors that contribute to the viability of a potential wind farm location. While potential electricity output, primarily determined by wind speeds, is a critical aspect of wind farm viability, it is essential to consider additional factors prior to undertaking development. One such factor is wind direction. Good wind resources are not solely defined by speed, but also direction and consistency. The wind rose in Figure 5.2 indicates a prevailing wind from the south with little variability. However, it is crucial to account for the shape of the land. In the scenario presented in Figure 5.1, with the wind rose in Figure 5.2, the placement of turbines would be limited. The wake effect prevents placing wind turbines close to each other in the prevailing wind direction, as the airflow is significantly slowed down by passing through the turbine blades.

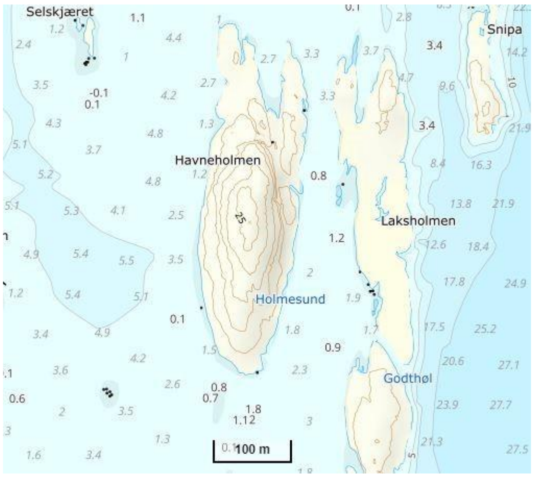

Figure 5.1: Picture of landmass: Source: (Norgeskart, n.d.).

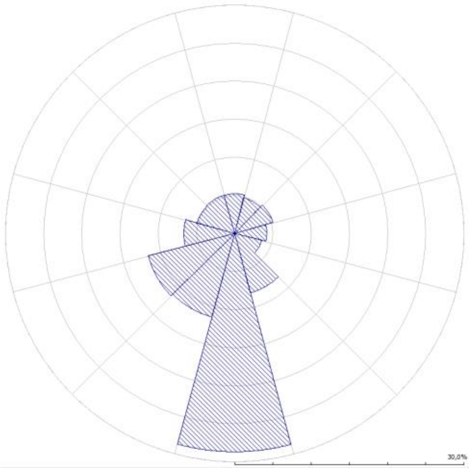

Figure 5.2: Example wind rose.

It is important to recognize that relying solely on the wind power equation, which emphasizes the significance of wind speed, can lead to misconceptions about what truly makes a wind site favorable for energy harvesting. The previous example serves as a reminder that a favorable wind resource alone is insufficient if the conditions for harnessing it effectively are lacking. Moreover, we should not underestimate the diverse nature of wind site assessment, as both natural and "political" factors come into play. Utilizing land for wind farms means using resources that could have been allocated differently, and it involves considerations regarding visual and noise pollution. The planning of theoretical wind farms quickly highlights the need to comprehensively understand the various consequences they present. By recognizing and addressing these various aspects, we can approach wind farm development with a thorough understanding of the complex implications involved.

5.1.2 Selection of Kårstø and Sjursøya as study sites

To conduct the sensitivity analysis, we selected two potential industrial wind park locations: Sjursøya and Kårstø. Sjursøya, located in Oslo, primarily serves as a container storage and bulk ship facility. Kårstø, situated in Rogaland, is a gas processing plant. These sites were chosen from a list of areas that had previously been considered as favorable locations for industrial wind parks (Gjerde, 2020). The decision to focus on these two locations was driven by multiple factors. Our aim was to select one site with a high wind potential, open space, and seclusion and one which had contrasting attributes Sjursøya, being small and located in the heart of Oslo, experiences limited wind resources and is in close proximity to residential areas. In contrast, Kårstø offers a larger area, remote surroundings, and is expected to be a more suitable location for a wind park.

5.1.3 Cost benefit analysis theory

The role of a cost benefit analysis in societal problems is to find an efficient allocation of resources. It takes up both positives and negatives and evaluates whether the upside is worth the potential negative consequences. In certain examples it’s also important to evaluate the alternative costs. With limit resources it is always an option to allocate the resources differently and find a better result. The purpose of a cost benefit analysis is to analysis consequences before the decision falls (Hervik, et al., 1998).

In our case the cost benefit analysis presents an efficient way to evaluate new potential wind parks. The analysis will help us evaluate the profitability of our wind parks.

5.2 Rebuilding nature scenarios

Under 4.7.4 we looked at the cost of rebuilding nature. In this section we look at the potential high and low-cost scenarios derived from these numbers.

We look at a potential low-cost scenario and a high-cost scenario:

Low Cost Scenario	Kårstø	Sjursøya
Foundation, Crane areas	990 000 kr	495 000 kr
Transformers and Buildings	220 000 kr	220 000 kr
Roads	1 050 000 kr	1 050 000 kr
Internal roads and cables	258 750 kr	258 750 kr
Sum	**2 518 750 kr**	**2 023 750 kr**

Table 5.1: Low-cost scenario for Kårstø and Sjursøya

High Cost Scenario	Kårstø	Sjursøya
Foundation, Crane areas	3 375 000 kr	1 687 500 kr
Transformers and Buildings	1 800 000 kr	1 800 000 kr
Roads	30 000 000 kr	30 000 000 kr
Internal roads and cables	885 500 kr	885 500 kr
Sum	**36 060 500 kr**	**34 373 000 kr**

Table 5.2: High-cost scenario for Kårstø and Sjursøya

The potential difference between the low cost and high-cost scenarios is severe. The reality of these calculation being accurate can be questioned. For example, the high cost scenario is based on the biggest possible areas used in the roughest terrain we have. We have to note that there is substantial price differences between a wind park of 42 turbines like Geitfjellet and our potential three turbines at Sjursøya.

