Analysis of wind condition and power production from wind turbines on farms in Norway

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Glossary

Cp = Power coefficiency

GHG = Green House Gases

NORA3 = The 3 km Norwegian reanalysis

SSR = Self-sufficiency ratio

SCR = Supply cover ratio

LOLP = Loss of load probability

Ab = Energy autonomy

W = Watt

kW = Kilowatt

GW = Gigawatt

TW = Terawatt

kWh = Kilowatt hours

GWh = Gigawatt hours

TWh = Terawatt hours

Preface

This master's thesis was written from the fall of 2022 to the spring of 2023 as a final part of my master’s degree in Sustainability.

The thesis takes on the field of wind and wind power in Norway to map out the possibility of using wind power on farms in Norway by using the NORA3 wind dataset from the Norwegian Meteorological Institute.

As a part of the master’s program, I used knowledge from different fields to use interdisciplinary methods. As a result, I have been using past knowledge from my bachelor's in renewable energy and current areas learned from the master's program.

During the year that this thesis was written, was a challenge, as I had to learn the programming language Matlab from scratch.

The book interdisciplinary environmental studies by Gunilla Öberg have been at the core of the master's program and has been used throughout parts of the thesis.

Thanks to Asgeir Sorteberg for being a fantastic supervisor and assisting me with Matlab, which I had no prior knowledge of before this thesis. And thanks to my co-supervisor Hugo Jose Herrera de Leon, who gave me valuable input throughout the writing period.

Bergen

15.05.2023

Ole August Grøtte Rathke

Summary

Our world is heating up; we have reached a global temperature of 1.1 °C and will surpass the 1.5-degree target (NASA, 2023), and as the world increases its electrification, more power is needed. The current global electricity mix comprises 63.3 % of fossil fuel and 36.7 % of renewables (Ritchie, Roser, & Rosado, 2022). In Norway, our primary electricity source is from hydroelectric dams (Energifakta Norge, 2022); however, as more energy is needed and to meet the 2030 GHG emission target (Regjeringen, 2022), more renewable energy source has to be built (Nyhus, 2022). Is it possible to have wind turbines on farms to meet this future demand and help with the energy transition?

- **What is the wind and power generation potential on Norwegian farms?**

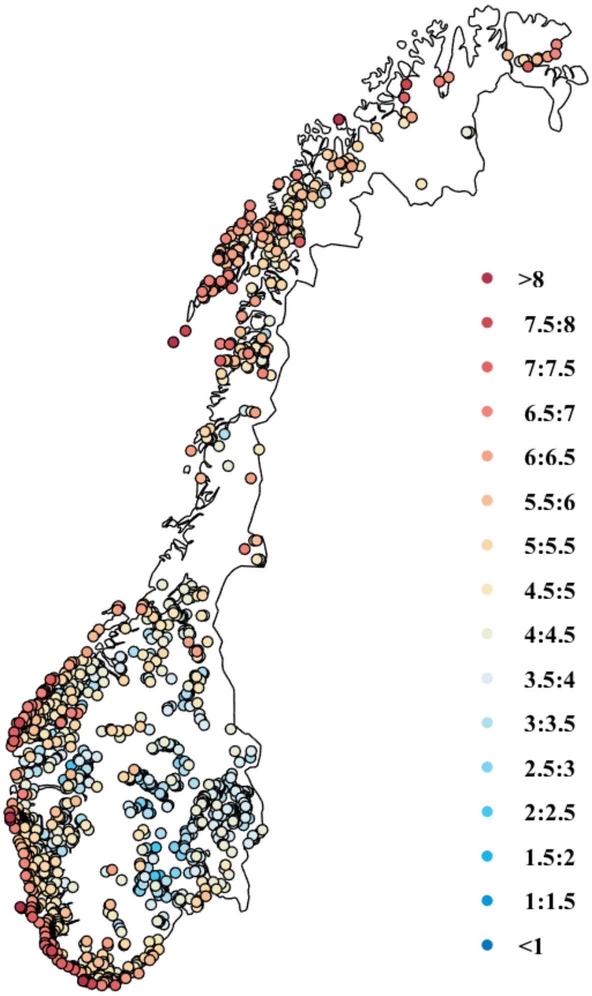


Figure 1: Average wind speeds at 40 meters for Norway in areas where there is agriculture.

With data taken from the NORA3 wind data set and map data on agricultural areas in Norway from Statistics Norway (SSB), I found the wind speed, at a height of 40 meters, for the major Norwegian agricultural areas between 2010 and 2018.

In my study I found that the best wind conditions are in Rogaland, with Nordland, Møre og Romsdal, Troms og Finnmark, and Agder having good wind conditions, especially near the coast . Vestland has medium good wind conditions while Trøndelag, Vestfold og Telemark, Viken, and Innlandet have the lowest wind speeds out of the 10 counties.

- **What is the typical power production potential for each county?**

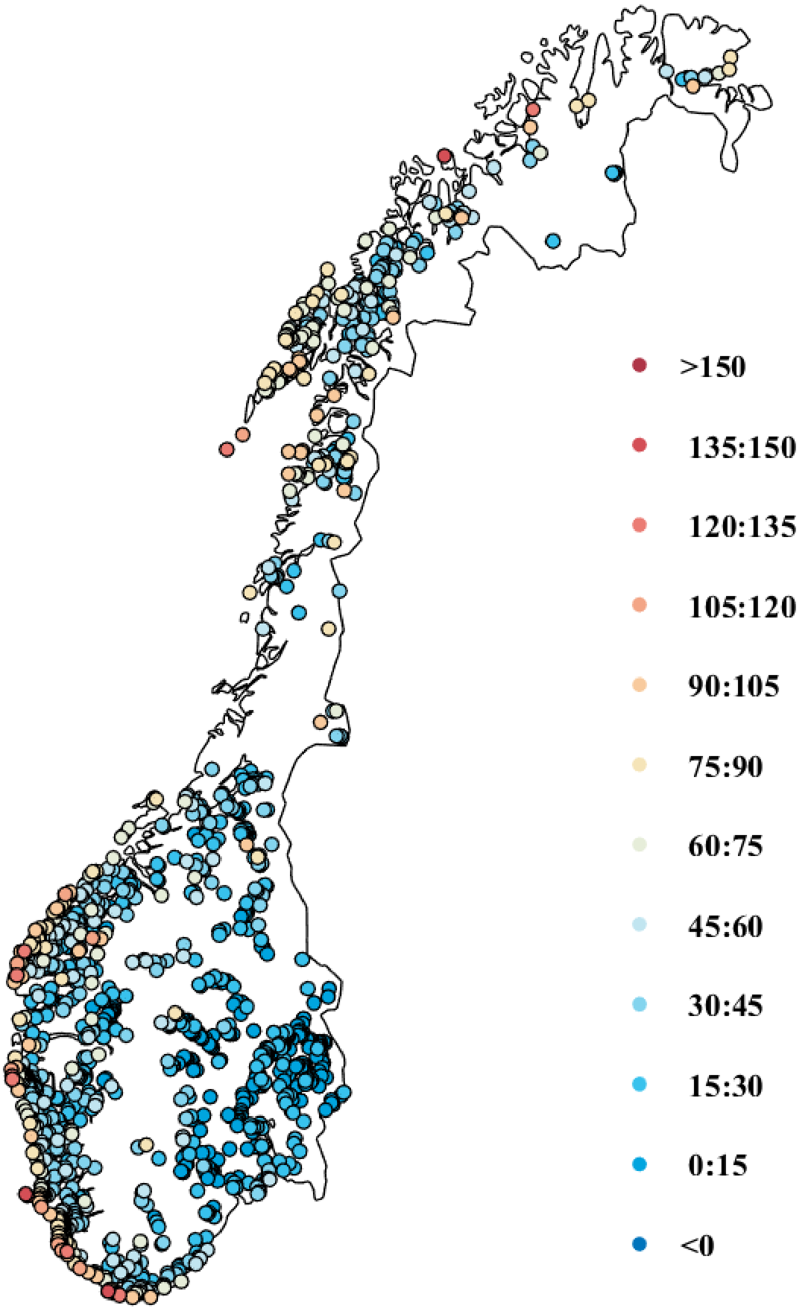


Figure 2: Maps showing the hourly electricity generated (kW) for the Vestas V39 wind turbine.

Hourly wind data from 2010 to 2018 was used to calculate the power generated by the turbine. The data presented on the map are in kWh, meaning that this is the energy each turbine generates during one hour on average.

Three turbines were selected; however, the Vestas V39 turbine has the potential to extract the most out of the wind available. Though the T100 turbine has the lowest power coefficiency, we can still expect it to perform better in lower wind situations due to its lower cut-in wind speed.

- **How does it compare to the power demand for a typical milk barn and household?**

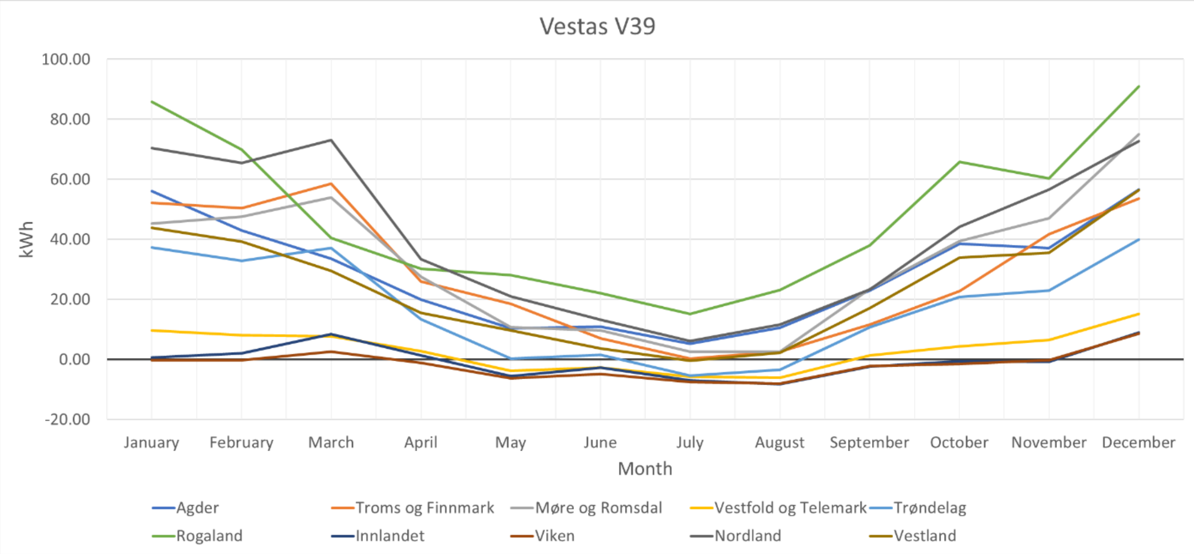


Figure 3: Graph showing the average sum of Vestas V39 power production plus the power demand of the milk barn and household.

The V39 turbine can generate enough energy for the farm in most of the counties. We can see that *Vestfold og Telemark* can generate enough electricity except from April to September. *Innlandet* and *Viken* can generate enough power in February, March, and December. *Trøndelag* also does not have enough wind for the V39 to meet demand in July and August. *Rogaland*, *Nordland*, *Troms og Finnmark*, *Møre og Romsdal*, *Agder*, and *Vestland* can meet the power demand of the farm during all months.

- **What sustainability issues can turbines cause?**

Wind turbines are a renewable energy source with no emissions during operation. Large-scale wind turbines emit 11 grams of CO_2/kWh and coal 980 grams of CO_2/kWh. A medium-scale turbine (500 kW) emits approximately 30 grams of $CO_{2\text{-eq}}$/kWh, and a 100 kW turbine releases approximately 55 grams of $CO_{2\text{-eq}}$/kWh (Mendecka & Lombardi, 2019). So, the smaller the turbine, the more CO_2 it will release during its lifetime. The fact that wind turbines can contribute to cleaner and more affordable energy does not mean that they are not harmful. Some of the SGDs can conflict with the gathering of material for the construction, operation, and the end of life for wind turbines.

Wind turbine uses various metals for its construction. These metals are a finite resource and will run out eventually. Many renewable technologies rely on these metals, including wind turbines (Hayes, 2020).

To meet demand future demand for metals, companies are exploring the potential of seafloor mining as the demand for these rare metal increase with the demand for more renewable energy sources. However, though sea floor mining might sound like a good idea to meet future demand, it is unknown territory, and we do not know the consequence the mining activities will have on fish and plants and the ecosystem.
Sediments can be kicked up during mining activity which then gently drop to the ocean floor again; however, due to ocean currents, these sediments can travel long distances past the mining area. This might cover plants and ocean-dwelling creatures with the sediments, limiting their feeding ability.

It is undoubtedly that wind turbines cause deaths among local fauna, and the placement of these turbines is related to this. Wind turbines on farms will likely have less impact on local fauna due to the turbine's smaller size and location. Current wind farms are placed primarily in areas untouched by humans; farms are in areas with human activities, and there is less likelihood that this will disturb feeding grounds for reindeer and flying predators.

Abstrakt

Verden vår varmes opp; vi har nådd en global temperatur på 1,1 °C og vil overgå 1,5-gradersmålet (NASA, 2023), og etter hvert som verden øker sin elektrifisering, trengs det mer energi. Den nåværende globale elektrisitetsmiksen omfatter 63,3 % fossilt brensel og 36,7 % fornybar energi (Ritchie, Roser, & Rosado, 2022). I Norge er vår primære strømkilde fra vannkraft (Energifakta Norge, 2022); men ettersom det trengs mer energi og for å nå 2030-målet for klimagassutslipp (Regjeringen, 2022), må det bygges flere fornybare energikilder (Nyhus, 2022). Er det mulig å ha vindturbiner på gårder for å møte denne fremtidige etterspørselen og hjelpe til med energiomstillingen?

- **Hva er vind- og kraftproduksjonspotensialet på norske gårder?**

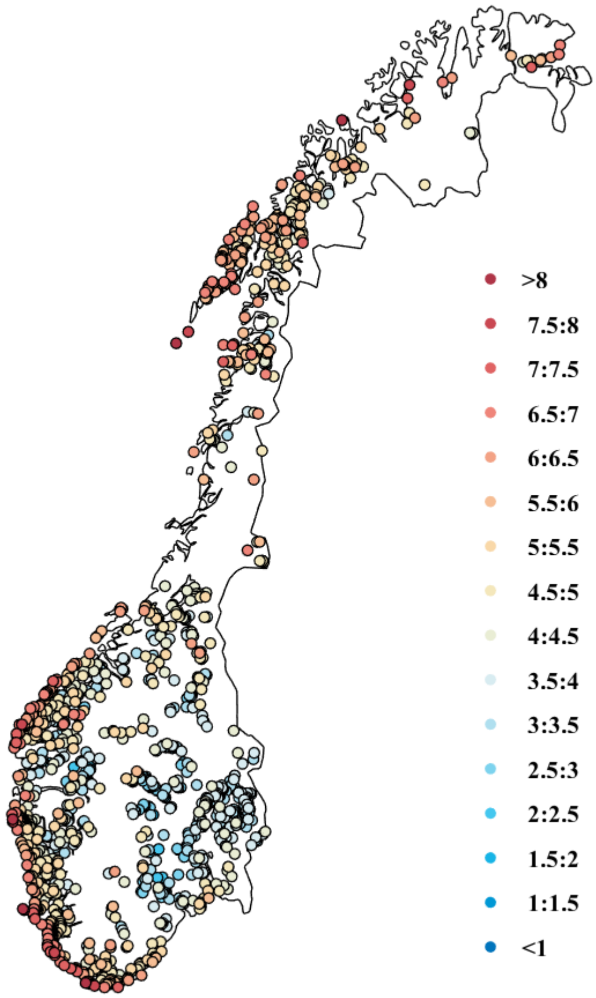


Figure 4: Gjennomsnittlig vindhastighet i 40 meter høyde for Norge i områder hvor det er jordbruk.

Med data hentet fra NORA3 vinddatasett og kartdata over jordbruksarealer i Norge fra Statistisk sentralbyrå (SSB), fant jeg vindhastigheten, i 40 meters høyde, for de store norske jordbruksområdene mellom 2010 og 2018.

I min studie fant jeg at de beste vindforholdene er i Rogaland, med Nordland, Møre og Romsdal, Troms og Finnmark og Agder som har gode vindforhold, spesielt nær kysten. Vestland har middels gode vindforhold, mens Trøndelag, Vestfold og Telemark, Viken og Innlandet har de laveste vindstyrkene av de 10 fylkene.

- **Hva er det typiske kraftproduksjonspotensialet for hvert fylke?**

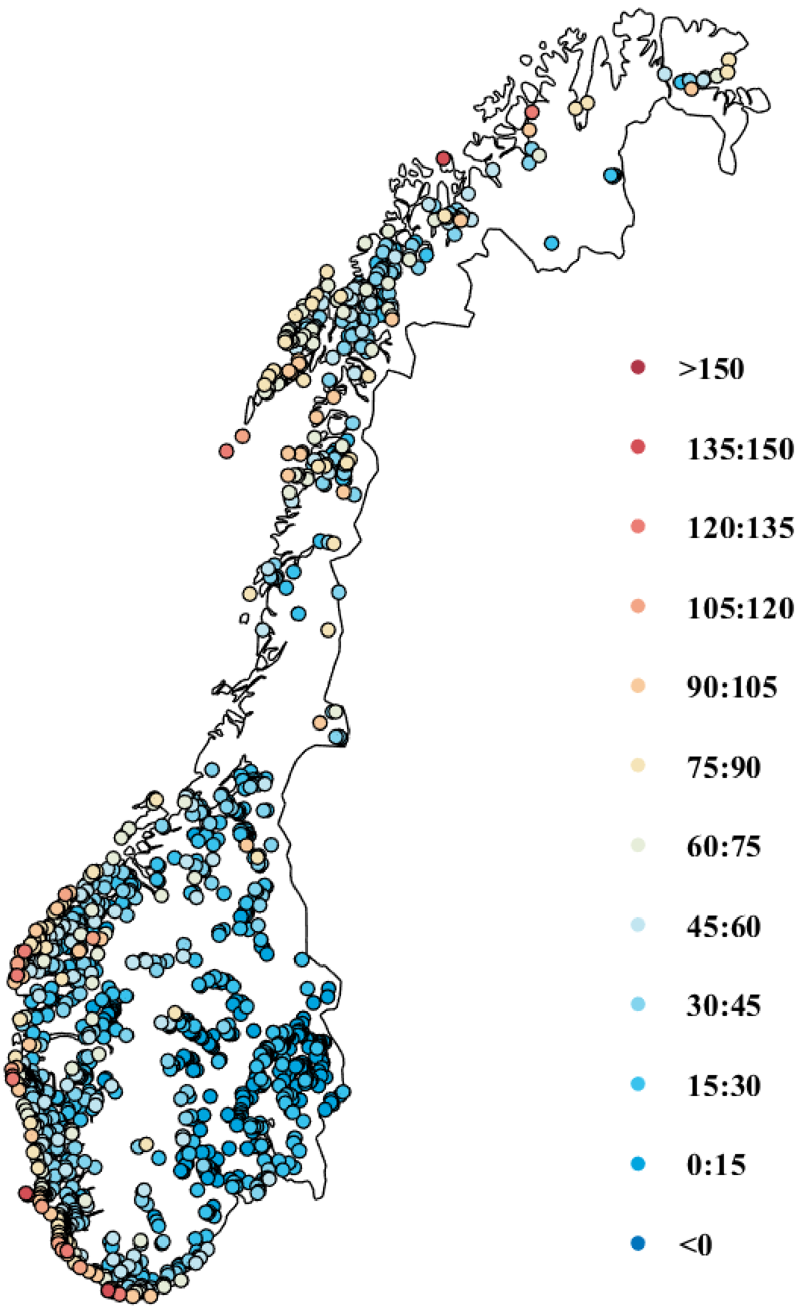


Figure 5: Kart som viser strøm produsert (kWh) hver time for Vestas V39 turbinen.