The most realistic and appropriate approach for us is to use the low-cost example in our calculations, and that is what we will do in our examples. We did however include the high-cost scenarios to show the potential costs.

5.3 Kårstø

The first location we want to evaluate is Karstø, a gas processing plant in the north of Rogaland. As discussed earlier, the site presents advantageous attributes when it comes to its location and size. Evaluation of the site will commence by assessing its wind resource. Figure 5.3.1 presents the middle wind of Kårstø as of 2019.

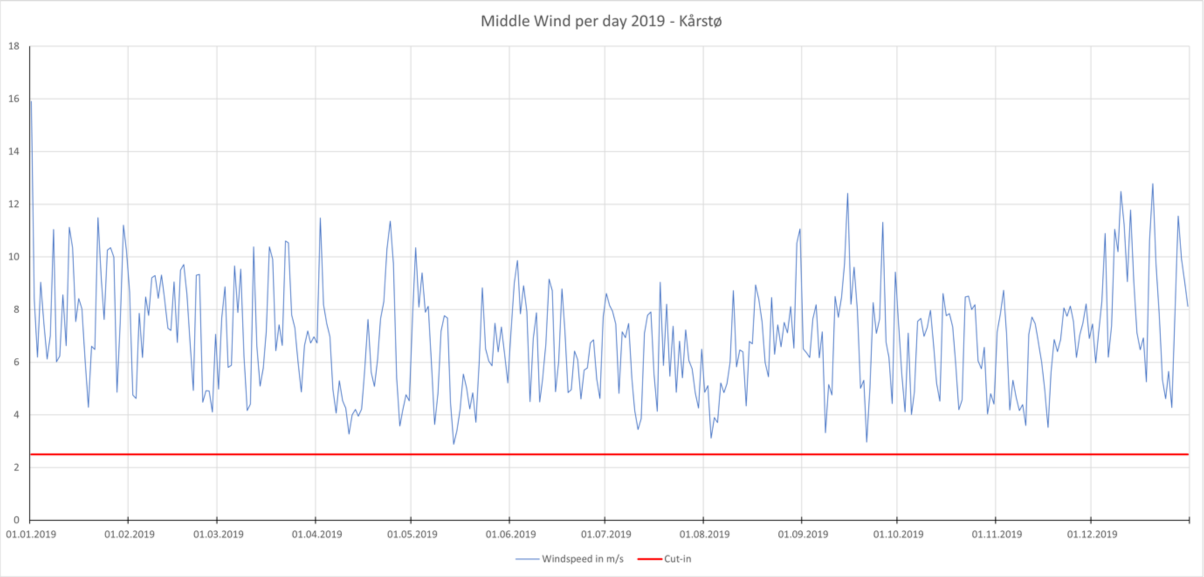

Figure 5.3.1: Wind data for Kårstø. Source: (Pfenninger & Staffell, n.d.).

Middle wind per day has been given data points, and as can be observed from 5.3.1 the middle wind throughout the year was around 7 m/s. We can also note how the middle wind consistently exceed the cut-in wind rating of the chosen turbine model (2,5 m/s).

Next, we will discuss the wind direction of the site, using figure 5.3.2

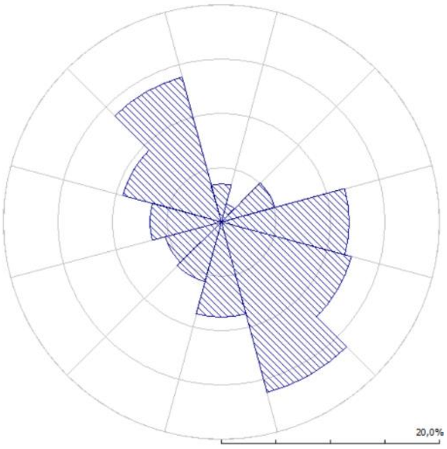

Figure 5.3.2: Wind rose for Kårstø, Source: (Global Wind Atlas, n.d.).

We observe that two prevalent wind directions occur. The south-west and north-east winds are the main wind directions of the site. Using this information and the layout of the power plant, we propose the following turbine locations given in figure 5.3.3.

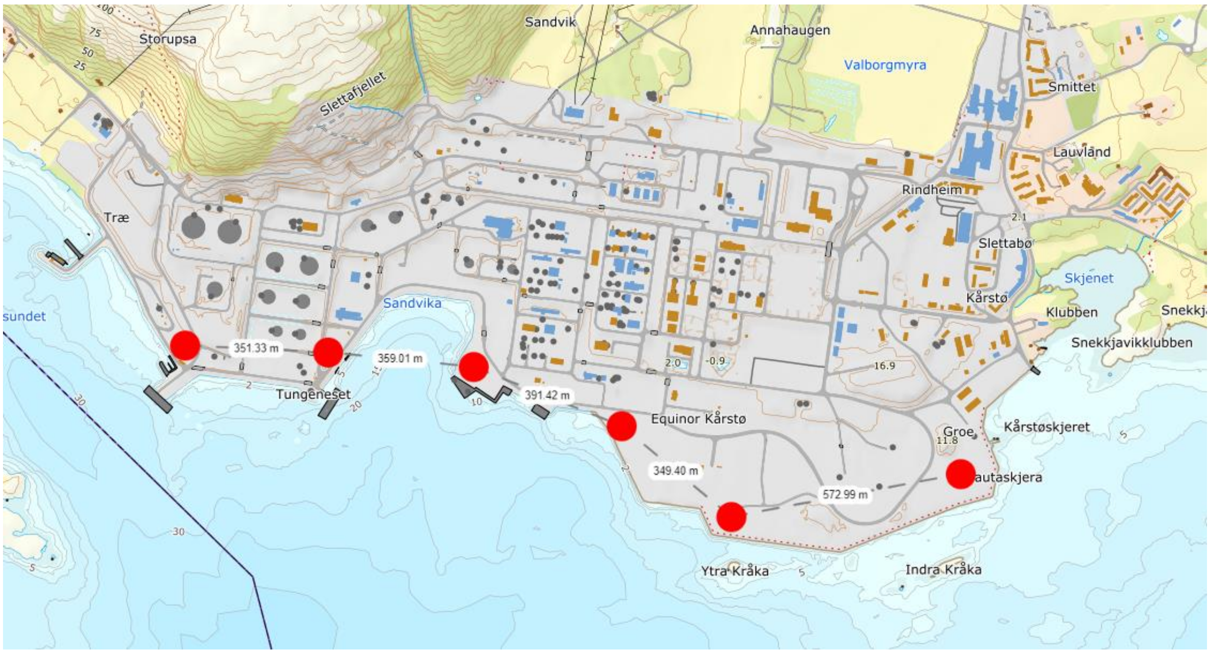

Figure 5.3.3: Wind turbine placement map, Kårstø, Source: (Norgeskart, n.d.).

Note that the proposed turbine locations were chosen with multiple factors in mind, mainly being spacing between turbines and distance to residential areas. The turbine locations also satisfy the required distance between themselves and are placed to capture wind in the prevalent directions. Placements near the shore were also prioritized to minimize obstruction of the operational power plant and to capture unobstructed wind from the fjord.

5.3.1 Power potential

The cost / benefit analysis will commence by calculating the amount of power the potential wind site can produce.

Using wind speed data from 2019 Ninja, we can calculate the capacity factor of Kårstø wind park. Ninja Renewables gives us the amount of theoretical power generated by the turbine each hour, which we then add together to compare to potential maximal power output. We get a total production of 4 932 628 kWh per year. Dividing this number by potential maximal output gives us the capacity factor:

$$\frac{4\,932\,628 kWh}{20\,148\,000 kWh} * 100 \approx 24.482\%$$

This capacity factor tells us that the total yearly production from Kårstø can be described as the turbines operating at maximal output for 24.48% of the time in a year. We then calculate total lifetime output by multiplying by the amount of turbines we plan to use:

$$4\,932\,628 kWh * 6 = 29\,595\,768 kWh = 29.59 GWh$$

Assuming a 25-year of operation for the turbines we get total lifetime production of Kårstø being:

$$29\,595\,768 kWh * 25 years \approx 739.9 GWh \;\; or \; 739\,894\,200 kWh$$

5.3.2 Cost

When calculating the cost of Kårstø we are using numbers supplied by NVE. The cost numbers used in this thesis is based on Norwegian wind power facilities in 2020. It is important to note that these numbers are mainly accurate towards wind power facilities in nature, but given that this thesis exists because of the lack of industrial wind facilities these numbers are the closest we can get. We do, however, make a point of assuming these cost numbers as worst-case scenario. It is reasonable to assume that roads, cables, buildings, terraforming etc. will present an equal cost, or be cheaper in an industrial setting than in an unpredictable rugged nature setting.

Land based wind power	**Year**	**2020**
Output represented	MW	474
Full load hours (average)	hours/year	4008
Investment costs (average)		
Turbines	kr/kW	7129
Foundation	kr/kW	396
Buildings/roads/docks/facilities	kr/kW	1471
Intern cables	kr/kW	454
Extern cables	kr/kW	233
Expropriation and one-time costs	kr/kW	42
Project management	kr/kW	347
Sum Investment costs	kr/kW	10071
Variable costs	øre/kWh	10
LCOE 2018 NOK	øre/kWh	30
Prerequisite		
Construction time	year	1,3
Lifespan	year	25
Discount rate	%/year	6 %

Table 4.1: Land based wind power costs 2020, Source: (Wold, 2023).

As discussed in chapter 4, we have used the numbers provided by NVE in our calculations. This means that we are assuming the same costs provided, as well as a 25 year lifespan and a discount rate of 6%.

We get a total investment cost of:

$$I = 10071\ kr/kW * 2300\ kW * 6\ turbines = 138\ 979\ 800\ kr$$

And using production numbers, we get a variable cost of:

$$V = 0.1\ kr/kWh * 739\ 894\ 200\ kWh = 73\ 989\ 420\ kr$$

Given that the cost numbers are based on NVE's calculations of existing "traditional" wind parks, they are likely to be inaccurate. In spite of this, we have not attempted to construct new numbers for industrial wind parks, as this could lead to significant discrepancies from actual costs and would ultimately be speculative in nature.

NVE's numbers dictate that the investment costs of buildings/road/dock/facility are listed as 1471 kr/kW or 20 299 800 kr total in this case. It is reasonable to assume that an already existing waterside industrial park with capacity for oil tankers to dock, this number will be lower. The same applies for external cables and land acquisitions. The chosen turbine model we have applied is smaller than the average big scale wind site turbine, as such it is reasonable to assume that this cost is smaller than presented in NVEs numbers. However, fundaments, internal cables and project management costs are likely to be equivalent in this case.

Another important factor to note is the money saved from not having to rebuild nature. As calculated under the low-cost scenario this is: 2 518 750 kr.