Timevis vinddata fra 2010 til 2018 ble brukt for å beregne kraften som genereres av turbinen. Dataene som presenteres på kartet er i kWh, noe som betyr at dette er energien hver turbin genererer i løpet av en time i gjennomsnitt.

Tre turbiner ble valgt, men Vestas V39-turbinen har potensial til å trekke ut mesteparten av den tilgjengelige vinden. Selv om T100-turbinen har den laveste effektkoeffisienten, kan vi fortsatt forvente at den vil prestere bedre i situasjoner med lavere vind på grunn av den lavere *cut-in* vindhastigheten.

- **Hvordan er det i forhold til strømbehovet for et typisk melkefjøs og husholdning?**

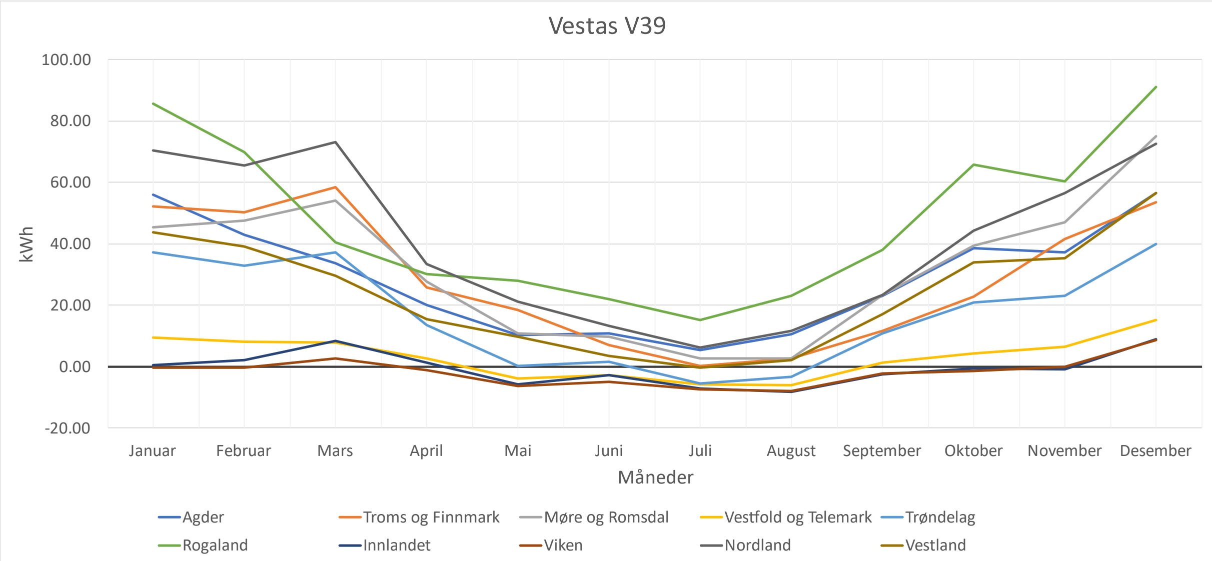


Figure 6: Graf som viser gjennomsnittlig sum av Vestas V39-kraftproduksjon pluss strømbehovet til melkefjøset og husholdningen.

V39-turbinen kan generere nok energi til gården i de fleste fylkene. Vi kan se at Vestfold og Telemark kan produsere nok strøm bortsett fra april til september. Innlandet og Viken kan produsere nok strøm i februar, mars og desember. Trøndelag har heller ikke nok vind til at V39 kan møte etterspørselen i juli og august. Rogaland, Nordland, Troms og Finnmark, Møre og Romsdal, Agder og Vestland kan møte kraftbehovet til gården i alle månedene.

- **Hvilke bærekraftsproblemer kan vindturbiner forårsake?**

Vindturbiner er en fornybar energikilde uten utslipp under drift. Storskala vindturbiner slipper ut 11 gram CO2/kWh og kull 980 gram CO2/kWh. En mellomstor turbin (500 kW) slipper ut omtrent 30 gram CO2-eq/kWh, og en 100 kW turbin slipper ut omtrent 55 gram CO2-eq/kWh (Mendecka & Lombardi, 2019). Så jo mindre turbinen er, jo mer CO2 vil den frigjøre i løpet av levetiden. At vindturbiner kan bidra til renere og rimeligere energi, betyr ikke at de ikke er skadelige. Noen av SGD-ene kan komme i konflikt med innsamling av materiale for konstruksjon, drift og slutten av levetiden for vindturbiner.

Vindturbinen bruker forskjellige metaller for sin konstruksjon. Disse metallene er en begrenset ressurs og vil gå tom til slutt. Mange fornybare teknologier er avhengige av disse metallene, inkludert vindturbiner (Hayes, 2020).

For å møte fremtidig etterspørsel etter metaller, utforsker selskaper potensialet til havbunnsgruvedrift ettersom disse sjeldne metallene øker med etterspørselen etter flere fornybare energikilder. Men selv om gruvedrift på havbunnen kan høres ut som en god idé for å møte fremtidig etterspørsel, er det ukjent territorium, og vi vet ikke hvilken konsekvens gruvevirksomheten vil ha på fisk og planter og økosystemet.

Sedimenter kan sparkes opp under gruveaktivitet som deretter forsiktig faller ned på havbunnen igjen; På grunn av havstrømmer kan imidlertid disse sedimentene reise lange avstander forbi gruveområdet. Dette kan dekke planter og havlevende skapninger med sedimentene, noe som begrenser deres evne til å mate.

Det er utvilsomt at vindturbiner forårsaker dødsfall blant lokal dyrebefolkning, og plasseringen av disse turbinene henger sammen med dette. Vindturbiner på gårder vil sannsynligvis ha mindre innvirkning på lokal dyrebefolkning, på grunn av turbinenes mindre størrelse og plassering. Nåværende vindparker er hovedsakelig plassert på områder uberørt av mennesker; Gårdene ligger i områder med menneskelig aktivitet, og det er mindre sannsynlighet for at dette vil forstyrre foringsplassen for rein og flygende rovdyr.

1. Introduction

Our planet is approaching a global temperature increase of 1.5 °C compared to pre-industrial temperatures (NASA, 2023). The world's current electricity mix comprises 63.3 % fossil fuel and 36.7 % renewables (Ritchie, Roser, & Rosado, 2022). There is a need for more energy in Norway as more gets electrified (Nyhus, 2022). In Norway, the majority of the electricity mix is from hydroelectric dams. Recently we have started installing more wind farms, a controversial topic which is often in much discussion. More people want turbines offshore and are mixed on wind turbines on land. Though this was not true in 2014, people were generally more positive towards wind turbines on land. (Gregersen, 2022). However, today turbines are mostly placed on mountain ranges due to higher wind speed in those areas and fewer obstacles to block the wind. As a by-product they are visible from long distances, disturbing the natural landscape. Are there possibilities for wind turbines on farms that are often situated in lower-lying areas less ideal for wind power production?

Most farmers have a more substantial power need than an average household and a more usable land area. Would it be beneficial for these farmers to install a wind turbine to generate power for the farm and potentially nearby houses? Early adoption of solar and wind has lowered the cost dramatically over the past years.

1.1 Research question and structure

This thesis is part of the master's in Sustainability with a specialization in climate change and energy transition. With this, the main research question that I will tackle is:

- How significant is the wind and power generation potential on Norwegian farms?

Secondary questions:

- What is the typical power production potential for each county?
- How does it compare to the power demand for a typical milk barn and household?
- What sustainability issues can turbines cause?

The thesis structure follows the IMRAD model, beginning with an introduction where I will introduce topics surrounding wind turbines and the law associated. A theory part for more technical topics about wind turbines. Data and methods to show what data was collected and how it was used, then results and ending with a discussion part.

1.2 Sustainability

Sustainability can have different meanings depending on whom you ask. In my field of climate change and energy transition, Sustainability can be described as a way to preserve the planet and its resources for future generations. Sustainability can also be defined as a wicked problem, a term first introduced by Horst Rittel and Melvin Webber (Rittel & Webber, 1973). Wicked problems have a set of characteristics that defines them. In the paper by Rittel and Webber, they describe ten of these,

"(1) There is no definitive formulation of a wicked problem.
(2) Wicked problems have no stopping rule.
(3) Solutions to wicked problems are not true-or-false, but good-or-bad.
(4) There is no immediate and no ultimate test of a solution to a wicked problem.
(5) Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
(6) Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
(7) Every wicked problem is essentially unique.
(8) Every wicked problem can be considered to be a symptom of another problem.
(9) The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
(10) The planer has no right to be wrong." (Rittel & Webber, 1973)

Though all of these are not relevant to a sustainability issue, they are still a challenge to solve. In 2015 the United Nations (UN) founded the Sustainable Development Goals (SDGs) to solve these issues for our planet and its people. There are 17 SDGs, all tackling different paths towards Sustainability. (UN, n.d.)

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure

10. Reduce inequalities
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice and strong institutions
17. Partnerships for the goals

1.3 Wind turbines on farms in Norway

There are a few sites in Norway where turbines are placed on farms. Solvind has some ongoing projects; one of them is Åsen 2. Placed south of Stavanger, near Bryne, Åsen farm installed two 800 kW wind turbines in 2012. Yearly they produce 4,2 GWh, enough to power 280 households annually. Public opinion on these turbines has been mostly positive and has not affected nearby recreational areas. (Solvind Prosjekt AS, n.d.)

Figure 7: The picture shows two wind turbines at Åsen farm. Photo taken from (Solvind Prosjekt AS, n.d.)

On Langøren farm at Byneset outside Trondheim, a 225 kW turbine and 450 m^2 of PV cells were installed in 2015. The turbine powers the farm and produces hydrogen from both excess electricity not used. The hydrogen is made from water through electrolysis and then stored. When energy is needed, a fuel cell can turn the hydrogen and oxygen from the air into water and electricity. (Nilsen, 2021)

South-east of Åsen 2 in Undheim, is a farm that installed a 45 kW wind turbine in 2012. The farmer, Svein Ove Risa, says the turbine has a yearly production of 105 000 kWh. This was expected to be higher; however, the turbine has suffered lengthy downtimes due to technical problems with the gearbox, turbine blades, and other components. Although the turbine cost was around 800 000 NOK, including the shipping, groundwork, cabling, and installation, the price is closer to one million NOK. According to the owner, the farm can use up to 90% of the power generated for its own use, which is more profitable than selling the electricity to the grid. (Norgesvel, n.d.)

1.4 Challenges with wind turbines

Intermittent winds

Wind turbines dependent on strong winds to produce the most power, making the power output variable, as the wind often changes speed and direction. This can cause issues when the energy needed is higher than the turbine can generate. (Energysage, 2022)

Noise

A turbine's noise can be a minor distraction if only heard for a short duration; however, the swishing and whistling of a turbine can become an annoyance for prolonged periods. A turbine makes two forms of noise, aerodynamical and mechanical. The aerodynamic noise comes from the blades, both from the rotation and turbulence. The rotational noise is tied to the size of each blade, the number of blades, and the pitch of the blades. Meaning the more wind a turbine captures, the more noise it makes. Mechanical noise comes from the system inside the hub (gearbox and generator). (Tummala, Velamati, Sinha, Indraja, & Krishna, 2015)

Visibility and recreation

Wind turbines' large size, height, and colour make them stand out from the environment where they are placed, causing many to use the term NIMBY (not in my backyard) as a slogan against wind turbines. (Tabassum-Abbasi, Premalatha, Abbasi, & Abbasi, 2013)

The shadows turbines cast can cause shadow flickering depending on the sun's position and intensity. The positioning of the turbines determines the intensity of the flickering (Sayed, et al., 2020). The turbines must be lit up to be visible to aircraft, making them visible to everyone else during nighttime.

The turbine's size means they are often distracting and, in the worst cases, can destroy local recreational areas such as hiking paths. In addition, roads leading to wind farms are often noticeable and can cross these hiking paths.

Wildlife impact

Due to the size of a turbine, there is unavoidable damage to local fauna, especially birds and bats. Turbines placed in areas where there are feeding and hunting areas for birds are causing a significant amount of bird deaths among predators. Most of this knowledge has been derived from countries where wind power is more widespread, such as the USA (Bevanger, May, & Stokke, 2017). Another flying predator that is that has had a significant local population decrease is bats. The bat deaths are primarily associated with the pressure variations from the spinning blades, resulting in barotrauma, where the lung expands causing damage and internal bleeding (Baerwald, D'Amours, Klug, & Barclay, 2008). The most discussed topic regarding turbine and their impact on fauna in Norway is the reindeer. The reindeer, specifically tame reindeer are one of the major arguments against wind turbines. The turbines affect the reindeers grazing land, which has been an important discussion recently due to the wind farm in Fosen. (Bevanger, May, & Stokke, 2017)

1.5 Laws and licences

Some laws need to be followed to construct wind turbines in Norway, and governmental foundations need to approve the placement and construction of wind turbines. Most application for the construction of wind turbines goes through NVE. An application must go through multiple steps and criteria to be approved. These steps differ depending on the capacity of the wind turbines.

Depreciation

Depreciation is a way to reduce a long-term investment's value gradually; this is done so that the buyer gets the correct tax deduction from the investment. Since turbines are an expensive long-term investment, they can be depreciated. Depending on the uses, the depreciation rate of the turbine varies.

Balance group	**Depreciation rate**	**Description**

H	4 – 6 – 10 %	Facility which is primarily used for heating for production.
J	10 %	Facility which is installed in or adjacent to a farm building which must cover the building's general needs as a building.
D	20 %	Facility which is mainly used for the production of heat which then gets sold.
D	20 %	Piping inside a farm building where heat is used in the production.
J	10 %	Piping in adjacent to building where heat must cover the building usability.
Private	Not depreciable	Private use over 50 %

Table 1: Table showing the different depreciation rates. (Gjølstad, 2023)

Table 1 shows different depreciation rates for different renewable investments. For a wind turbine, the balance group depends on what the turbine will be used for. If more than half of the turbine's capacity covers the farm building's needs to function normally, it falls under group J with a depreciation rate of 10 %. If half the turbine's production is used to sell power to the energy grid, it will go under group D with a 20 % depreciation rate. (Gjølstad, 2023)

Sale of electricity to the grid

If a person is a consumer and producer of electricity and connected to the energy grid, they are a *"plusskunde".* They do not pay a fee to sell power to the grid as long as the amount does not at any time exceeds 100 kW. If the electricity exceeds 100 kW, 1.36 øre/kWh VAT excluded (as of 2023) for all the power sold to the grid must be paid. (Norges vassdrags- og energidirektorat, 2023)

Less than 1 MW

If a person (or company) plans to produce less than 1MW of electricity and have no more than five turbines, they can apply for a licence through their local municipality. This application is less strict than for larger production of electricity. (Olje- og energidepartementet, kommunal- og moderniseringsdepartementet, 2015)

Less than 10 MW

If the builder applies for a license to install a wind farm between 1MW and 10MW, the application will go through NVE. The application needs to have an impact assessment for landscape, fauna, flora, and cultural value contributed by the turbine(s) as part of the application. (Noregs vassdrags- og energidirektorat, n.d.)

More than 10 MW

Like smaller wind farms, the builder must apply for a license. However, for wind farms larger than 10MW, this application needs to be significantly more in-depth. First, a notice must be sent to NVE. If it gets accepted, the builder must produce a detailed impact assessment for nearby fauna and flora and the consequences for the nearby population (shadow cast, noise, and visibility). The builder then sends in an application and the impact assessment to NVE. After NVE has considered the application and it is of sufficient quality, a notice gets sent to the nearby population. Where people can talk to the builder to bring up complaints towards the project; if a compromise is reached, the builder can start installing wind turbines. (Noregs vassdrag- og energidirektorat, n.d.)

2. Theory

2.1 Wind Turbines

For many years humans have taken the kinetic energy from water and wind into mechanical energy, be it to make flour from wheat or to drive machinery like saws. A wind turbine functions on the same principle. They consist of a few main parts to achieve energy conversion. Starting with the turbine blades, the blades work similarly to an aircraft wing, meaning they create lift to take some of the energy in the wind and turn it into mechanical energy that rotates a shaft. The shaft is then connected to a gearbox, increasing the rotation speed on a second shaft connected to a generator. The generator then turns the mechanical energy into electrical energy. Smaller turbines often do not have a gearbox, instead connecting the blades directly to the generator with one shaft. (Watson, 2015) The performance of a turbine is shown as cut-in, rated wind speed, cut-out, rated power, and power coefficient. The turbine cut-in is what the minimum wind speed needs to be for the blades to start spinning and start generating electricity. The rated wind speed is the wind speed at which the turbine will not generate more electricity than the rated power. When the wind speed increases, the turbine will stop generating electricity to protect itself, known as cut-out. The rated power is the maximum power output, at rated wind speed, that the turbine can generate. .

Wind power

A turbine's power production is determined by the power that is in the wind. This can be calculated with the following equation.

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

Equation 1: Equation for calculating the power in the wind.

Where ρ is the air pressure at sea level (1.225 kg/m^3), A is the area, and u^3 is the air velocity squared. P refers to the power in the wind (W).

Wind turbine power coefficient

The power coefficiency tells us how efficient every part of a system is together. For a wind turbine, the efficiency of the system would depend on the efficiency of the blades, gearbox, and generator. Both gearbox and generator are often very efficient (≥90%), with the blades being the least efficient part of the system. The Betz Limit limits the blade efficiency.

Each selected turbine has different efficiencies; a coefficiency graph can be made to better understand each turbine's capabilities. This can be done with the following formula:

$$Cp = \eta_t * \eta_m * \eta_e$$

Equation 2: Overall turbine efficiency. Where ηt is turbine efficiency, ηm is mechanical efficiency, and ηe is electrical efficiency.

Power coefficiency can also be found by taking the power produced by the turbine (P_{out}) and dividing it by the power in the wind (P_{in}), we can calculate the Cp:

$$Cp = \frac{P_{out}}{P_{in}}$$

Equation 3: Finding coefficiency with how much power the turbine generates and how much power is in the wind.

P_{out} is the turbine power output, and P_{in} is the power in the wind, which can be calculated with Equation 1.