5.3.3 Income

The amount of value gained from the wind park can be calculated using the Present Value method. We assume two scenarios here with electricity prices of 50 øre/kWh and one with electricity price of 100 øre/kWh. We use the NPV formula provided by (Regjeringen, 1998).

$$NPV = -I_0 + \sum_{i=1}^{n} \frac{U_i}{(1+k)^i}$$

where,

I_0: is the initial investment costs

U_i: is the cash flow in period i (Revenue – variable costs)

k: is the discount factor (6%)

Scenario 1 gives:

$$NPV_1 = -(10\ 071 * 2300 * 6) + \sum_{i=0}^{25} \frac{(29\ 595\ 768 * 0.5) - (0{,}1 * 29\ 595\ 768)}{(1 + 0.06)^i}$$

$$NPV_1 = -138\ 979\ 800 + 151\ 333\ 297$$

$$NPV_1 = 12\ 353\ 497\ kr$$

Scenario 2 gives:

$$NPV_2 = -(10\ 071 * 2300 * 6) + \sum_{i=0}^{25} \frac{(29\ 595\ 768 * 1) - (0{,}1 * 29\ 595\ 768)}{(1 + 0.06)^i}$$

$$NPV_2 = -138\ 979\ 800 + 340\ 499\ 919$$

$$NPV_2 = 201\ 520\ 119\ kr$$

Which tells us that the profitability of the Kårstø project is not very sensitive to power prices. We find that Kårstø has a positive netto present value when the energy price is 46.73 øre/kWh or higher, all else being equal:

$$138\ 979\ 800 = \sum_{i=1}^{25} \frac{(29\ 595\ 768 * x) - (0.1 * 29\ 595\ 768)}{(1 + 0.06)^i} \quad \rightarrow \quad x \approx 0.4673 kr/kWh$$

5.3.4 LCOE

To calculate the potential LCOE of the Kårstø project, we are using a modification of the discounting method proposed by (Shen, et al., 2020).

$$LCOE_{discounting} = \frac{I_0 + \sum_{t=1}^{T}(V_t/(1+d)_t)}{\sum_{t=1}^{T} E_t/(1+d)^t}$$

where,

E_t: Is the amount of power generated in period t.

Using this approach, we get the LCOE of Kårstø being:

$$LCOE_{discounting} = \frac{138\ 979\ 800\ kr + 69\ 801\ 340\ kr}{378\ 333\ 243\ kWh} \approx 0.552\ kr/kWh$$

This calculation assumes a constant discount rate of 6% and a 25 year lifespan of the wind farm.

Production	378 333 243 kW
Expenses	208 781 140 kr
Discount rate	6%
LCOE	**55.2 øre/kWh**

Table 5.3: LCOE Kårstø.

5.3.5 Noise

Kårstø is remote in the sense that there are no residential areas close by. There are some inhabited houses in the area though, but these have been accounted for in the turbine placements. Figure 5.3.4 shows the distance between the closest turbines to inhabited housing. We observe that all the turbines are satisfactory in their distance to inhabited housing. Given this fact, noise pollution is not expected to be an issue for the site.

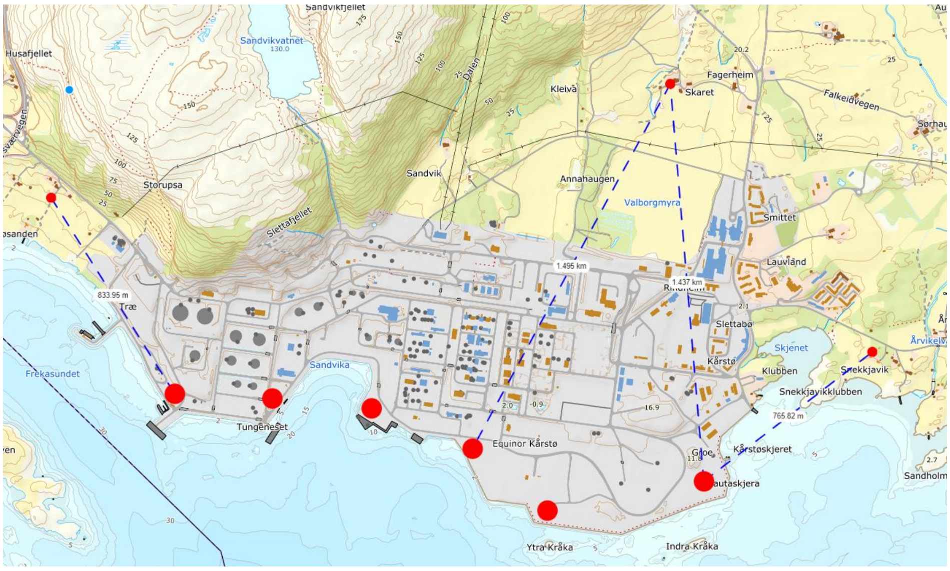

Figure 5.3.4: Wind turbines in relation to neighbors, Kårstø, Source: (Norgeskart, n.d.).

5.3.6 Visual impact

Figure 5.3.4 depicts an example of how the turbine placements could look like in practice. The turbines have been scaled to approximately represent their visual impact.

Figure 5.3.5: Wind turbine visualization, Kårstø. Source: (energi24, 2022).

As Kårstø is a big site that spans a large area the wind turbines do not appear too prominent. That being said, the turbines would still be visible from a large portion of the Ryfylke basin, as depicted in figure 5.3.6. It is worth noting that this area has a large portion of international tourism and domestic tourism, and as such the area is potentially sensitive to visual pollution presented by wind turbines.

Figure 5.3.6: Visual impact map, Kårstø, Source: (Norgeskart, n.d.).

5.4 Sjursøya

Sjursøya is the second area that will be analyzed as a potential wind park location. Sjursøya is used as a container and petroleum port and serves as the primary oil port for Eastern Norway. While the notion of having a wind power production site in the heart of Oslo is intriguing, it is likely unfavorable due to potential noise and visual pollution. Therefore, it is crucial to assess the viability of Sjursøya as a wind energy production site thoroughly. This section will begin by analyzing the wind data of the site, as presented in table 5.4.1.

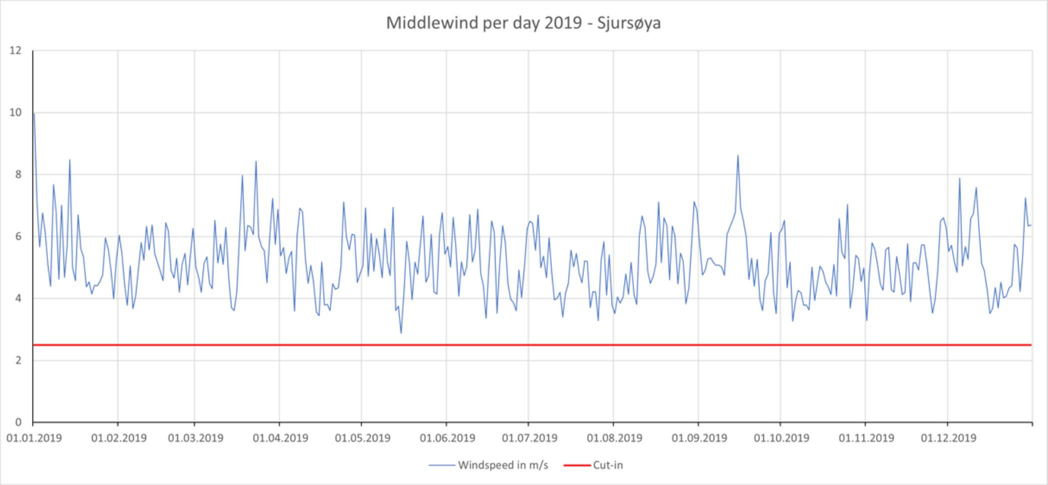

Figure 5.4.1 Wind data for Sjursøya. Source: (Pfenninger & Staffell, n.d.).

The graph above is constructed with hourly wind data gathered from (NINJA), where the daily average has been given data points. We see that the middle wind of Sjursøya was relatively low and centered around 5 m/s. The red line represents the lowest wind speeds that the chosen turbine model can produce electricity at ("Cut-in" 2,5 m/s).

Next the wind rose, or the wind direction data of the area will be discussed.

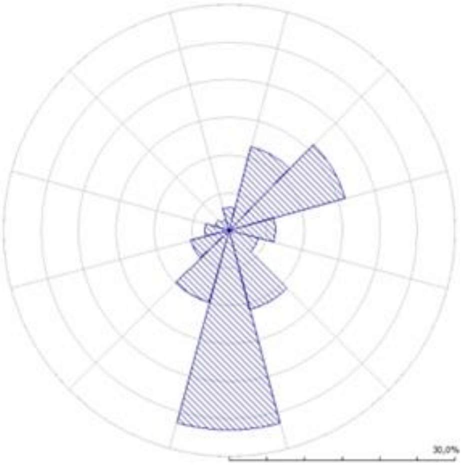

Figure 5.4.2 Wind rose for Sjursøya, source: (Global Wind Atlas, n.d.).

The wind rose in figure 5.4.2 indicates that the most prevailing wind directions in Sjursøya are from the south and northeast. Given the shape of the peninsula, the wind direction is propitious, as we can space the turbines out in a crosswise direction and harvest most of the wind. Through close inspection and looking at various pictures of the area, we find three potential wind turbine locations; marked in red in figure 5.4.3.

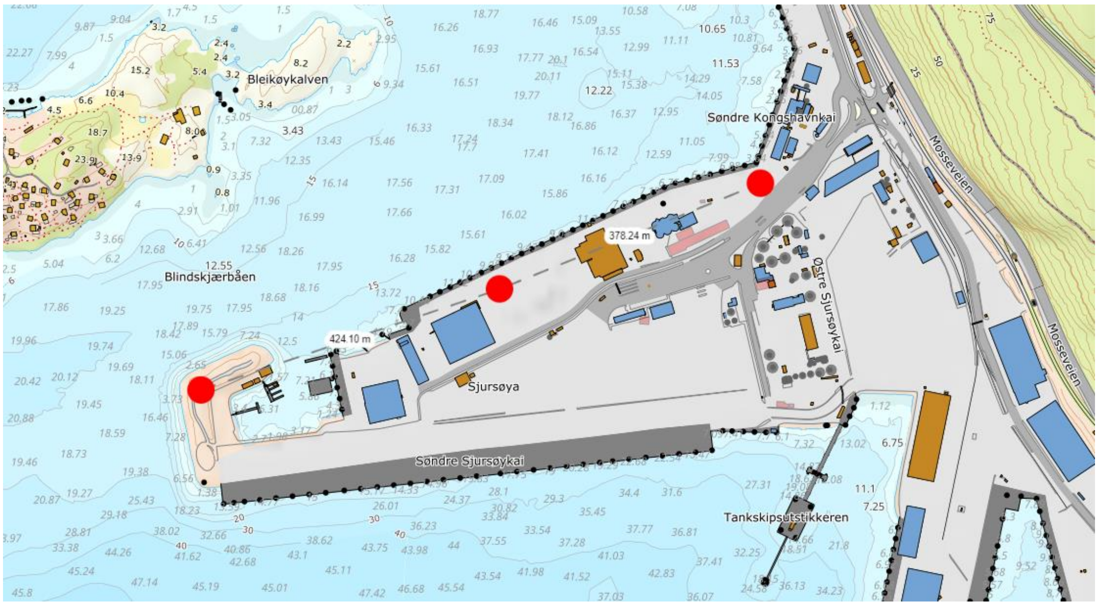

Figure 5.4.3 Wind turbine placement map Sjursøya, Source: (Norgeskart, n.d.).