The Betz Limit

German physicist Albert Betz created the Betz limit. It states that the efficiency of the blades on a turbine cannot excide 59.2% efficiency. No matter how efficient a wind turbine is, it can never convert over half of the wind's kinetic energy into electrical energy.
The Betz Limit is an essential theoretical concept in wind energy but is not a strict limit in practice. In reality, most wind turbines cannot achieve the Betz Limit due to various factors such as wind turbulence and blade drag. However, the Betz Limit provides a useful theoretical benchmark for comparing the performance of different wind turbine designs. (REUK.co.uk, n.d.)

2.2 Energy storage

Wind energy has one critical flaw: they do not produce a constant source of electricity. A wind turbine could produce no electricity when energy is needed the most. Storing energy for later use can solve this. There are different ways of storing energy for later use; one of the more used solutions is batteries. They have the benefit of being inexpensive and at the forefront of innovation. (ACCIONA, n.d.) However, current battery tech suffers from capacity loss as they age and have varying charging rates. They do not charge at constant speeds from 0% to 100%. Batteries charge quicker when their Battery State of Charge (BSOC) is low and slow when the BSOC is high (≈80%).

Additionally, batteries are often limited to not reaching full charge on the battery to avoid rapid degradation. (Korthauer, 2018) (Honsberg & Bowden, 2019)

2.3 LCA

LCA (life cycle assessment) determines the total release of GHG throughout the life of an object, in this case, a wind turbine. It can be used to find the total emissions of a turbine, find improvements in its life, and see if a turbine's lifetime energy production is lower than fossil fuel energy production when it comes to lifetime emissions. (NORSUS, n.d.)

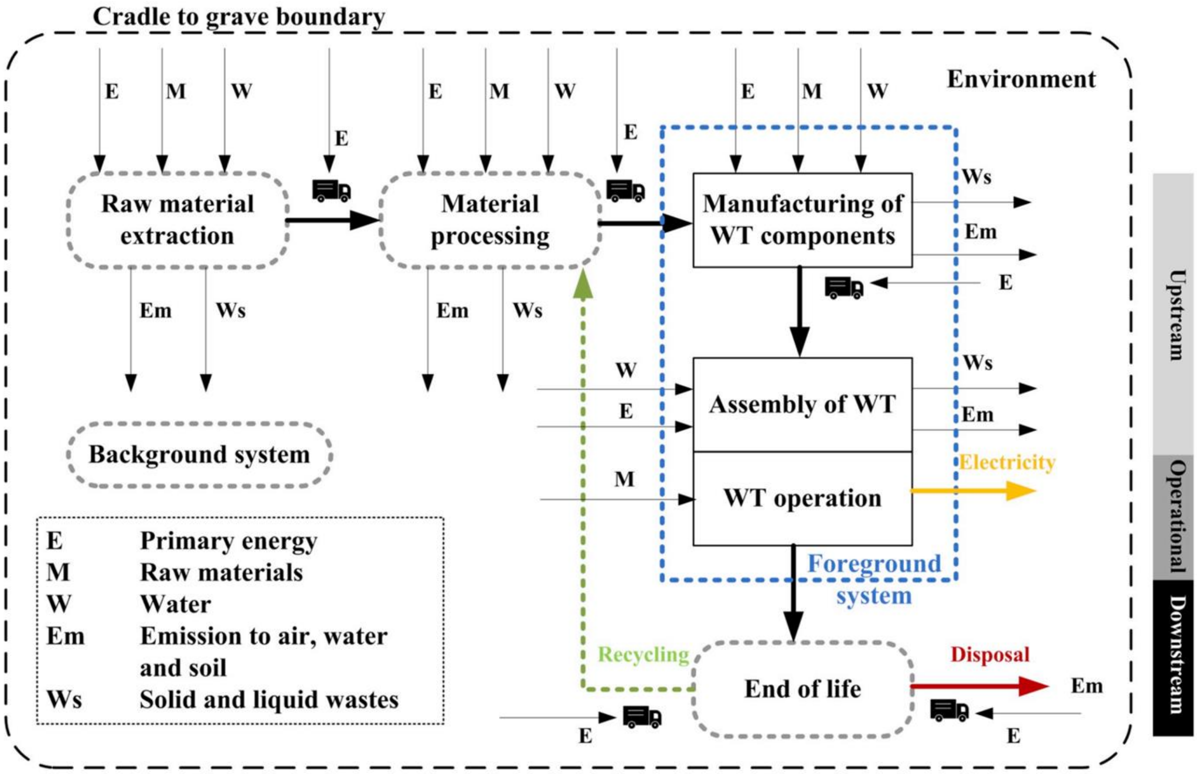


Figure 8:This show the life cycle of a wind turbine, with inputs and outputs. (Mendecka & Lombardi, 2019)

The figure above is a simple visualization of the cradle-to-grave LCA (starting with the raw materials used in the production to the end of the turbine's life, where it is decommissioned). The image goes through every major step in a wind turbine's construction, starting with the raw materials extraction. These are the unprocessed materials such as copper, iron, oil, sand, and rare earth metals such as neodymium. (Podmore, 2022) These raw materials are then transported by land or sea to be processed. These materials are processed into steel, fibreglass, plastics, and aluminium. These materials are used to manufacture each turbine component, such as the blades, generator, and electronics. These are then transported to where the turbine will be installed. When the turbine reaches the end of its life, it can be either recycled or disposed.

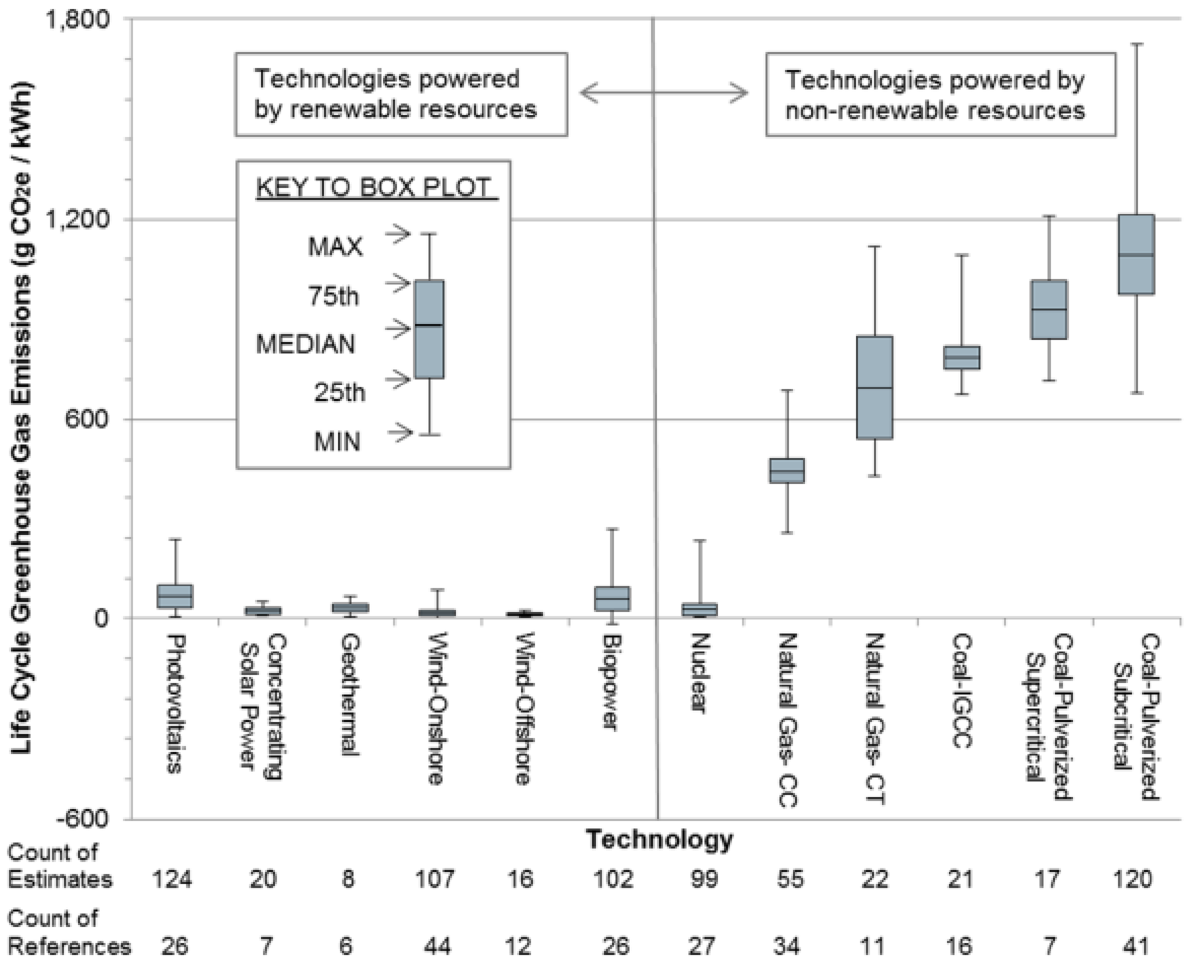


Figure 9: The image above shows the CO_2 released from different energy sources (Mai, et al., 2012).

The figure shows the different energy sources and their CO_2 equivalents released during their lifetime. Wind turbines release the least amount of CO_2 during their lifetime compared to other renewable technologies.

3. Method and Data

This thesis is based on the NORA3 wind dataset and Matlab software/coding language to make graphs and tables to show the results. Before this thesis, I had no experience with Matlab and was assisted by my primary supervisor.

This is an interdisciplinary study, where interdisciplinary means.

"Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice."
(National Academies of Sciences, Engineering, and Medicine., 2005, p.2)

The methods I used are primarily from using my knowledge in renewable energy, mathematics, and coding.

The book Interdisciplinary Environmental Studies by Gunilla Öberg (Öberg, 2011) has be used a guide to the interdisciplinary work done here. By positioning myself as a "*Navel-gazer*", on the reflection scale (p. 26), I believe I can find potential outcomes, meanings, and implications from this thesis.

3.1 Data

NORA3 Dataset

The wind and temperature data were retrieved from the NORA3 reanalysis. The NORA3 data set is a high-resolution reanalysis from the Norwegian Meteorological institute. It has a resolution of a three-by-three km grid that covers the Nordic countries and divides the atmosphere into 65 vertical layers. The data is hourly and covers the period 1979 to present (Haakenstad, et al., 2021).
I gathered 10- and 50-meter wind speed data from the research to later be interpolated to match a turbine's hub height. Temperature data at 2 meters was gathered to correctly calculate power usage by considering outside temperatures. Wind data coordinates for every location where the wind was measured were also gathered. The data is hourly, between 2010 to 2018.

Turbines

The turbines selected for this thesis were selected by their ability to perform differently at low- to high-wind speeds. These turbines have differing cut-in, rated, and cut-out wind speeds. Where cut-in is the lowest wind speed where the turbine can spin and generate electricity. Rated wind speed is where the turbine starts performing at rated capacity. Cut-out wind speed is the maximum wind speed that the turbine can handle before shutdown.

Argolabe Ingeniería T100

The T100 is made by Argolabe Ingeniería with a rated power of 100 kW. It stands 22.5 meters tall with a cut-in speed of 3.5 m/s, a rated speed of 10.5 m/s, and a cut-out speed of 20 m/s. (Argolabe Ingeniería, n.d.)

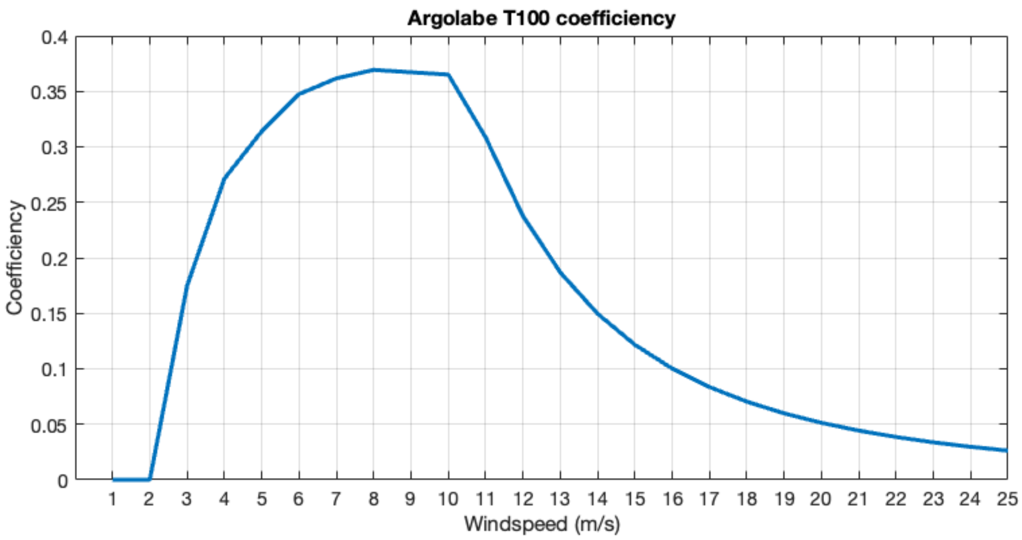


Figure 10: Graph showing a Argolabe T100 turbine coefficiency.

ACSA A27/225

The ACSA A27/225 is a 225 kW wind turbine made by ACSA Aerogeneradores Canarios, S.A. It features a height of 45.7 meters with a cut-in speed of 3.5 m/s, a rated speed of 13.5 m/s, and a cut-out speed of 25 m/s. (Wind Turbine Models, 2022)

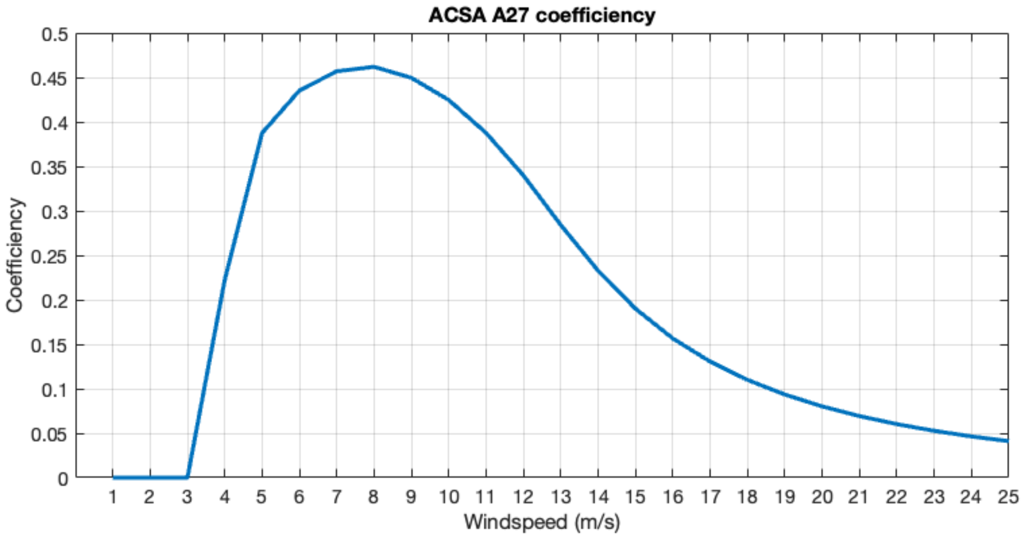


Figure 11: Graph showing the ACSA A27 turbine coefficiency.

Vestas V39

The Vestas V39, made by Vestas Wind Systems A/S, is rated for 500 kW. It is 40.5/53 meters tall and has a cut-in speed of 4 m/s, a rated speed of 15 m/s, and a cut-out speed of 25 m/s. (Wind Turbine Models, 2017)

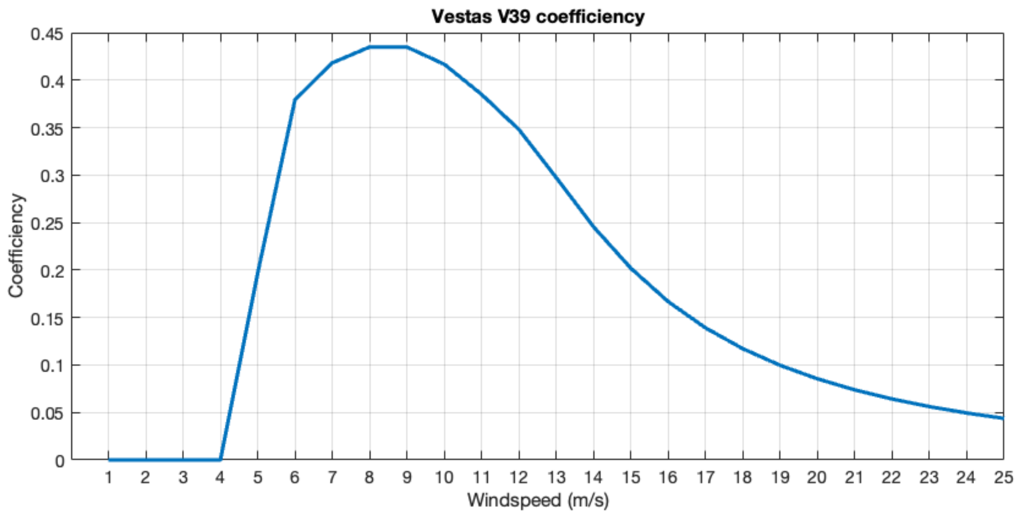


Figure 12: Graph showing the Vestas V39 turbine coefficiency.

Turbine specifications				
Variable	**Argolabe Ingenieria T100**	**ACSA A27/225**	**Vestas V39**	**Unit**
P_{rated}	100 000	225 000	500 000	Watt
D	22.5	27	39	Meter

h_{hub}	34	45.7	53	Meter
$u_{cut\text{-}in}$	3.5	3.5	4	m/s
u_{rated}	10.5	13.5	15	m/s
$u_{cut\text{-}out}$	20	25	25	m/s

Table 2: Table showing the specification of the three turbines, P_{rated} is the turbines max power output in Watts and D is the diameter of the rotor.

3.2 Method

Location selection

Wind and temperature data were extracted from locations where agricultural activity is taking place by selecting areas having a high density of agricultural properties using the one-by-one km grid map of agricultural properties (landbrukseiendommer (AGP)) in Norway, taken from SSB (Statistisk sentralbyrå, 2020). Areas having more than ten properties per 1 km^2 were selected.

County	**Data-points**
Agder	89
Oslo	0
Troms og Finnmark	129
Møre og Romsdal	139
Vestfold og Telemark	55
Trøndelag	96
Rogaland	103
Innlandet	191
Viken	72
Nordland	146
Vestland	243

Table 3: Table showing the number of data points for each county.

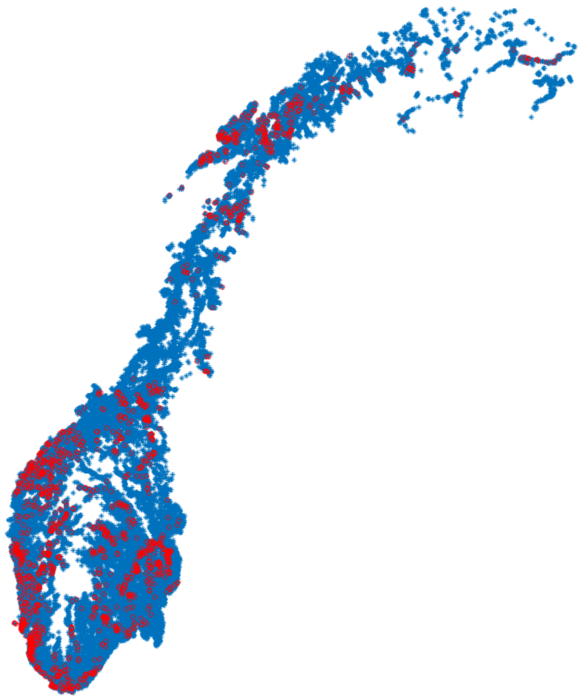


Figure 13: Map of agricultural lacations.

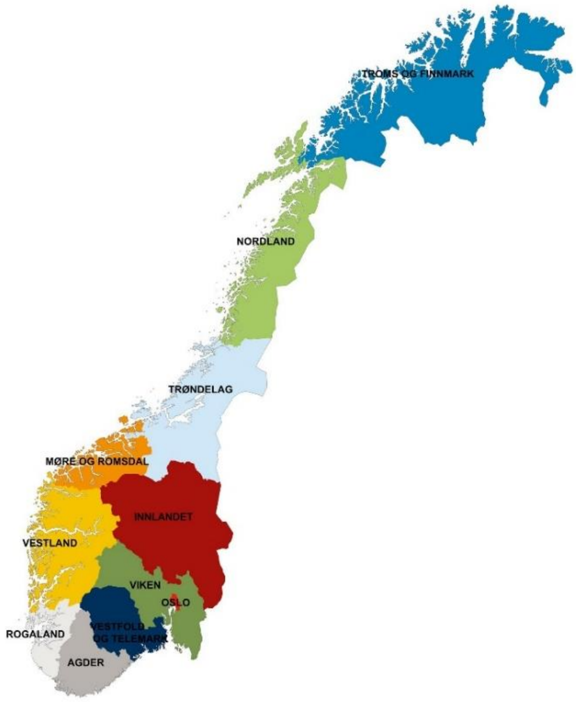


Figure 14: Map of Norway's counties (as of 2023). (Kommunal- og distriktsdepartementet, 2019)

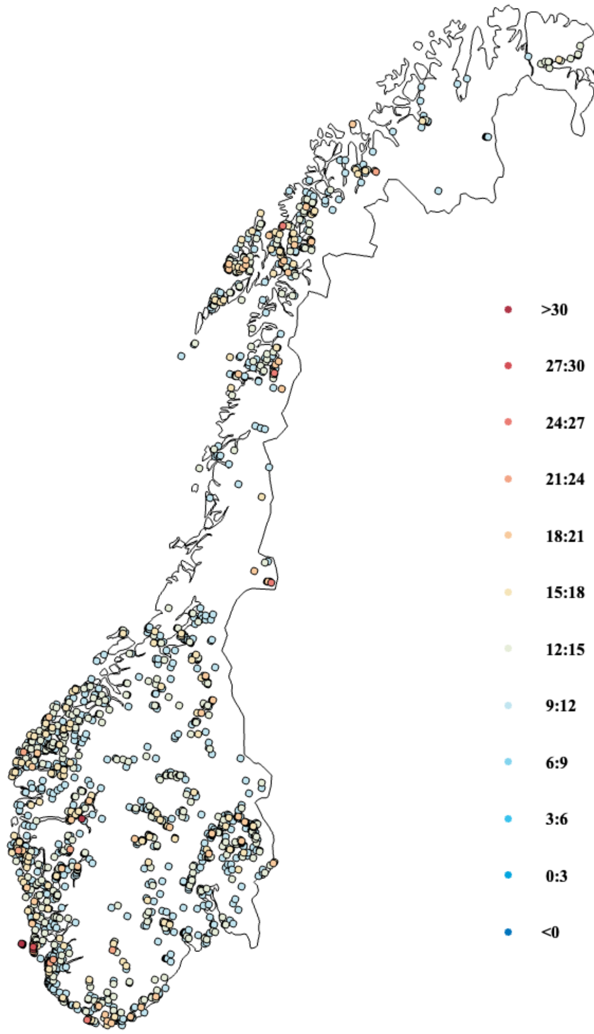


Figure 15: Maps showing the number of farms per data-point (1x1 km^2).

Figure 13 shows the locations of agricultural properties; highlighted in red are the regions that I will be looking at, and in blue are other areas with a smaller density of agricultural properties that are not selected. Figure 15 shows the density of areas agricultural properties (number) for each 1 km^2 area. In total, there are 37 362 properties in the SSB dataset. The selected data were then sorted into the 11 counties in Norway.

County-specific statistics are based on the hourly wind speeds and hourly wind power estimates for each selected point.

3.3 Calculations

Wind speed interpolation

As mentioned earlier, the wind data is separated into 10- and 50-meter heights; this needed to be interpolated to get the wind speed to the correct wind speed at the turbine's hub height.

$$u_{hub} = u_{z_1} * \left(\frac{h_{hub}}{z_1}\right)^{\frac{\log\left(\frac{u_{z_2}}{u_{z_1}}\right)}{\log\left(\frac{z_2}{z_1}\right)}}$$

Equation 4: Interpolation equation, where,z1 is 10 meters, z2 is 50 meters, uz1 is the wind speed at 10 meters, and uz2 is the wind speed at 50 meters.

The h_{hub} is the height of the turbine where the blades connect.

Wind speed probability

To find wind probability, we can use the following equation.

$$\Phi_u = \frac{N_u}{N}$$

Equation 5: Equation for wind probability.

Where u is the intervals of each wind speed, meaning that when $u = 1$, the wind speed is between 0.5 to 1.4 m/s, 1.5 to 2.4 for 2 m/s. N_u is the number of hours the wind speed is within u, and N is the total amount of reading gathered during the period.

We can multiply the wind probability with the energy in the wind for a given windspeed to get the distribution of power.

$$P_u \phi_u = \left({}^1/_2 * \rho * u^3\right)\phi_u$$

Equation 6: Equation for power potential.

Where:

The density of air (rho) is $\rho = 1.225\, {}^{kg}/_{m^3}$ at sea-level.

The air flow area is defined as $A = \pi r^2$, where *r* is the turbine blade radius.

Wind speed to the third power is defined as u^3

Power calculations

To find the power generated by the turbines P_{out}, we need the wind speed, the turbine's rated power P_{rated}, cut-in $u_{cut\text{-}in}$, rated wind speed u_{rated}, cut-out $u_{cut\text{-}out}$, and air density ρ to calculate the power produced by the three turbines. If the wind speed was lower than the cut-in speed of the turbine, then $P = 0$. If the wind speed was higher, then the following formula was used:

$$P_{out} = \begin{cases} 0, & u < u_{cut-in} \\ \dfrac{u^3 - u_{cut-in}{}^3}{u_{rated}{}^3 - u_{cut-in}{}^3}, & u_{cut-in} \leq u < u_{rated} \\ 1, & u_{rated} \leq u < u_{cut-out} \\ 0, & u_{cut-out} \leq u \end{cases}$$

Equation 7: Formula for calculating power produced by a turbine.

To find each turbines capacity factor I used the following equation:

$$\frac{P_{out}(t)}{P_{rated}(t)}$$

Equation 8: Equation for capacity factor, P_{out} is the turbines actual power output, P_{rated} is the theoretical max power the turbine can generate, and t is the time span.

Power consumption

To find the total power consumption of a typical farm, I took data collected from a milk barn and household. The power usage for a household varies mainly by the size of the house, amount of people living there, what type of heating is used, and the age of the occupants. Similarly, the power usage for a barn varies with the number of animals in the barn.

In two papers by A. Klipping and E. Trømborg, are collected data from a survey of 1550 people in southern Norway asking for floor space, heating systems, number of household members, and age. The data retrieved was from 2 October 2013 to 30 April 2014. Based on this and daily heating degree days, they estimate hourly power usage for different household sizes using variables collected from the survey. (Klipping & Trømborg, 2016) (Klipping & Trømborg, 2015).

The daily heating degree was calculated for each data point and finding the difference between 17 °C and outdoor temperature.

$$HDD_d = \begin{cases} 17 - T_d, & for\ T_d < 17 \\ 0, & else \end{cases}$$

Equation 9: Equation for HDD (daily heating degree).

Where T_d is the daily temperature and 17 is in degrees celsius. If $T_d \geq 17$ °C, HDD is zero.

The difference in heating degree days was calculated with the following:

$$HDD1st_d = HDD_d - HDD_{d-1}$$

Equation 10: Equation for finding the daily difference in HDD.

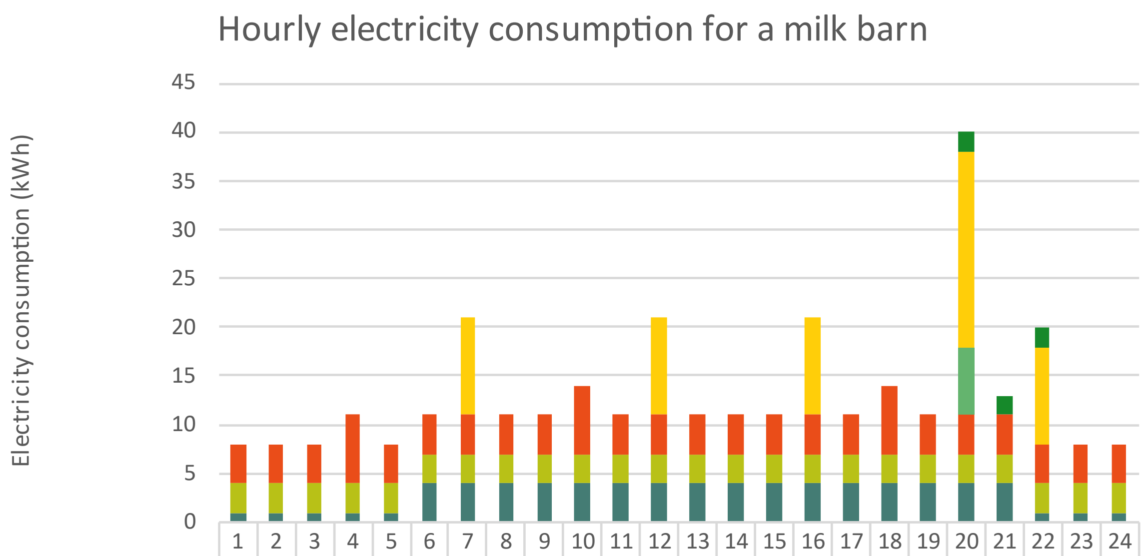
A positive HDD1st indicates that T_d is lower compared to the day before.

I used some of these variables to calculate power consumption for a household:

Variable	Description	Value
HDD_d	Daily h*eating degree days*	Not constant
HDD1st	Use difference in HDD between day and day before	Yes
Adults	Number of adults living in the household	2
Children	Number of children living in the household	2
Cold storage	Does the household have cold storage	Yes
Dryer	Does the household have a dryer	Yes
Heat-pump	Does the household have an air-to-air heat pump	Yes
School break	School break assumed from 20th of Jun to 15th of Aug	Yes
Floor space	Floor space of the household	150 m^2

Table 4: Table showing the variables used in calculating the power consumption for a household.

When calculating the power consumption for barns, I used a paper by Lovise Johanne Seter and Ingvar Kvande, on the energy usage of a milk barn. Their data uses actual data from a barn with 50 cows. In the extract below is a figure showing the electricity usage for a barn for each hour of the day. (Sæter & Kvande, 2021)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Washing																				2	2	2		
Feeding							10					10				10				20		10		
Manure handling																				7				
Milking robot	4	4	4	7	4	4	4	4	4	7	4	4	4	4	4	4	4	7	4	4	4	4	4	4
Milk tank	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Lights	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	1	1	1

Figure 16: Shows the electricity usage for the different systems in a barn every hour. (Sæter & Kvande, 2021) *[Translated from Norwegian to English]*

In addition to this, they provide power consumption for January and June. This was used to see how power demand changes between winter and summer (see Figure 25 and Figure 26).

Battery storage

A simple generic model was used for calculating energy inside a battery. The system includes a self-discharge α, time as *t*; the charging efficiency is defined by ε_c, charging speed is limited by $E_{c,max}$, maximum charge that the battery can hold is defined by $E_{cap,max}$, and battery charge as E_{bat}.
The charging of the battery depends on if there is enough electricity generated from the wind turbine to cover consumption.

$$E_{bat}(t) = min\big[(1-\alpha)E_{bat}(t-1) + min\big[\varepsilon_c\big(E_{avali,prod} - E_{consum}\big)E_{c,max}\big]E_{cap,max}\big]$$

Equation 11: Equation for calculating the charge rate of a battery at a certain time.

The discharge of the battery is dependent on a lack of electricity generated by the turbine.

$$E_{bat}(t) = max\left[(1-\alpha)E_{bat}(t-1) + min\left[\frac{1}{\varepsilon_{dc}}\left(E_{consum} - E_{avail,prod}\right)E_{dc,max}\right]E_{cap,max}\right]$$

Equation 12: Equation for calculating the discharge rate of a battery at a certain time.

The $E_{dc,max}$ is the battery maximum discharge rate and the ε_{dc} is the battery discharging efficiency. For my calculations the ε_c and ε_{dc} is at 0,95, $E_{dc,max}$ and $E_{c,max}$ was 10 kW, and E_{bat} was 128 kWh. $E_{cap,max}$ is determined by f_{cap} which is the fraction of the nominal battery capacity that can be used (E_{nom}).

$$E_{cap,max} = f_{cap}E_{nom}$$

Equation 13: Equation for maximum charge a battery can hold.

Similarly, the minimum charge the battery needs to store to prevent damage is $E_{cap,min}$

$$E_{cap} = f_{min}E_{cap,max}$$

Equation 14: Equation for minimum charge a battery can hold.

In my calculations f_{cap} was set to 0,99 and f_{min} was 0,01.

To calculate the total amount of electricity in the system the following equation was used.

$$E_{gen} = E_{prod} + E_{bat,dc}$$

Equation 15: Total electricity in the system.

Where E_{prod} is the electricity generated by the wind turbine and $E_{bat,dc}$ is the amount of energy that can be used.

The total available energy in the battery is determined by the total amount of electricity minus what is used to charge the battery and losses in the system. These losses can be related to inverters and converters.

$$E_{avail} = E_{gen} - (E_{bat,c} + E_{losses})$$

Equation 16: Equation to find the available electricity that can be used.

To see whether the system can export electricity to the grid if it produces more electricity than demand or must import electricity from the grid if battery charge is too low to meet demand, can be calculated with the following equations.

$$E_{grid,exp} = max[(E_{avail} - E_{demand}), 0]$$

Equation 17: Equation to calculate the amount of electricity that can be exported.

$$E_{grid,imp} = min[(E_{avail} - E_{demand}), 0]$$

Equation 18: Equation to calculate the amount of electricity that has to be imported.

Variable	**Description**	**Values selected**	**Unit**
E_{nom}	Nominal battery capacity at reference temperature	125	kWh
ε_c	Charging efficiency	95	%
ε_{dc}	Discharging efficiency	95	%
α	Self-discharge rate of the battery	1	%/day
$E_{c,max}$	The batteries maximum charging rate	10	kWh/hour
$E_{dc,max}$	The batteries maximum discharging rate	10	kWh/hour
f_{cap}	Percentage of rated capacity that can be used	99	%
f_{min}	Percentage of minimum capacity needed in the battery	10	%
E_{gen}	Total amount of electricity on-site	(Not constant)	kWh
E_{avail}	Total available electricity for consumption	(Not constant)	kWh
$E_{grid,exp}$	Electricity exported to the grid	(Not constant)	kWh
$E_{grid,imp}$	Electricity imported from the grid	(Not constant)	kWh
E_{losses}	Electricity losses in the system	0	kWh

Table 5: Table showing each variable and the values selected for the battery system.

Power production system

To determine the site's ability to export and dependency in import, we need to find the SSR (self-sufficiency ratio) and SCR (supply cover ratio), with the following equations.

$$SSR = \frac{\sum_{t=1}^{N} min[E_{avail}, E_{demand}]}{\sum_{t=1}^{N} E_{demand}}$$

Equation 19: Equation for calculating the self-sufficiency ratio (SSR).

The SSR represents a fraction of how much the site own electricity generation cover the electricity demand.

$$SCR = \frac{\sum_{t=1}^{N} min[E_{avail}, E_{demand}]}{\sum_{t=1}^{N} E_{prod}}$$

Equation 20: Equation for calculating the supply cover ratio (SCR).

The SCR is the fraction of the generated electricity from the turbine that is used for on-site consumption.

The LOLP (loss of load probability) is the fraction of time where the site is unable to generate enough electricity to meet the demand. It can be calculated with the following equation.

$$LOLP = \frac{\left(\sum_{t=1}^{N} f(t) \begin{cases} f(t) = 1 & E_{avail} < E_{demand} \\ f(t) = 0 & E_{avail} \geq E_{demand} \end{cases}\right)}{N}$$

Equation 21: Equation to find the loss of load probability (LOLP).

To find the fraction of time when 100% of the demand can be matched by on-site electricity generation (known as energy autonomy (A_b)), we use the following equation.

$$A_b = 1 - LOLP$$

Equation 22: Equation to find the energy autonomy (Ab).

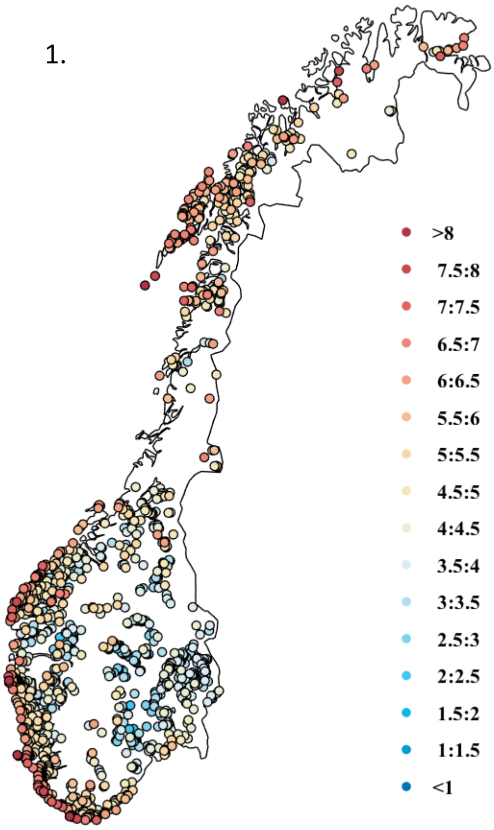
4. Results

The results presented will answer my research question, how significant is the wind and power generation potential on Norwegian farms? And secondary research questions, what is the typical power production potential for each county, and how does it compare to the power demand for a typical milk barn?

All results are based on the hourly NORA3 wind dataset.

4.1 Wind resources

1.



17 shows three climatological maps on the wind speed from every county in Norway. The data is from 2010 to 2018. This is done so we can get a visual idea of how the wind speed changes throughout Norway.

1. The first map shows the mean wind speeds.
2. On the second map is the 25th percentile.
3. Map three is the 75th percentile.