The locations were selected based on multiple factors such as the wind direction previously mentioned, the necessary distance between turbines and the availability of unoccupied space at the ground level.

5.4.1 Power potential

The cost / benefit analysis will commence by calculating the amount of power the potential wind site can produce.

Using wind speed data from 2019 Ninja, we can calculate the capacity factor of Sjursøya wind park. Ninja Renewables gives us the amount of theoretical power generated by the turbine each hour, which we then add together to compare to potential maximal power output. We get a total production of 1 987 772kWh. Dividing this number by potential maximal output gives us the capacity factor:

$$\frac{1\ 987\ 772\ kWh}{20\ 148\ 000\ kWh} * 100 \approx 9.866\%$$

This capacity factor tells us that the total yearly production from Sjursøya can be described as the turbines operating at maximal output for 9.866% of the time in a year. We then calculate total lifetime output by multiplying by the number of turbines we plan to use:

$$1\ 987\ 772\ kWh * 3\ turbines = 5\ 963\ 316\ kWh = 5.96\ GWh$$

Assuming a 25-year of operation for the turbines we get total lifetime production of Sjursøya being:

$$5\ 963\ 316\ kWh * 25 years \approx 149 GWh\ or\ 149\ 082\ 900\ kWh$$

5.4.2 Cost

When calculating the cost of Sjursøya we are using numbers supplied by NVE. The cost numbers used in this thesis is based on Norwegian wind power facilities in 2020. It is important to note that these numbers are mainly accurate towards wind power facilities in nature but given that this thesis exists because of the lack of industrial wind facilities these numbers are the closest we can get. We do, however, make a point of assuming these cost numbers as a worst-case scenario. It is reasonable to assume that roads, cables, buildings, terraforming and everything else will be the same cost or cheaper in an industrial setting than in an unpredictable rugged nature setting.

Land based wind power	**Year**	**2020**
Output represented	MW	474
Full load hours (average)	hours/year	4008
Investment costs (average)		
Turbines	kr/kW	7129
Foundation	kr/kW	396
Buildings/roads/docks/facilities	kr/kW	1471
Intern cables	kr/kW	454
Extern cables	kr/kW	233
Expropriation and one-time costs	kr/kW	42
Project management	kr/kW	347
Sum Investment costs	kr/kW	10071
Variable costs	øre/kWh	10
LCOE 2018 NOK	øre/kWh	30
Prerequisite		
Construction time	year	1,3
Lifespan	year	25
Discount rate	%/year	6 %

Table 4.1: Land based wind power costs 2020, Source: (Wold, 2023).

We are once again using numbers provided by NVE and assuming a discount rate of 6% as well as a lifespan of 25 years.

We get a total investment cost of:

$$I = 10071\ kr/kW * 2300\ kW * 3\ turbines = 69\ 489\ 900\ kr$$

Calculated production numbers give a variable cost of:

$$V = 0.1 \frac{kr}{kW} * 149\ 082\ 900\ kWh = 14\ 908\ 290\ kr$$

When calculating the cost of Sjursøya we are looking at the same numbers used to look at Kårstø, but instead of using six wind turbines we only use three. The rough cost estimate for Sjursøya then becomes 23 163 300 kr times three; 69 489 900 kr.

As noted under the section on Kårstø, we realize that these numbers are based on facilities that are different to the ones we are working with. But once again we will abstain from attempting to construct new cost numbers as we are unqualified to do so. Sjursøya is similar to Kårstø in respect to its water bound location and ease of access.

Lastly we once again note the important factor of money saved from not having to rebuild nature. As calculated under the low-cost scenario this is: 2 023 750 kr.

5.4.3 Income

The amount of value gained from the wind park can be calculated using the Present Value method. We assume two scenarios here with electricity prices of 50 øre/kWh and one with electricity price of 100 øre/kWh. Using the NPV formula provided by (Regjeringen, 1998):

$$NPV = -I_0 + \sum_{i=0}^{n} \frac{U_i}{(1+k)^i}$$

where,

I_0: is the initial investment costs

U_i: is the cash flow in period i (Revenue – variable costs)

k: is the discount factor (6%)

Scenario 1 gives:

$$NPV_1 = -(10\,071 * 2300 * 3) + \sum_{i=0}^{25} \frac{(5\,963\,316 * 0.5) - (0.1 * 5\,963\,316)}{(1+0.06)^i}$$

$$NPV_1 = -69\,489\,900 + 30\,492\,477$$

$$NPV_1 = -38\,997\,423\ kr$$

Scenario 2 gives:

$$NPV_2 = -(10\,071 * 2300 * 3) + \sum_{i=0}^{25} \frac{(5\,963\,316 * 1) - (0.1 * 5\,963\,316)}{(1+0.06)^i}$$

$$NPV_2 \approx -69\,489\,900 + 68\,608\,073$$

$$NPV_2 \approx -881\,827\ kr$$

Which tells us that the profitability of the Sjursøya project is moderately dependent on energy prices. We find that Sjursøya has a positive netto present value when the energy price is 101.2 øre/kWh or higher, all else being equal:

$$69\,489\,900 = \sum_{i=1}^{25} \frac{(5\,963\,316 * \mathrm{x}) - (0.1 * 5\,963\,316)}{(1+0.06)^i} \quad \rightarrow \quad x \approx 1.012 kr/kWh$$

5.4.4 LCOE

To calculate the potential LCOE of the Sjursøya project, we are using a modification of the discounting method proposed by (Shen, et al., 2020).

$$LCOE_{discounting} = \frac{I_0 + \sum_{t=1}^{T}(V_t/(1+d)_t)}{\sum_{t=1}^{T} E_t/(1+d)^t}$$

where,

E_t: Is the amount of power generated in period t.