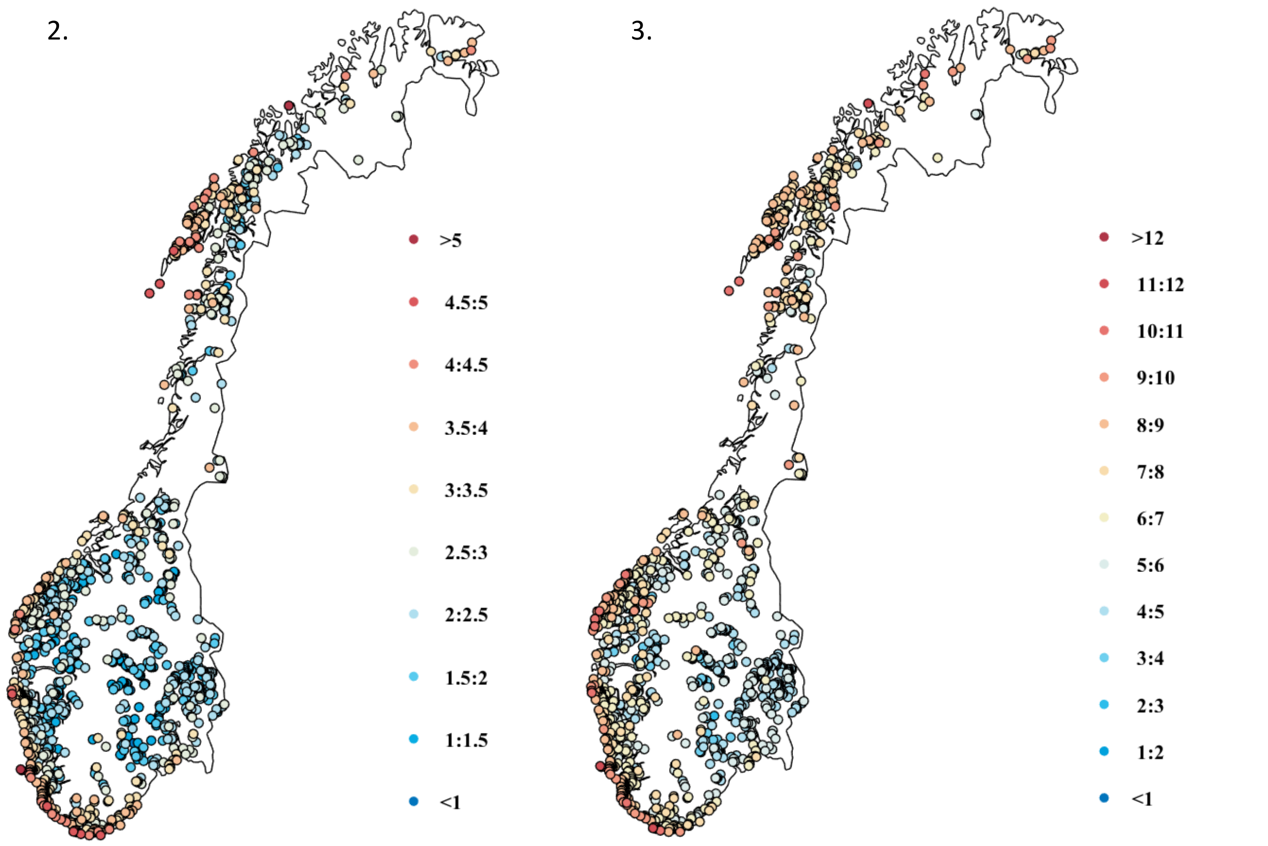


Figure 17: Maps of wind speed (m/s) in Norway, 1. mean wind speed, 2. 25 percentile, and 3. 75 percentile.

The three maps in Figure 17 show stronger winds near the coast and much calmer winds further inland. On the 25th percentile map (2), we can see that on the coast, the wind speed is approximately 3 m/s or higher 75% of the time, which is around the cut-in speed for some of the turbines. The 75th percentile map has wind speeds close to the turbine's rated speed at the coast, meaning that around 25% of the time, the turbines would not produce any energy.

Table 6 shows the different wind speeds in each county, separated into four quarters and the annual average. The table is meant to show the difference in wind speed for 10 meters and 50 meters and how the wind speed changes throughout the year averaged over all selected locations (Table 3). based on wind speed from 2010 to 2018. This gives us an idea of how the wind speed changes depending on the height and time of the year.

2010 - 2018										
	Jan-Feb-Mar		Apr-May-Jun		Jul-Aug-Sep		Oct-Nov-Dec		Annually	
County	10 m	50 m	10 m	50 m	10 m	50 m	10 m	50 m	10 m	50 m
Agder	3,79	6,21	3,11	5,04	3,07	4,94	3,73	6,19	3,43	5,60
Troms og Finnmark	4,46	6,12	3,48	4,76	2,86	4,07	3,94	5,63	3,68	5,14
Møre og Romsdal	4,03	5,76	3,24	4,54	2,87	4,08	4,09	5,90	3,56	5,07
Vestfold og Telemark	2,55	4,23	2,41	3,87	2,26	3,67	2,44	4,19	2,41	3,99
Trøndelag	3,62	5,61	2,78	4,24	2,48	3,88	3,27	5,26	3,04	4,75
Rogaland	4,40	6,56	3,70	5,42	3,67	5,36	4,59	6,82	4,09	6,04
Innlandet	2,38	3,92	2,40	3,83	2,20	3,58	2,23	3,86	2,30	3,80
Viken	2,25	3,84	2,29	3,74	2,16	3,57	2,21	3,92	2,23	3,77
Nordland	4,73	6,75	3,61	5,14	3,15	4,60	4,34	6,36	3,95	5,71
Vestland	3,63	5,34	2,95	4,27	2,73	4,01	3,68	5,49	3,24	4,78

Table 6: Table showing wind speeds averaged over selected locations from 2010 to 2018 for every county divided into four.

Table 6 shows that throughout the year, wind speeds are higher during winter and calmer during summer. The annual results show that *Agder, Troms og Finnmark, Møre og Romsdal, Rogaland*, and *Nordland* have annual winds over 5 m/s at a height of 50 meters. On average, *Rogaland* has the strongest winds (6.04 m/s at 50 meters), and has on average 58 % higher wind speeds than *Viken* with the lowest wind speeds on average.

However, during summer, when wind speed is calm, some of the turbines with a hub height lower than 50 meters might on average not have enough wind to reach the cut-in speed. Furthermore, we can expect significantly weaker winds further inland, as shown by the maps above, indicating there might be little wind for the wind turbines to generate electricity.

Comparing the 25th and 75th percentile maps, we can see an increase in average wind speeds across all counties on map 3. *Innlandet*, *Viken*, and *Vestfold og Telemark* have the smallest increase in wind speed compared to other counties. However, *Vestlandet* has significantly higher wind speeds at the coast and further inland.

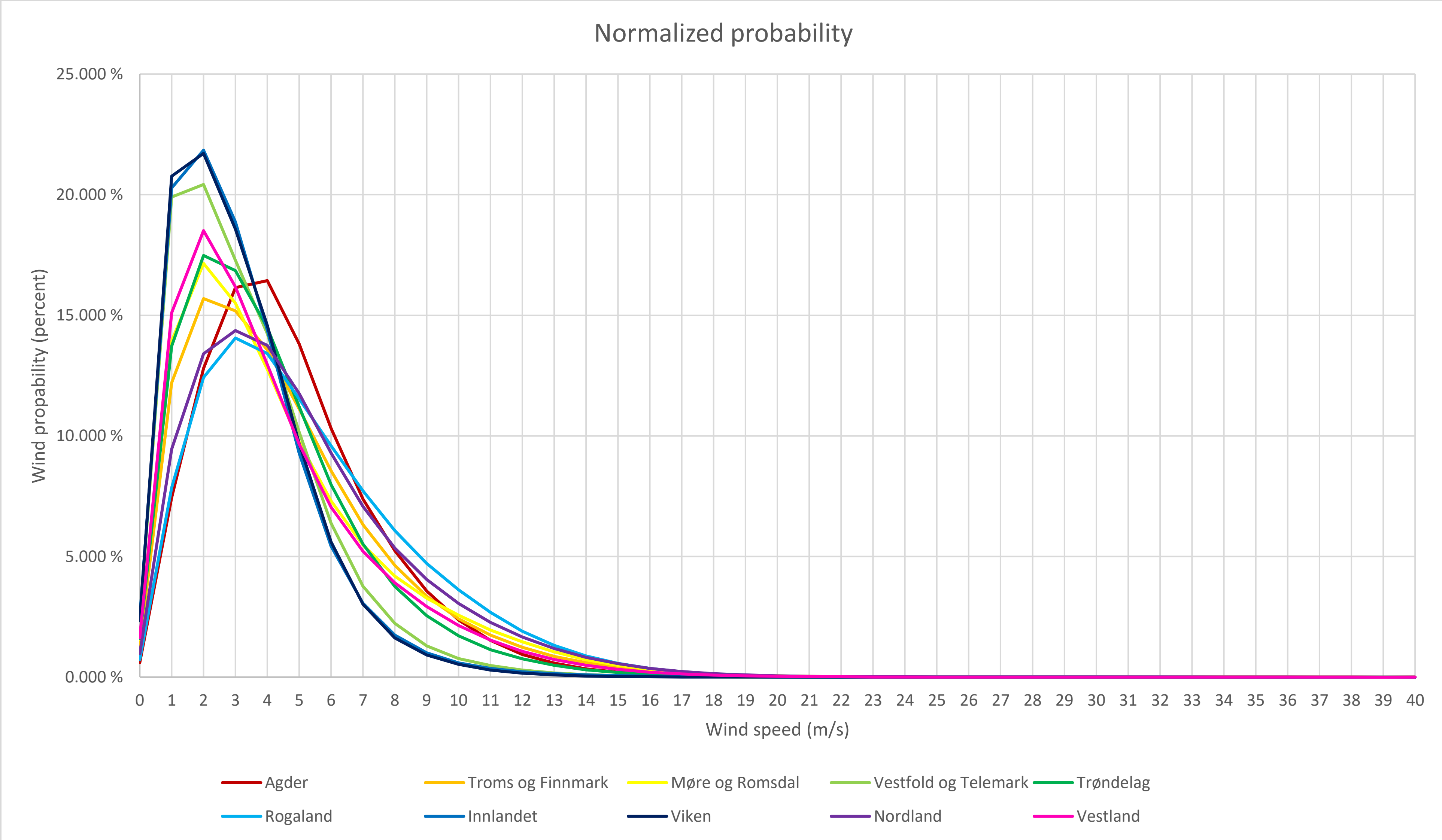


Figure 18: Graph of wind probability for each county.

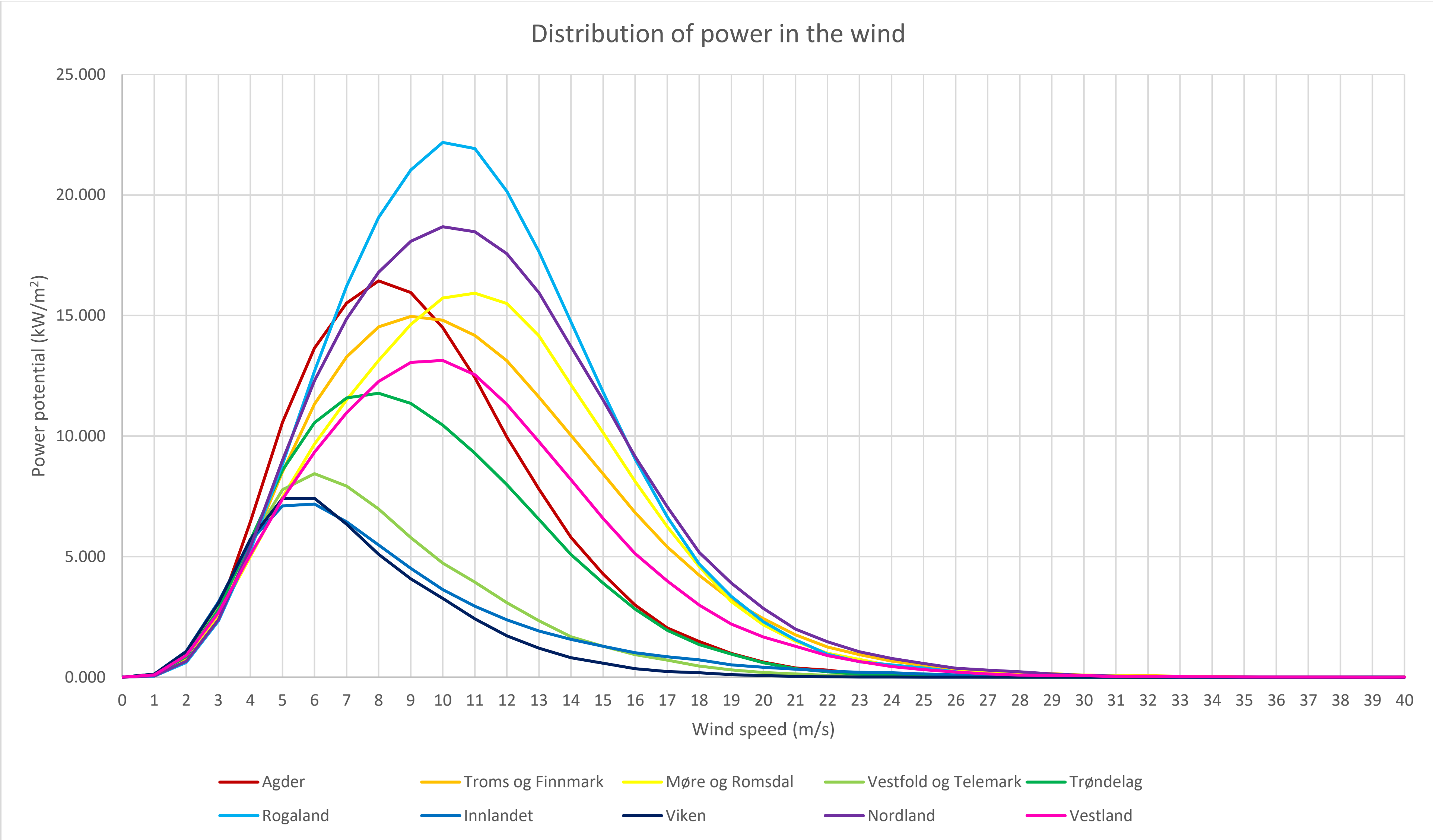


Figure 19: Graph that shows the wind potential for each county.

Figure 15 represents the probability in percentage that a wind with a certain wind speed occurs in a county. The most likely wind speed is below 3 – 4 m/s, which is less than the rated cut-in for the selected turbines. This means there are likely prolonged timespans where the turbines generate no energy*. Innlandet* and *Viken* have a nearly identical probability graph. *Agder* peaks at a higher wind speed than the other counties. *Rogaland* has the lowest peak but has a less steep drop-off; we see this with the other counties with high average winds compared to counties with less wind speed which have a steeper drop-off after the peak.

Figure 16 shows how much energy there is in the wind multiplied by the probability of the different wind speeds for each county. The distribution of the power graph tells us that even though the most probable wind is between 1 – 4 m/s, the most energy that can be harvested is between 5 – 17 m/s for some areas, with peaks near the turbine's rated wind speed. Figure 19 has graphs that are opposite to that of Figure 18. *Rogaland* has the highest peak power potential but drops more significantly. *Nordland* does not have the same peak power potential as *Rogaland* but does have higher potential at wind speeds higher than 16 m/s than the other counties. However, this matters little as the largest selected turbine has the highest rated power at 15 m/s out of the three turbines. *Innlandet* and *Viken* no longer have the same graph, instead *Innlandet* has a higher power potential.

4.2 Power production

The power generated from each turbine is presented in map format and as a table. This will show us how much electricity the three turbines will generate in each county. The values in the table are hourly, meaning that it shows how much electricity is generated in one hour.

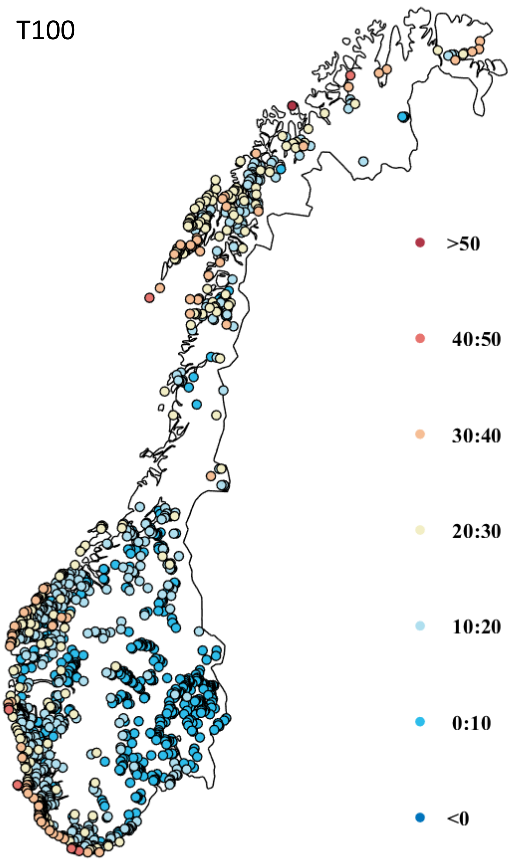


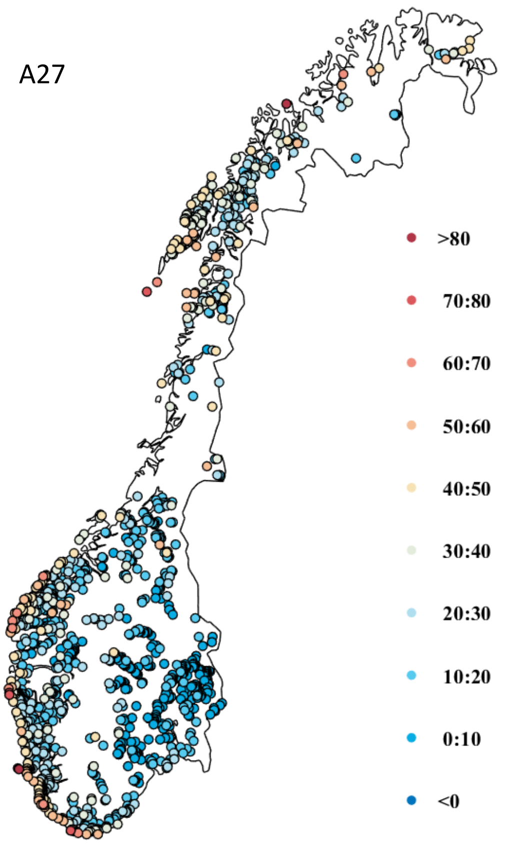
Figure 20 show the average electricity production from the three selected turbines (for details see section 3.1).

We can see that the Argolabe T100 turbine can barely reach half of its rated power (100 kW) in some areas with strong winds.

The A27 has its highest production values near the coast at around 80 kWh.

The V39 seem to be able to do nearly double the power generation of the A27

All three turbines have largely similar power generation inland.



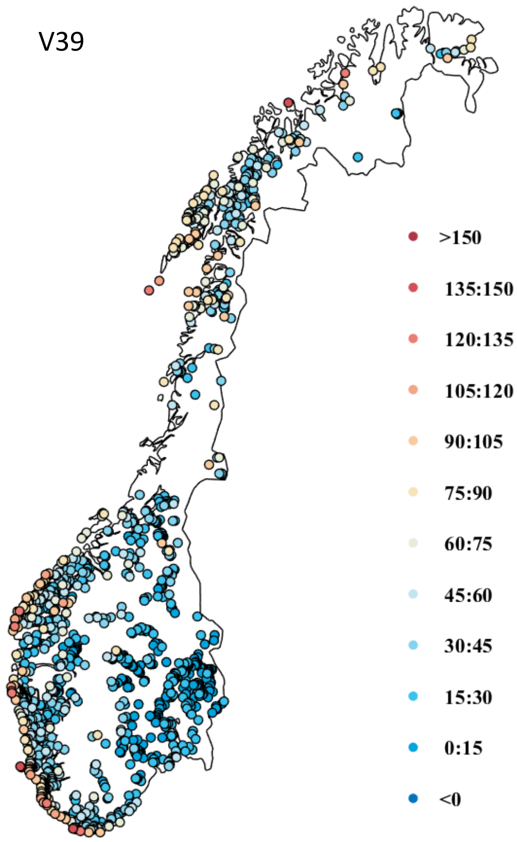


Figure 20: Map showing the power production for each turbine across the data points.

On Figure 20, we can see that the Argolabe T100 turbine seems to reach an electricity production of 20 to 30 kWh near the coast, and in-land electricity production stagnates at approximately 10 to 0 kWh. The ACSA A27 has a max energy production of 80 kWh, and Vestas V39 produces a max of 150 kWh. It is interesting to note that the power inland seems to be similar between the three turbines. It indicates that the wind speed is less than the cut-in speed.

County	Turbine	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
Agder	T100	25.36	21.66	18.44	13.73	10.62	10.98	8.82	10.55	14.82	20.09	19.58	24.45
	ACSA A27	39.90	33.23	28.02	20.46	15.41	15.68	12.49	15.27	22.06	30.28	29.77	39.65
	Vestas V39	73.65	60.52	50.81	36.52	26.93	27.09	21.34	26.60	39.38	54.75	54.03	74.10
Troms og Finmark	T100	23.71	23.45	25.78	16.37	13.98	10.13	7.16	8.13	11.02	15.05	20.66	24.46
	ACSA A27	38.10	37.17	41.21	24.22	20.29	13.94	9.85	11.21	16.07	22.19	32.28	38.88
	Vestas V39	70.31	68.40	76.13	42.94	35.61	23.72	16.55	19.03	28.24	39.43	58.93	71.47
Møre og Romsdal	T100	20.85	21.68	23.58	16.35	10.69	10.68	7.86	7.74	14.15	19.07	21.22	29.20
	ACSA A27	33.86	35.03	38.24	24.69	15.64	15.16	11.02	10.98	21.95	30.27	34.37	49.01
	Vestas V39	62.81	64.98	71.14	44.23	27.43	26.19	18.78	18.85	39.86	55.70	63.81	92.44
Vestfold og Telemark	T100	9.69	9.31	8.83	7.15	5.07	5.46	4.30	4.06	6.82	7.81	8.47	10.96
	ACSA A27	15.12	14.31	13.81	10.86	7.45	7.88	6.17	5.96	10.10	11.68	13.04	17.77
	Vestas V39	27.55	25.84	25.10	19.37	12.76	13.37	10.31	10.09	17.73	20.72	23.55	33.01
Trøndelag	T100	19.41	17.95	19.24	11.45	6.92	7.62	4.54	5.21	10.50	13.90	14.05	19.59
	ACSA A27	30.19	27.79	29.90	17.03	9.95	10.61	6.43	7.52	15.41	20.79	22.00	31.26
	Vestas V39	55.28	50.69	54.55	30.22	17.10	18.06	10.76	12.83	27.33	37.34	40.20	57.76
Rogaland	T100	32.50	28.66	20.80	18.43	17.59	15.98	13.07	15.71	20.85	28.68	26.60	33.59
	ACSA A27	54.66	46.85	31.76	26.56	25.31	22.20	18.19	22.39	30.54	44.89	41.97	57.16
	Vestas V39	103.21	87.27	57.52	46.72	44.55	38.42	31.23	39.13	54.21	81.93	76.99	108.26
Innlandet	T100	6.54	7.07	8.95	6.74	4.43	5.61	3.77	3.23	5.47	5.95	5.79	9.12
	ACSA A27	10.40	11.14	14.20	10.21	6.55	8.06	5.47	4.81	8.16	9.03	9.19	14.63
	Vestas V39	18.91	20.19	25.89	18.09	11.13	13.65	9.06	8.01	14.18	15.98	16.59	26.97
Viken	T100	6.30	6.44	7.10	5.81	4.08	4.67	3.55	3.22	5.49	5.63	6.10	9.13
	ACSA A27	9.85	9.89	11.06	8.79	6.06	6.76	5.17	4.82	8.21	8.55	9.48	14.46
	Vestas V39	17.79	17.73	19.99	15.50	10.28	11.36	8.54	8.07	14.30	15.06	17.01	26.56
Nordland	T100	29.02	27.92	29.31	18.70	15.11	12.32	9.33	11.27	14.67	21.91	24.72	29.79
	ACSA A27	47.43	44.90	48.35	28.11	21.68	17.29	13.14	16.07	22.19	33.51	39.77	48.49
	Vestas V39	88.15	83.18	90.49	50.30	38.00	29.90	22.48	27.92	39.86	60.70	73.64	90.31
Vestland	T100	20.11	19.04	16.20	12.28	10.16	8.15	6.53	7.31	12.49	17.60	18.00	23.73
	ACSA A27	32.90	30.60	25.49	18.10	14.95	11.59	9.23	10.57	18.71	27.44	28.44	39.35
	Vestas V39	61.36	56.67	46.72	32.13	26.39	19.97	15.74	18.36	33.48	50.20	52.31	73.92

Table 7: Table showing the average power generated each hour, each month, displayed in kWh.

Table 7 shows the location-averaged power output for each selected turbine in each county. Again, we can see similarities between the table and the maps. The turbines produce significantly higher energy near coastal areas, such as *Rogaland, Agder, Troms og Finnmark, Vestland*, and *Nordland*.

Capacity factor

T100

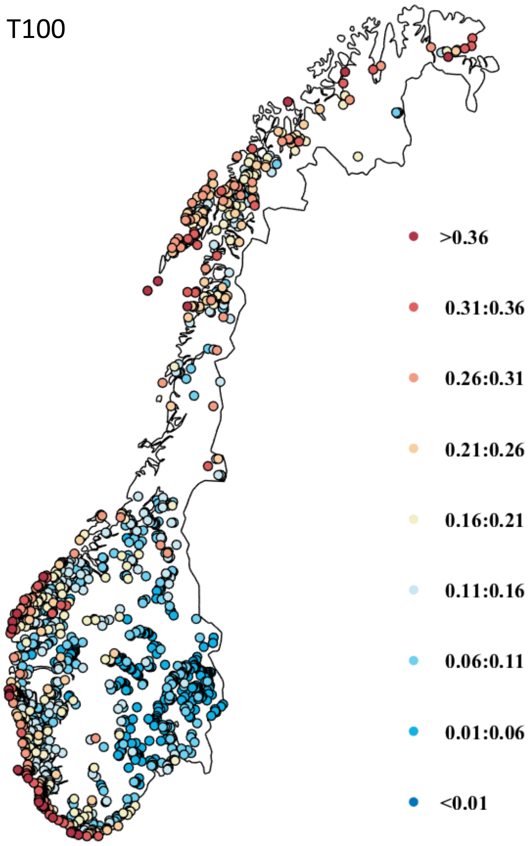


Figure 21 show the three turbines capacity factor, The capacity factor tells us how well a turbine performs compared to its rated power, where 1 is the highest a turbine can reach if it runs constantly for a full year at rated wind speed.

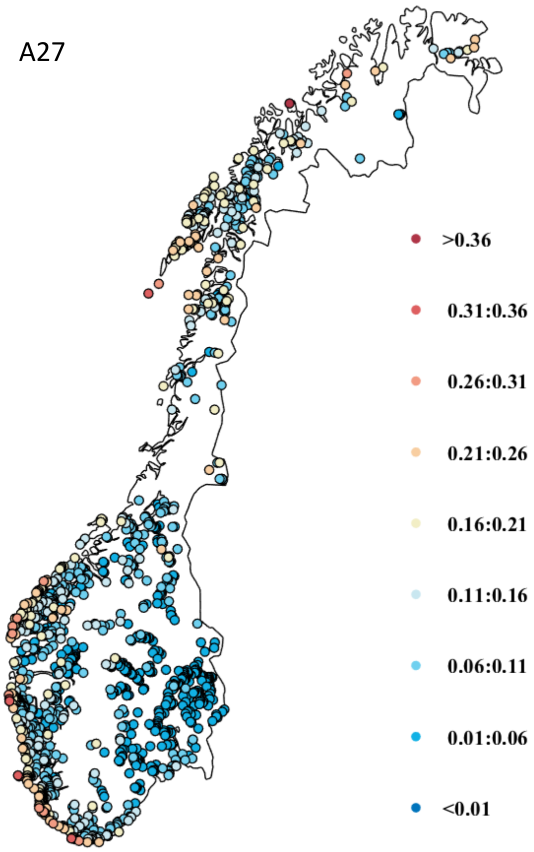
- T100

  The average capacity factor is 14.5 %
- A27

  The average capacity factor is 10 %
- V39

  The average capacity factor is 8 %

A27



V39

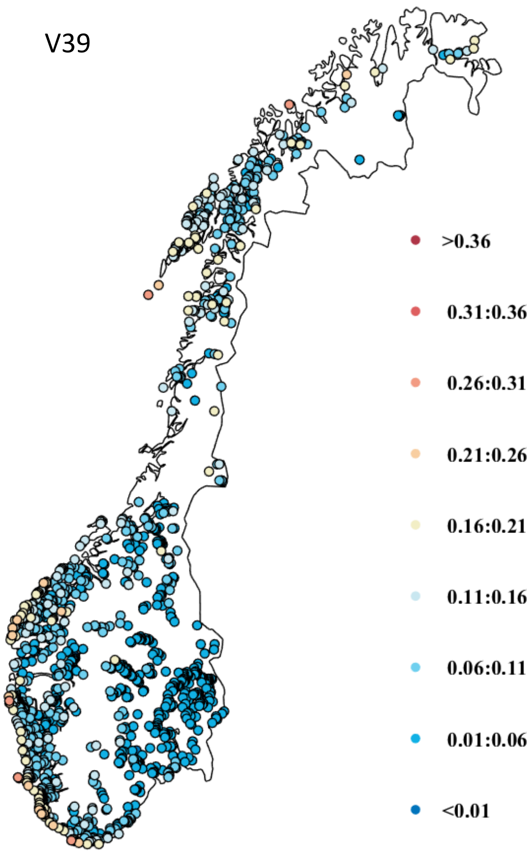


Figure 21: Maps showing the capacity factor for the three turbines, where 1 is the highest a turbine can theoretically reach.

Figure 21 shows how much each turbine operates at max-rated power output (capacity factor). The T100 has a higher capacity factor than the other turbines due to it having a lower cut-in and rated power. The A27 and V39 have a much more similar capacity factor, especially further inland, compared to the T100. We can see that the capacity factor becomes lower as the turbine scales in size, indicating that there is not enough wind for the larger turbines, so they cannot reach the rated wind speed.

4.3 Power production and usage

Table 8 shows the total power needed for the milk barn and household (described in the power calculation section of 3.3) throughout a year.

County	Month												
	January	February	March	April	May	June	July	August	September	October	November	December	Average
Agder	17.66	17.64	17.19	16.55	16.57	16.22	16.03	16.12	16.37	16.24	16.88	17.49	16.75
Troms og Finnmark	18.07	18.01	17.64	17.00	17.07	16.73	16.32	16.42	16.69	16.68	17.27	17.86	17.15
Møre og Romsdal	17.50	17.44	17.13	16.62	16.72	16.49	16.22	16.23	16.43	16.25	16.84	17.40	16.77
Vestfold og Telemark	17.95	17.86	17.33	16.63	16.59	16.17	16.00	16.13	16.44	16.41	17.11	17.78	16.87
Trøndelag	17.95	17.83	17.40	16.78	16.80	16.51	16.18	16.26	16.55	16.51	17.18	17.79	16.98
Rogaland	17.44	17.41	17.02	16.45	16.56	16.32	16.09	16.09	16.27	16.09	16.69	17.26	16.64
Innlandet	18.31	18.12	17.54	16.82	16.77	16.33	16.09	16.26	16.61	16.63	17.34	18.07	17.07
Viken	18.12	17.98	17.40	16.68	16.62	16.20	16.00	16.15	16.48	16.49	17.20	17.91	16.93
Nordland	17.81	17.77	17.43	16.85	16.95	16.63	16.28	16.34	16.59	16.51	17.07	17.65	16.99
Vestland	17.56	17.51	17.15	16.59	16.66	16.38	16.16	16.21	16.43	16.26	16.85	17.43	16.77

Table 8: Table showing monthly changes in power demand from the milk barn and household, displayed in kWh.

From Table 8 we see small changes in electricity consumption, the changes we do see are from temperature differenced between the countries. *Troms og Finnmark* has the highest average power consumption out of the ten counties. *Viken* has some of the highest power consumption during colder periods and the lowest during warmer periods. Over all the counties, we can see small changes in power usage throughout the year.

Figure 19 to 21 combines the power needed for the barn and household and the power generated by each turbine. This will show if the turbines can generate enough electricity during the months of the year.

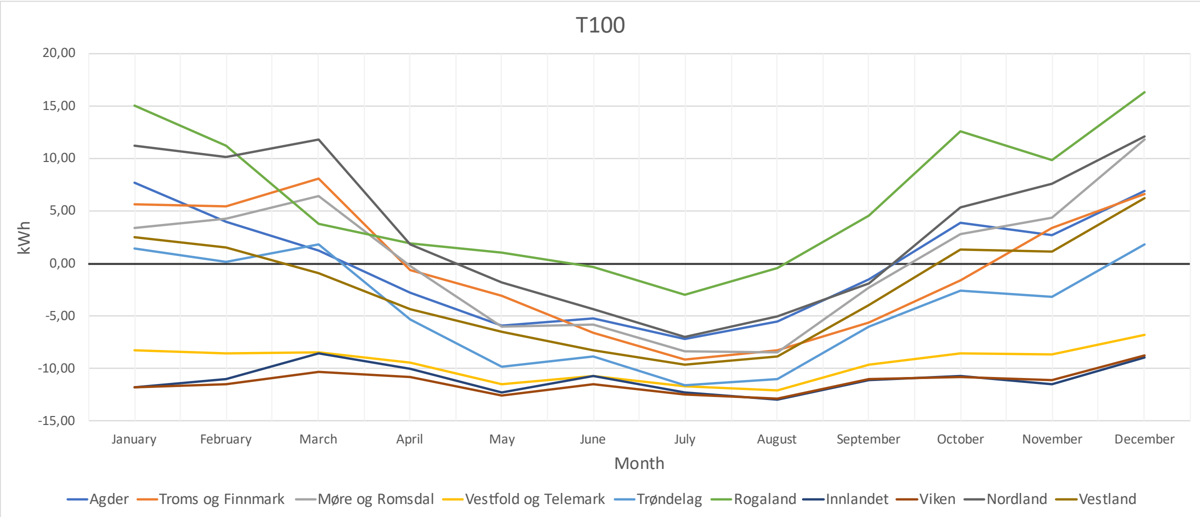


Figure 22: Graph showing the Argolabe T100 power production plus the power demand.

We see that the T100 turbine struggles to generate energy for the farm, increasing the farm's grid dependency. *Rogaland* is the only county where the T100 can meet the power demand, June and August the T100 can, on average, generate enough power to barely meet the demand. In July, the turbine cannot meet the demand. *Vestfold og Telemark, Innlandet*, and *Viken* does not have enough wind, so the T100 cannot generate enough in any of the months.

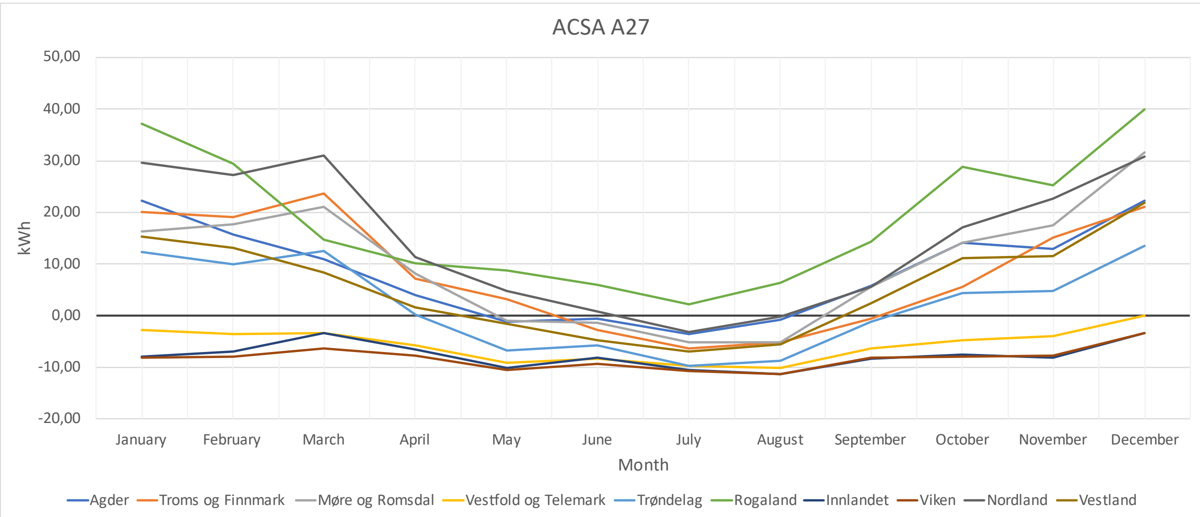


Figure 23: Graph showing the ACSA A27 power production plus the power demand.

The A27 turbine is more capable of generating energy compared to the T100. *Rogaland* is the only county that can meet the power demand during all months. We see that all the other counties are no more than 10 kWh in the negative. There is also less difference between the counties during summer compared to Figure 22. *Vestfold og Telemark, Innlandet*, and *Viken* still cannot generate enough power to meet the demand on the farm.