Using this approach, we get the LCOE of Kårstø being:

$$LCOE_{discounting} = \frac{69\,489\,900\ kr + 14\,064\,425\ kr}{76\,231\,192\ kWh} \approx 1.096\ kr/kWh$$

This calculation assumes a constant discount rate of 6% and a 25 year lifespan of the wind farm. Utilizing the discounting method we get:

Production	76 231 192 kWh
Expenses	83 554 325 kr
Discount rate	6%
LCOE	**109.6 øre/kWh**

Table 5.4: LCOE Sjursøya.

5.4.5 Noise

Since Sjursøya is in the “middle” of Oslo, it’s important to discuss the noise aspect of the wind farm. Wind turbine noise can be experienced as unpleasant and because of this we have laws for minimal distance between house and turbine, as well as laws for maximal decibel levels from a wind turbine on the plot of inhabited housing. The recommended limit-value of 45 dB is usually found in the distance of 600 - 800 meters from the turbines (Norges vassdrags- og energidirektorat, 2023). As presented in Figure 5.4.4, we see that the wind turbine locations chosen are in fact to close to inhabited housing. The leftmost turbine of the site is only 285 meters away from the closest housing, and as such would most likely stop the project from being developed. We have chosen to place this turbine and look away from this fact though, as the cost / benefit potential of the site will provide useful insight.

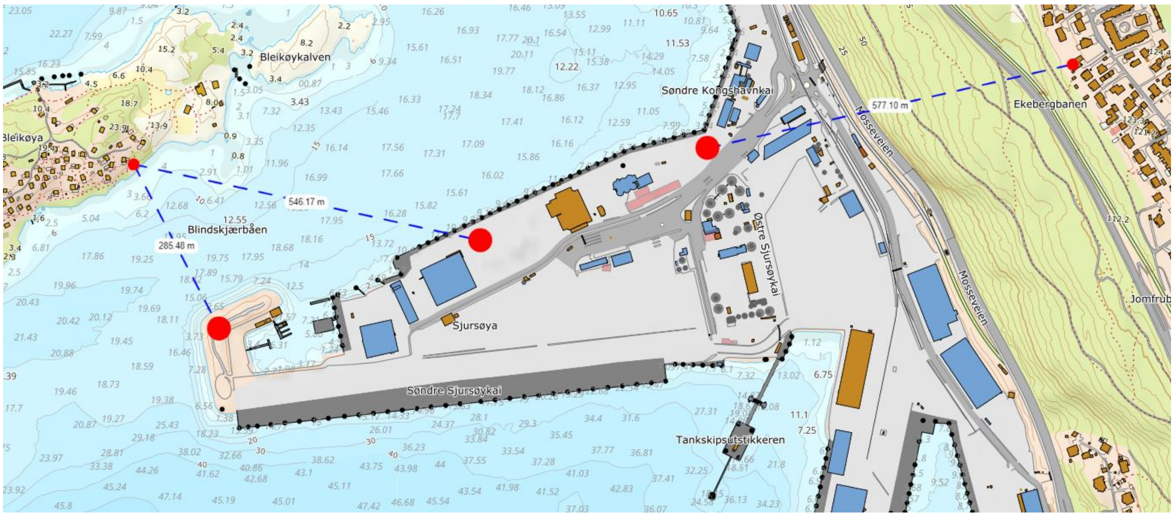

Figure 5.4.4 Turbine distance to residential areas, Sjursøya, Source: (Norgeskart, n.d.).

5.4.6 Visual impact

In conjunction with producing unpleasant noise, wind turbines can also appear intrusive to the visual aspect of an area. Given that Sjursøya is in the “middle” of Oslo, it is highly susceptible to visual pollution, and would likely cause issues with people living in close vicinity to the site. It is important to note that this is a case where even a good wind resource would be insufficient in providing a good wind site location, because of political implications. Figure 5.4.5 aims to provide an approximate visual of how the turbines would look like on Sjursøya.

Figure 5.4.5 Wind turbines realistic map, Sjursøya. Source: (Valderhaug, n.d.).

6. Comparison of Sjursøya and Kårstø

In this section, we will compare the two wind turbine parks based on income and cost, number of wind turbines and placements, and potential issues related to visual impact and noise.

Cost comparison:

As calculations for the two sites are based on the same numbers, they are quite similar in nature. Kårstø has twice the capacity of Sjursøya and as such the investment cost of Kårstø is twice that of Sjursøya. However, the variable costs differ, as the production potential of the two sites are different. The numbers below do not take the discount factor into account and are based on the total lifespan of the sites.

	Sjursøya	Kårstø
Total investment costs	69 489 900 kr	138 979 800 kr
Total variable costs	14 908 290 kr	73 989 420 kr
Total costs	**84 398 190 kr**	**212 969 220 kr**

Table 6.1: Total costs Sjursøya / Kårstø.

Benefit comparison:

Comparisons of revenue (sum of cash flows) and NPV makes the differences in potential between Sjursøya and Kårstø evident.

	Sjursøya (50 øre/kWh)	Sjursøya (100 øre/kWh)	Kårstø (50 øre/kWh)	Kårstø (100 øre/kWh)
Revenue:	30 492 477 kr	68 608 073 kr	151 333 297 kr	340 499 919 kr
Netto Present Value:	**-38 997 423 kr**	**-881 827 kr**	**12 353 497 kr**	**201 520 119 kr**

Table 6.2: Netto present value: Sjursøya / Kårstø

Sjursøya has an insufficient wind resource to present a positive NPV even at an energy price level of 100 øre/kWh, while Kårstø presents healthy numbers at both price points. Once again, the importance of wind speed is observed, as can be further exemplified by the LCOE calculations of the two sites:

	Sjursøya	Kårstø
LCOE	**109.61 øre/kWh**	**55.18 øre/kWh**

Table 6.3: LCOE Sjursøya / Kårstø.

Energy production at Sjursøya is almost twice as expensive as energy production at Kårstø.

Visual impact:

Both locations may present issues related to visual impact. The wind turbines at Kårstø will possibly be visible from Stavanger, which might cause additional pushback. Similarly, Sjursøya is only a few kilometers south of Oslo, and the turbines will be visible from housing from all angles. The visual impact could result in significant backlash from the surrounding communities.

Noise pollution:

Noise is a major concern at Sjursøya as it falls below the proposed distance from housing. In contrast, Kårstø falls within the government's proposed ranges and is less likely to present any challenges with local communities.

7. Discussion

In this last section the main findings of the thesis will be discussed further. We will address the pros and cons of industrial wind projects. Moreover, the question of whether it is worth it to build down nature for the sake of wind power will be discussed.

The main findings of the thesis is the importance of wind quality when building a wind park. Both in terms of profitability and energy efficiency, a good wind resource is key. In a time when energy is a resource we need more of, it is clear why we build down nature to access the wind resources that have the highest potential. As mentioned in the technology section of this thesis, wind speed is crucial. A doubling of wind speed theoretically increases power output eightfold. The difference of 5 m/s at Sjursøya and ca 7 m/s at Kårstø leads to huge discrepancies in production.

Wind power is after all an attempt to get a sustainable future without the uncertainty of fossil fuels. In this effort the by far most important point is the middle wind speed. Both when discussing the economical and power aspect of a site, wind matters most. When examining our two potential wind parks at Sjursøya and Kårstø it becomes evident why we have built down so much nature for the sake of wind power generation.

The main costs of a wind park are always prevalent, the turbine itself is responsible for 70% of the investment costs for the whole project. Knowing that the costs will stay high, one needs good wind resources to compensate. This thesis does not state that good wind resources don’t exist in industrial environments, but that sites with beneficial attributes should be prioritized.

An interesting part of this thesis is the cost of rebuilding. As previously stated, it is written in the law that a wind farm developer must restore the nature after leaving the project site. NVE has, as shown, given estimations on the price of such an endeavor. What is interesting is that the cost of rebuilding nature is negligible when compared to the profitability of a properly situated windfarm.

This again sheds light on why industrial wind farms haven’t been a more attractive option in the past. It also says something about how much the state values nature. The developers given concessions does only have to pay whatever it costs to restore nature after 25 years. There is no payment needed for the “loss” of nature in the time the wind farm is operative. In other words, there is seemingly very little incentive to build in industrial areas. Or at the very least explore solutions which could make this more attractive.

At the end of the day the main findings of this thesis is that industrial wind simply isn’t efficient enough to compete with windfarms in remote areas. The difference in production numbers between the proposed industrial wind parks and traditional wind parks is severe. Sjursøya produced about 2 GWh per turbine while Kårstø produced about 5 GWh per turbine. In comparison, Geitfjellet, a wind park outside of Trondheim produces closer to 13 GWh per turbine per year (NVE, 2020). Another point is the sheer number of turbines you have the capability to fit in remote areas. Geitfjellet has installed 43 turbines which causes the wind site to produce more in one year than Sjursøya would do in its entire lifetime. The advantages of constructing wind parks in natural settings become evident through the economic benefits derived from the economics of scale, particularly in deploying a larger number of turbines.

8. Summary

This thesis aimed to evaluate the potential of industrial wind parks. To illustrate the viability of industrial wind parks, two potential site locations were presented, Kårstø and Sjursøya. Through careful evaluation of the two wind sites, we observed how they are unable to compete with already established wind parks such as Geitfjellet. While the energy and economic prospects of the proposed wind park are comparatively weaker than existing installations, they can be profitable and are theoretically viable to develop.

Sjursøya is an example of a site that is unlikely to be developed. As stated, the energy potential is lackluster. Secondly the visual impact in the center of our biggest city is sure to present too severe challenges to consider developing. Even if the visual pollution could be tolerated, the noise factor presents undisputable challenges which will cause the wind park to not be built.

Kårstø is an example of a site that could potentially be constructed. While the energy potential is comparatively much greater than Sjursøya, it is still not great enough to be competitively viable when compared to traditional wind parks. The visual impact is the biggest downside of Kårstø. The wind park’s location is visible from a large area and could affect many residents and tourists. The noise pollution is unlikely to cause issues in this example.

In summary industrial wind parks are a definite possibility, that given optimal attributes could potentially provide great value. However, it quickly becomes apparent why the prospect hasn’t been prioritized to a larger degree, given the more advantageous financial aspect of developing wind farms in nature.

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