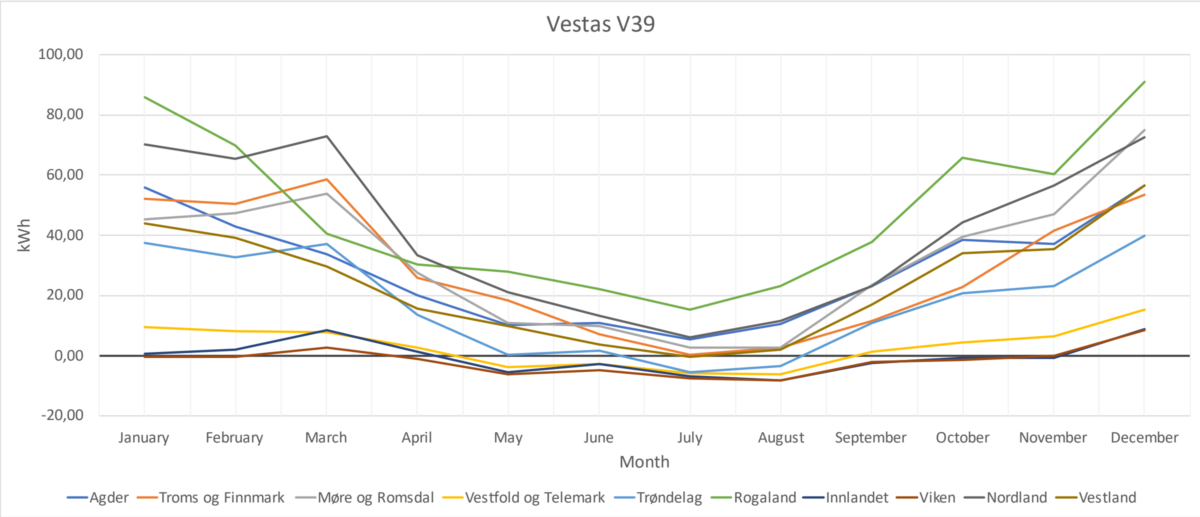


Figure 24: Graph showing the Vestas V39 power production plus the power demand.

The V39 turbine can generate enough energy for the farm in most of the counties. Compared to Figure 22 and Figure 23 we can see that *Vestfold og Telemark* can generate enough electricity except from April to September. *Innlandet* and *Viken* can generate enough power in February, March, and December. *Trøndelag* also does not have enough wind for the V39 to meet demand in July and August. *Rogaland*, *Nordland*, *Troms og Finnmark*, *Møre og Romsdal*, *Agder*, and *Vestland* can meet the power demand of the farm during all mouths.

Figure 25 and 26 shows the location-averaged energy production and consumption for the different counties throughout a day in January and June. As mentioned at the end of section 3.3, the barn data here is unique for January and June. This will give an idea of what hourly differences in power generation we can expect during winter and summer.

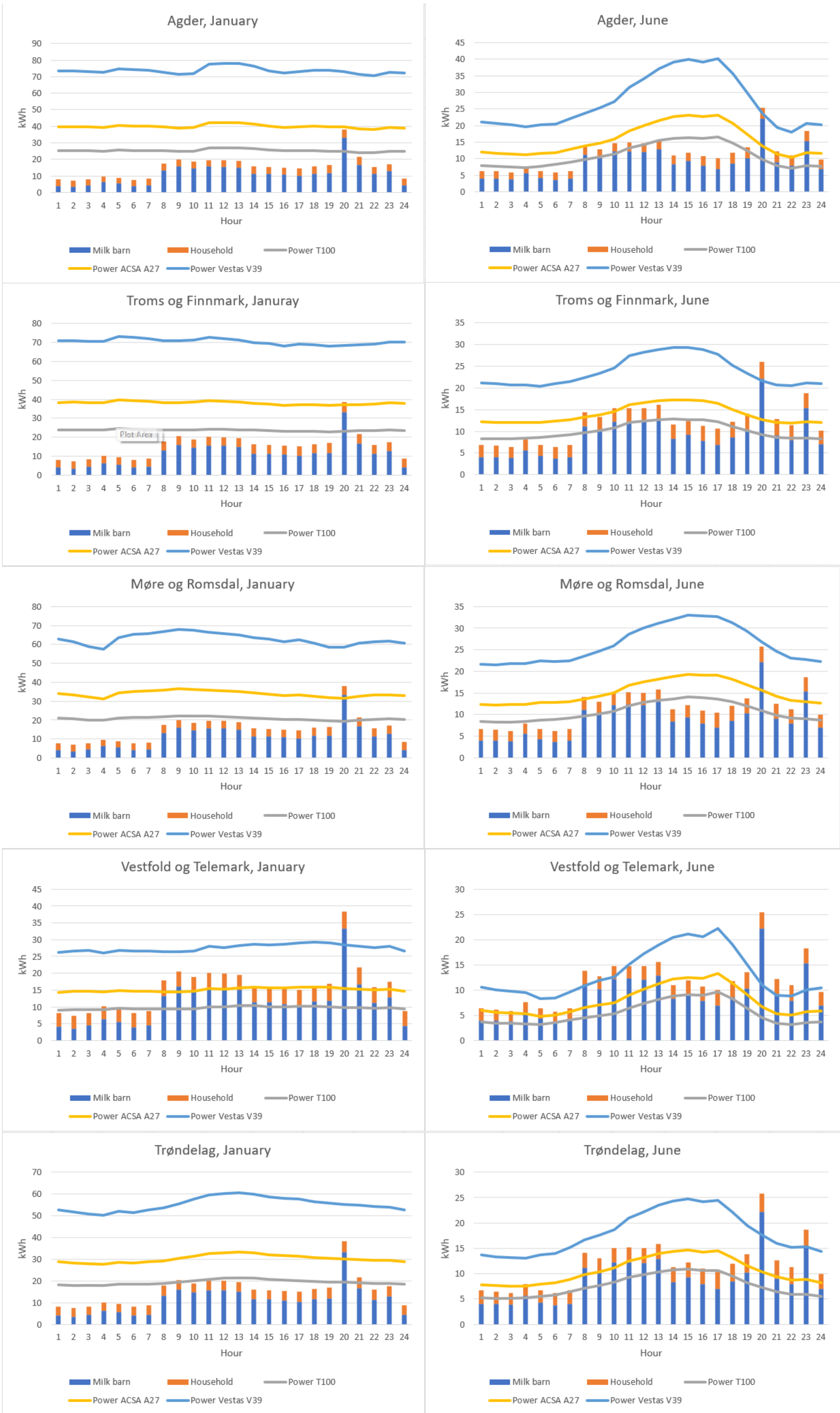


Figure 25: Graphs showing the hourly power generated from the three turbines and the power demand from the barn and household.

Figure 26: Graphs showing the hourly power generated from the three turbines and the power demand from the barn and household.

Figure 25 shows hourly power production and demand for *Agder*, *Troms og Finnmark*, *Møre og Romsdal*, *Vestfold og Telemark*, and *Trøndelag*. Figure 26 shows hourly power production and demand for *Rogaland*, *Innlandet*, *Viken*, *Nordland*, and *Vestland*. These graphs show that the three turbines can on average generate enough energy throughout the day in most counties. We see that for January the V39 turbine can generate enough electricity for demand in most areas, however for *Møre og Romsdal*, *Vestfold og Telemark*, *Innlandet*, and *Viken* the turbine cannot generate enough electricity at 8 pm, where the electricity consumption spikes. *In Vestfold og Telemark*, *Innlandet*, and *Viken* the T100 and A27 is not able to meet the power consumption during daytime.
In June the wind speed is lower compared to January which can also be seen on Figure 22, Figure 23, and Figure 24. The T100 cannot generate enough in almost all counties except for Rogaland, though at 8 and 11 pm there is an energy spike that the turbine cannot handle. The A27 performs a bit better in *Agder*, *Troms og Finnmark*, *Møre og Romsdal*, *Rogaland*, and *Nordland*, where the turbine can meet demand except for the usage spikes. The more powerful V39 is not enough for the demand in *Innlandet* and *Viken*.
What is interesting to note is that the wind fluctuates more throughout the day during summer compared to winter periods. However, this may not be a problem as the wind increases during daytime where the power demand is the highest.

As the above figures display location and time averaged values they do not tell us if there is enough energy on a given hour on a given date. We can get a better idea by using SSR, SCR, LOLP, and Ab. Where the Self-sufficiency ratio will show how self-sufficient the farm is, meaning how much of the time (in percentage) the turbine is able to generate enough electricity to exceed the usage. The supply cover ratio will tell how much of the generated electricity from the turbine is used for on-site consumption and the remaining being exported to the grid. The loss of load probability is the fraction of time where the site is unable to generate enough electricity to meet the demand. Energy autonomy is the fraction of time when 100% of the demand can be matched by on-site electricity generation.

County	Turbine	SSR	SCR	LOLP	Ab
Agder	T100	41.3 %	45.5 %	70.5 %	29.5 %
	ACSA A27	49.1 %	36.8 %	63.0 %	37.0 %
	Vestas V39	55.2 %	23.4 %	53.1 %	46.9 %
Troms og Finnmark	T100	36.9 %	40.4 %	72.7 %	27.3 %
	ACSA A27	41.6 %	30.8 %	68.1 %	31.9 %
	Vestas V39	45.3 %	19.0 %	61.5 %	38.5 %
Møre og Romsdal	T100	34.9 %	37.5 %	73.4 %	26.6 %
	ACSA A27	39.3 %	27.9 %	69.2 %	30.8 %
	Vestas V39	42.6 %	16.9 %	63.4 %	36.6 %
Vestfold og Telemark	T100	22.3 %	56.9 %	86.4 %	13.6 %
	ACSA A27	28.3 %	49.1 %	81.4 %	18.6 %
	Vestas V39	32.8 %	33.1 %	74.2 %	25.8 %
Trøndelag	T100	31.4 %	45.1 %	78.3 %	21.7 %
	ACSA A27	37.3 %	36.2 %	72.9 %	27.1 %
	Vestas V39	41.8 %	23.0 %	65.5 %	34.5 %
Rogaland	T100	46.5 %	35.7 %	63.4 %	36.6 %
	ACSA A27	52.1 %	26.5 %	57.8 %	42.2 %
	Vestas V39	56.5 %	16.0 %	50.3 %	49.7 %
Innlandet	T100	18.9 %	58.4 %	89.1 %	10.9 %
	ACSA A27	24.5 %	51.0 %	84.9 %	15.1 %
	Vestas V39	28.9 %	34.9 %	78.4 %	21.6 %
Viken	T100	18.8 %	59.3 %	89.5 %	10.5 %
	ACSA A27	24.8 %	52.0 %	84.8 %	15.2 %
	Vestas V39	29.4 %	35.5 %	77.8 %	22.2 %
Nordland	T100	42.6 %	37.1 %	67.4 %	32.6 %
	ACSA A27	48.0 %	27.4 %	62.0 %	38.0 %
	Vestas V39	52.1 %	16.5 %	54.7 %	45.3 %
Vestland	T100	31.7 %	40.8 %	76.6 %	23.4 %
	ACSA A27	36.5 %	31.6 %	72.2 %	27.8 %
	Vestas V39	40.1 %	19.6 %	66.0 %	34.0 %

Table 9: Table showing the SSR, SCR, LOLP, and Ab for the farm.

What we can see from Table 9 is like the previous tables and figure, *Rogaland* is the highest performer out of the other counties. In the counties where wind in not as strong, such as *Vestfold og Telemark*, *Innlandet*, and *Viken* the loss of load probability is higher than 80% for the T100, meaning that there is an 80% of the time the turbine does not have enough wind to power the farm.

Battery storage

One of the challenges with wind turbines are power intermittency, meaning that the power output of the turbine fluctuates corresponding to the wind speed. A method of solving this is by storing excess energy when the wind is strong and power output is higher than the power demand of the farm. The storage of electricity can be achieved with different technologies, I went with a battery to store the electricity. As mentioned in Battery storage of chapter 3.3, I opted to use a 125-kWh battery along with a set of other specifications and variables (see Table 5). With the addition of a battery, we can also have a look at how much electricity can be exported and imported.

County	Turbine		Month (average taken between 2010 to 2018)												Average
			January	February	March	April	May	June	July	August	September	October	November	December	
Agder	T100	Export	14,95	12,19	9,46	6,36	3,95	4,22	2,86	4,24	7,26	10,96	10,54	14,61	8,47
		Import	7,34	8,30	8,31	9,30	10,00	9,55	10,17	9,91	8,95	7,21	8,02	7,81	8,74
	ACSA A27	Export	27,93	22,24	17,38	11,53	7,14	7,45	5,10	7,49	13,08	19,68	19,13	28,19	15,53
		Import	5,79	6,78	6,67	7,77	8,45	8,09	8,77	8,48	7,54	5,75	6,45	6,20	7,23
	Vestas V39	Export	60,46	48,28	38,84	26,28	17,29	17,54	12,67	17,52	29,24	43,01	42,10	61,37	34,55
		Import	4,59	5,53	5,37	6,49	7,13	6,82	7,55	7,21	6,40	4,62	5,18	4,94	5,99
Troms og Finnmark	T100	Export	14,26	13,95	15,79	8,85	6,95	4,26	2,73	3,35	5,26	7,90	11,82	14,62	9,15
		Import	8,74	8,65	7,76	9,62	10,13	10,94	11,98	11,71	11,04	9,63	8,60	8,17	9,75
	ACSA A27	Export	27,66	26,73	30,37	15,85	12,33	7,18	4,61	5,58	9,33	14,00	22,39	28,05	17,01
		Import	7,76	7,72	6,91	8,77	9,23	10,06	11,19	10,89	10,07	8,60	7,56	7,19	8,83
	Vestas V39	Export	59,04	57,16	64,52	33,75	26,79	16,09	10,51	12,63	20,62	30,36	48,17	59,82	36,62
		Import	6,94	6,92	6,16	7,97	8,39	9,22	10,42	10,14	9,22	7,74	6,70	6,38	8,02
Møre og Romsdal	T100	Export	12,49	13,40	15,00	9,47	5,25	5,23	3,60	3,49	8,13	11,63	13,25	19,06	10,00
		Import	9,20	9,30	8,63	9,86	11,35	11,13	12,03	12,05	10,52	8,97	8,97	7,43	9,95
	ACSA A27	Export	24,52	25,86	28,85	17,01	9,37	8,90	6,05	5,98	15,08	21,95	25,49	38,00	18,92
		Import	8,22	8,43	7,82	9,06	10,53	10,33	11,34	11,32	9,68	8,10	8,06	6,57	9,12
	Vestas V39	Export	52,68	55,07	61,04	35,83	20,36	19,17	13,16	13,17	32,23	46,67	54,20	80,75	40,36
		Import	7,43	7,70	7,13	8,36	9,76	9,60	10,71	10,66	8,96	7,40	7,34	5,90	8,41
Vestfold og Telemark	T100	Export	4,30	4,20	3,85	2,71	1,29	1,30	0,84	0,96	2,49	3,12	3,77	5,45	2,86
		Import	12,61	12,84	12,40	12,28	12,86	12,09	12,59	13,08	12,18	11,79	12,51	12,36	12,47
	ACSA A27	Export	8,39	7,94	7,49	5,19	2,48	2,50	1,61	1,80	4,59	5,71	7,06	10,89	5,47
		Import	11,30	11,59	11,09	11,07	11,69	10,89	11,52	12,04	11,03	10,52	11,25	11,01	11,25
	Vestas V39	Export	19,69	18,38	17,60	12,61	6,67	6,82	4,68	4,91	11,18	13,65	16,47	24,98	13,14
		Import	10,19	10,53	9,94	10,02	10,61	9,76	10,49	11,06	10,01	9,45	10,19	9,88	10,18
Trøndelag	T100	Export	10,55	9,57	10,88	5,51	2,32	2,45	1,17	1,59	4,83	6,95	7,21	10,87	6,16
		Import	9,18	9,58	9,15	10,94	12,27	11,43	12,85	12,70	11,00	9,67	10,47	9,22	10,70
	ACSA A27	Export	20,00	18,11	20,43	9,98	4,23	4,36	2,12	2,89	8,62	12,55	13,78	21,18	11,52
		Import	7,86	8,29	8,04	9,85	11,17	10,37	11,93	11,71	9,90	8,40	9,11	7,88	9,54
	Vestas V39	Export	43,99	39,92	44,14	22,18	10,33	10,81	5,56	7,26	19,57	28,04	30,85	46,57	25,77
		Import	6,78	7,22	7,12	8,87	10,15	9,41	11,08	10,81	8,96	7,37	8,00	6,78	8,55

Table 10: Battery storage table showing hourly export and import of electricity from a monthly average.

On Table 10 we see that the T100 in *Vestfold og Telemark* performs very poorly, exporting very little to the grid and having to import 12,47 kWh compared to 16,87 kWh of the average power demand for that county from Table 8. In *Møre og Romsdal* we see that the V39 performs the best being able to export on average 40,36 kWh, however, the import is still high (8,41 kWh), approximately 50% of the average power demand in that county (see Table 8).

County	Turbine		Month (average taken between 2010 to 2018)												Average
			January	February	March	April	May	June	July	August	September	October	November	December	
Rogaland	T100	Export	21,75	18,66	12,00	10,05	8,99	8,25	5,99	7,90	11,80	18,90	16,82	22,37	13,62
		Import	6,74	7,53	8,36	8,18	8,12	8,69	9,10	8,43	7,37	6,47	7,04	6,24	7,69
	ACSA A27	Export	42,90	35,85	21,85	17,15	15,60	13,55	10,07	13,56	20,43	34,23	31,16	44,85	25,10
		Import	5,74	6,54	7,26	7,14	7,02	7,78	8,08	7,42	6,33	5,60	6,01	5,15	6,67
	Vestas V39	Export	90,65	75,45	46,67	36,41	33,86	28,95	22,16	29,40	43,24	70,58	65,37	95,11	53,15
		Import	4,95	5,72	6,33	6,27	6,07	6,98	7,16	6,54	5,48	4,91	5,20	4,32	5,83
Innlandet	T100	Export	2,70	2,88	4,23	2,58	1,05	1,39	0,59	0,56	1,68	2,13	2,26	4,38	2,20
		Import	14,51	14,02	12,87	12,72	13,43	12,19	12,96	13,62	12,89	12,87	13,88	13,40	13,28
	ACSA A27	Export	5,36	5,76	8,31	4,95	2,00	2,64	1,19	1,11	3,19	4,00	4,48	8,69	4,31
		Import	13,33	12,84	11,73	11,64	12,29	11,01	11,87	12,62	11,73	11,67	12,71	12,22	12,14
	Vestas V39	Export	12,77	13,73	18,93	11,81	5,44	7,07	3,69	3,31	8,11	9,83	10,79	19,96	10,45
		Import	12,25	11,78	10,68	10,66	11,19	9,90	10,82	11,65	10,68	10,59	11,66	11,18	11,09
Viken	T100	Export	2,42	2,33	2,79	1,90	0,84	0,91	0,43	0,55	1,68	1,77	2,15	4,28	1,84
		Import	14,27	13,94	13,14	12,83	13,42	12,51	12,92	13,51	12,74	12,69	13,33	13,14	13,20
	ACSA A27	Export	4,68	4,51	5,47	3,66	1,63	1,81	0,91	1,10	3,19	3,35	4,19	8,29	3,57
		Import	13,01	12,69	11,87	11,64	12,25	11,34	11,81	12,48	11,55	11,37	12,01	11,83	11,99
	Vestas V39	Export	11,50	11,22	13,26	9,28	4,72	5,25	3,15	3,33	8,19	8,68	10,53	19,25	9,03
		Import	11,91	11,58	10,76	10,59	11,16	10,25	10,73	11,49	10,49	10,22	10,86	10,72	10,90
Nordland	T100	Export	18,27	17,35	18,82	10,41	7,40	5,46	3,82	5,46	7,82	13,17	15,06	18,83	11,82
		Import	7,19	7,32	7,04	8,71	9,35	9,86	10,89	10,60	9,86	7,90	7,59	6,83	8,60
	ACSA A27	Export	35,59	33,28	36,97	18,82	12,90	9,44	6,65	9,32	14,29	23,74	29,01	36,50	22,21
		Import	6,11	6,29	6,16	7,72	8,30	8,88	9,93	9,68	8,84	6,88	6,49	5,81	7,59
	Vestas V39	Export	75,46	70,72	78,35	40,14	28,28	21,13	15,08	20,34	31,08	50,09	62,01	77,52	47,52
		Import	5,28	5,45	5,41	6,87	7,38	7,98	9,05	8,88	7,97	6,06	5,62	5,02	6,75
Vestland	T100	Export	12,16	11,40	9,20	6,31	4,83	3,53	2,51	3,20	6,58	10,49	10,72	14,88	7,98
		Import	9,66	10,01	10,23	10,72	11,42	11,83	12,20	12,18	10,63	9,29	9,68	8,76	10,55
	ACSA A27	Export	23,94	22,05	17,50	11,20	8,71	6,12	4,38	5,64	11,86	19,39	20,17	29,52	15,04
		Import	8,66	9,10	9,25	9,80	10,53	11,00	11,38	11,38	9,71	8,36	8,69	7,79	9,64
	Vestas V39	Export	51,57	47,34	37,85	24,41	19,32	13,73	10,12	12,69	25,82	41,37	43,22	63,28	32,56
		Import	7,83	8,33	8,40	9,00	9,72	10,25	10,63	10,67	8,93	7,61	7,87	7,00	8,85

Table 11: Battery storage table showing export and import of electricity.

From Table 11 we can see that *Rogaland* and *Nordland* has the highest average export and smallest import of electricity. *Innlandet* and *Viken* are very similar on average with low export and high import. However, *Innlandet* has higher export compared to *Innlandet*, but also import.

What we can gather from the Table 10 and Table 11 is that the export increases more with a more powerful turbine and the import has less of a change compared to export. This is likely due to the periods where the wind speed is below the cut-in of the turbines.

Power production system

If we compare Table 9 and the same system, but with the battery as energy storage, we can see if each county's SSR, SCR, LOLP, and Ab improve. Where the SSR show how self-sufficient the farm is. The SCR will tell how much of the generated electricity from the turbine is used for on-site consumption and the remaining being exported to the grid. The LOLP is the fraction of time when the site is unable to generate enough electricity to meet the demand. Ab is the fraction of time when 100% of the demand can be matched by on-site electricity generation.

County	Turbine	Without battery				With battery			
		SSR	SCR	LOLP	Ab	SSR	SCR	LOLP	Ab
Agder	T100	41,3 %	41,3 %	70,5 %	29,5 %	47,9%	52,9%	63,9%	36,1%
	ACSA A27	49,1 %	36,8 %	63,0 %	37,0 %	56,9%	42,8%	55,0%	45,0%
	Vestas V39	55,2 %	23,4 %	53,1 %	46,9 %	64,3%	27,5%	46,3%	53,7%
Troms og Finnmark	T100	36,9 %	40,4 %	72,7 %	27,3 %	43,1%	47,4%	67,3%	32,7%
	ACSA A27	41,6 %	30,8 %	68,1 %	31,9 %	48,4%	36,1%	62,2%	37,8%
	Vestas V39	45,3 %	19,0 %	61,5 %	38,5 %	53,2%	22,6%	56,6%	43,4%
Møre og Romsdal	T100	34,9 %	37,5 %	73,4 %	26,6 %	40,6%	44,0%	68,5%	31,5%
	ACSA A27	39,3 %	27,9 %	69,2 %	30,8 %	45,6%	32,7%	63,9%	36,1%
	Vestas V39	42,6 %	16,9 %	63,4 %	63,4 %	49,8%	20,1%	59,0%	41,0%
Vestfold og Telemark	T100	22,3 %	56,9 %	86,4 %	13,6 %	26,1%	66,6%	82,8%	17,2%
	ACSA A27	28,3 %	49,1 %	81,4 %	18,6 %	33,3%	57,9%	76,6%	23,4%
	Vestas V39	32,8 %	33,1 %	74,2 %	25,8 %	39,7%	40,6%	69,6%	30,4%
Trøndelag	T100	31,4 %	45,1 %	78,3 %	21,7 %	36,9%	53,1%	73,3%	26,7%
	ACSA A27	37,3 %	36,2 %	72,9 %	27,1 %	43,8%	42,6%	67,1%	32,9%
	Vestas V39	41,8 %	23,0 %	65,5 %	34,5 %	49,6%	27,5%	60,4%	39,6%
Rogaland	T100	46,5 %	35,7 %	63,4 %	36,6 %	53,8%	41,6%	56,7%	43,3%
	ACSA A27	52,1 %	26,5 %	57,8 %	42,2 %	59,9%	30,7%	50,5%	49,5%
	Vestas V39	56,5 %	16,0 %	50,3 %	49,7 %	65,0%	18,6%	44,5%	55,5%
Innlandet	T100	18,9 %	58,4 %	89,1 %	10,9 %	22,2%	68,1%	86,2%	13,8%
	ACSA A27	24,5 %	51,0 %	84,9 %	15,1 %	28,9%	59,9%	80,9%	19,1%
	Vestas V39	28,9 %	34,9 %	78,4 %	21,6 %	35,0%	42,5%	74,1%	25,9%
Viken	T100	18,8 %	59,3 %	89,5 %	10,5 %	22,0%	69,3%	86,3%	13,7%
	ACSA A27	24,8 %	52,0 %	84,8 %	15,2 %	29,2%	61,3%	80,4%	19,6%
	Vestas V39	29,4 %	35,5 %	77,8 %	22,2 %	35,7%	43,3%	73,3%	26,7%
Nordland	T100	42,6 %	37,1 %	67,4 %	32,6 %	49,4%	43,2%	61,2%	38,8%
	ACSA A27	48,0 %	27,4 %	62,0 %	38,0 %	55,3%	31,7%	55,3%	44,7%
	Vestas V39	52,1 %	16,5 %	54,7 %	45,3 %	60,3%	19,3%	49,3%	50,7%
Vestland	T100	31,7 %	40,8 %	76,6 %	23,4 %	37,1%	48,2%	72,0%	28,0%
	ACSA A27	36,5 %	31,6 %	72,2 %	27,8 %	42,6%	37,3%	67,0%	33,0%
	Vestas V39	40,1 %	19,6 %	66,0 %	34,0 %	47,2%	23,6%	61,6%	38,4%

Table 12: Table showing the SSR, SCR, LOLP, and Ab averaged over all selected locations for each county, with and without a battery for energy storage.

On Table 12 we can see that the changes in SSR are very similar between the counties, except in *Innlandet* and Viken which have slightly lower changes in SSR compared to the other counties. We can see that the SCR has increased most for these counties with weak wind, especially for the smaller T100 turbine. *Agder, Rogaland,* and *Nordland* have had the highest reduction in LOLP with the addition of a battery, and of *Innlandet* and *Viken* the LOLP changes less.

5. Discussion

5.1 Where in Norway are the best wind conditions for turbines.

Figure 13 shows that the best wind conditions are in *Rogaland*, with *Nordland, Møre og Romsdal, Troms og Finnmark*, and *Agder* having good wind conditions, especially near the coast (Figure 17). *Vestland* is in the middle of the counties, *Trøndelag, Vestfold og Telemark, Viken*, and *Innlandet*, with the worst wind speed out of the ten counties. Looking at the power coefficiency of the three turbines and comparing them against Figure 19, we can see that the Vestas V39 turbine has the potential to extract most of the wind available. Though the T100 turbine has the lowest power coefficiency, we can still expect it to perform better in lower wind situations due to its lower cut-in. We can see this in the capacity factor map (Figure 21), where the T100 can reach closer to its theoretical max power output. The ACSA A27 and Vestas V39 have similar capacity factors even if the V39 has double the rated power; this means that the V39 can generate close to double the electricity of the A27, and we can see this on the power map (Figure 20). The T100 in Figure 20 has the lowest power output of the three turbines; however, the three turbines have very similar electricity generation in inland areas. This means there is little gain when increasing turbine size, so having small-scale turbines might be the best option for these areas.
Looking at Table 7 and Figure 22 to Figure 24, we can see that the wind is more stable throughout the year in the counties where the wind is weaker and fluctuates more in areas where the wind is stronger.

When we add power generation and power demand together, as seen in Figure 22, Figure 23, and Figure 24, the V39 turbine is the only turbine that seems to generate enough electricity throughout a year. However, comparing power generation to power demand from Figure 25 and Figure 26, we can see that the T100 and A27 turbines struggle to generate enough electricity during summer.

5.2 Use of batteries

In Table 10 and Table 11, I added batteries to the system that can store excess energy. Areas with high winds benefited by exporting more electricity to the grid, and areas with less wind can be more self-sufficient, as shown in Table 12. Here we can see that adding a battery to store energy will benefit the system up to a certain point, low wind areas like Innlandet still have a loss of load probability of 74,1 % with a battery, and none of the counties are able to be 100 % self-sufficient.

However, this might not be true for some areas on the coast. It is clear from Table 12 that adding a battery for energy storage benefits the system as a whole.

However, are batteries the best solution for storing electricity? Batteries consist of multiple rare earth metals like lithium and cobalt; these rare earth metals are limited and will eventually run out. Cobalt is a particular issue as only the Democratic Republic of Congo is the only major exporter of cobalt in the world (Kelly, 2023). Congo is known for its political difficulties and work that takes place in poor conditions, which can lead to uncertainty around the export of cobalt. In 1978, the price of cobalt skyrocketed due to internal conflicts, and this is referred to as the "Cobalt Crisis" (Gourley, Or, & Chen, 2020).

5.3 SDGs

The topic of this thesis can fall under some of the UN’s sustainable development goals. Therefore, I have selected the most relevant SDGs for this thesis topic.

7. Clean and affordable energy

As the average temperature increases around the world, wind turbines are a crucial way to slow down or stop the temperature increase we expect in the coming year. In the thesis, I selected locations having a total of 37 682 agricultural properties, and if the data is representative, we assume that adoption is high and that 5 % of these properties install one Vestas V39 wind turbine, which would be a total of 942 MW of potential electricity. If we look at the average capacity factor of the Vestas V39 turbine, which is 8 %, we can expect a yearly production of 660 GWh of electricity. This is 0.42 % of the total yearly energy demand for 2021 in Norway and 5.6 % of the total wind power production for 2021 (SSB, 2023). It is possible to assume that this added electricity to the grid would lower electricity prices, especially when there is not enough water for hydroelectric dams to generate enough electricity.

13. Climate Action

Wind turbines are a renewable energy source with no emissions during operation. Comparing wind turbine emissions against other energy sources from Figure 9, we can see that wind turbines emit 11 grams of CO_2/kWh, coal 980 grams CO_2/kWh. However, this data is from large-scale wind turbines, other papers show that a medium-scale turbine (500 kW) emits approximately 30 grams of $CO_{2\text{-}eq}$/kWh, and a 100 kW turbine releases approximately 55 grams of $CO_{2\text{-}eq}$/kWh (Mendecka & Lombardi, 2019). So, the smaller the turbine, the more CO_2 it will release during its lifetime. However, it is not wise to install larger turbines only due to the CO_2 released during its lifetime.

Larger turbines require more materials and metals. Compared to other sources of electricity, wind turbines are among the cleanest. If we take the yearly production from earlier of 660 GWh yearly and compare that to the leading electricity source, coal (2019) (Ritchie, Roser, & Rosado, 2022) we can see how big the difference is between the two technologies. A coal power plant with a CO_2 emission of 900 g CO^2/kWh totalling 646 800 tons CO^2. For the 500 kW turbines this would result in 19 800 tons of CO_2. This means that a coal power plant releases 30 times more CO_2 than a 500 kW wind turbine.

However, the fact that wind turbines can contribute to cleaner and more affordable energy, does not mean that they are not harmful. Some of the SGDs can conflict with the gathering of material for the construction, operation, and the end of life for wind turbines.

12. Responsible Consumption and Production

As mentioned above and in the LCA in Chapter 9.6, the wind turbine uses various metals for its construction. These metals are a finite resource and will run out eventually. Many renewable technologies rely on these metals, including wind turbines (Hayes, 2020). It is crucial that wind turbines get used for as long as possible, and at the end of the life of the turbine, it gets recycled. However, currently not everything on the turbine can be recycled, such as the blades connected to the hub which are made of fibreglass. They are not recyclable due to current recycling methods that destroy the glass fibre, decreasing its strength and durability (Conserve Energy Furture, n.d.). However, recent advancements have made it possible to recycle fibreglass, this is still new tech, and it remains to be seen if it will be cheaper to make new fibreglass than to reuse (Energy.gov, 2022).

14. Life Below Water

To meet demand future demand for metals, companies are exploring the potential of seafloor mining as the demand for these rare metal increase with the demand for more renewable energy sources. However, though sea floor mining might sound like a good idea to meet future demand, it is unknown territory, and we do not know the consequence the mining activities will have on fish and plants and the ecosystem.
The currently proposed method for collecting these nodules is with a rover that is connected to a boat with a pipe that brings the nodules and other materials like ocean sediments up to the boat. These sediments must then be dumped from the boat at 1000 meters below the ocean surface as the sunlight cannot reach further than 1000 meters. This is done to avoid the sediments blocking the sunlight and stopping photosynthesis. These sediments then gently drop to the ocean floor again;

however, due to ocean currents, these sediments can travel long distances past the mining area. This might cover plants and ocean-dwelling creatures with the sediments, limiting their ability to feed.

15. Life on Land

In chapter 4.5.4 we looked at the impact of wind turbines on wildlife. It is undoubtedly that wind turbines cause deaths among local fauna, and the placement of these turbines is related to this. Wind turbines on farms will likely have less of an impact on local fauna due to the turbine's smaller size and location. Current wind farms are placed primarily on areas untouched by humans; farms are in areas with human activities, and there is less likelihood that this will disturb feeding grounds for reindeer and flying predators. Unfortunately, there is no existing research on the effects on local fauna near small and medium turbines placed on farms, so it's impacts it will genuinely have, are uncertain.

5.4 Societal opinion towards turbines (and how it might affect adoption)

Conflicts surrounding wind turbines are often in the news, usually regarding the destruction of untouched nature and feeding grounds for fauna. Societal opinions on wind turbines and where they should be placed are mixed. From a study looking at societal opinion on wind turbines on land or sea, they found that people born in 1959 or earlier are 45% positive towards wind turbines on land, 1960 – 1989 at 42%, and people born in 1990 or later are 41% for wind turbines on land; both generations do agree that they prefer offshore wind turbines over land-based turbines (Gregersen, 2022). The Fosen case recently had large engagements in the news due to the wind farm disrupting the Sami people's reindeer husbandry.

In the results, we see that there are good wind conditions in Sørlandet (Agder), Vestlandet (Rogaland, Vestland, and Møre og Romsdal), Trøndelag, and Nord-Norge (Nordland and Troms og Finnmark). These areas have the highest negativity towards turbines on land (Gregersen, 2022), which are also areas where there are multiple wind farms already existing. Indicating that people are more in favour of wind turbines on land if they do not have wind turbines nearby.

5.5 Weaknesses and limitations

Due to time constraints and difficulties with Matlab, some things were omitted from the calculations. The power calculations for the three turbines used a relatively simple way to calculate electricity output. It would have been better to use each turbine's power coefficiency to get a more accurate electricity output unique to each turbine.

The battery system used a simple model; in an actual situation, there would be more losses, varying charging- and discharging rates, and max charge depending on temperature.

The electricity usage calculations for the milk barn and household are for a specific size; therefore, the power consumption part may be less general than the production part.

5.6 Future work

I only looked at average wind speeds for every county in Norway, I would recommend a future study that would go into more detail for each county with comparisons between coastal areas and inland areas. A study where the income that a turbine may generate from the electricity it exports may be interesting with the addition of the cost of the turbine and maintenance.

6. Conclusion

In this thesis, I have looked closer at the research questions, "*How significant is the wind and power generation potential on Norwegian farms.", "What is the typical power production potential for each county?"*, "*How does it compare to the power demand for a typical milk barn and household?*", and *"What sustainability issues can turbines cause?"* In my analysis, I use the NORA3 wind dataset for 10- and 50 meters and temperature data for Norway. This was used in combination with a milk barn and a theoretical household to see the electricity demand against the electricity production of three turbines. the data was separated into 11 counties and calculated using the programming language Matlab. Through the results and discussions, I have come to the following conclusions.

The results show that the best average wind conditions at 40 meters are in coastal areas such Rogaland, Vestland, Agder, Møre og Romsdal, and Nordland. Further inlands, the wind speed stagnates we see this in Innlandet, Viken, and Vestfold og Telemark.

Rogaland has a power potential of 22 kW/m^2 at 10 m/s, which is the highest of the other counties. Nordland, with good average wind condition and Møre og Romsdal, Troms og Finnmark, Vestland, Trøndelag and Agder having average wind conditions. In Nordland at 10 m/s the power potential is at 18,6 kW/m^2, and Agder, Møre og Romsdal, Troms og Finnmark, Vestland, and Trøndelag, at a power potential between 11,7 to 16 kW/m^2 at 8 to 11 m/s. Vestfold og Telemark, Viken, and Innlandet have the worst average wind speed out of the ten counties. Vestfold og Telemark is slightly higher at 8,4 kW/m^2 for 6 m/s. Innlandet and Viken are mostly similar with a power potential of 7 kW/m^2 at 5-6 m/s.
The largest turbine (Vestas V39) generates the most amount of electricity in all areas, however, by looking at the capacity factor, the smaller turbine (T100 turbine) can reach closer to its rated power output.

Looking at power generation to power demand, we can see that the small (T100) and medium-sized (A27) turbines struggle to generate enough electricity during summer periods. The Vestas V39 can meet the average demand for most areas. The SSR (self-sustainability ratio) shows that *Rogaland* is the highest performer out of the other counties, at 56.5% for the V39. Innlandet has the lowest SSR at 28.9% for the V39.
The LOLP (loss-of-load probability) in Rogaland is as high as 50.3% for the V39. In the counties where the wind in not as strong, such as *Vestfold og Telemark*, *Innlandet*, and *Viken* the loss of load probability is higher than 80% for the smaller T100 turbine and 75% for the V39.

Adding a battery with 125 kWh nominal capacity (approximately twice the size of an ordinary electric vehicle battery). From the results it is clear that adding a battery as energy storage benefits the system. We can see that the SSR increases very similarly between the counties, except in *Innlandet* and Viken which have slightly lower changes in SSR compared to the other counties. We can see that the SCR has increased most for these counties with weak wind, especially for the smaller T100 turbine. *Agder, Rogaland,* and *Nordland* has had the highest reduction in LOLP with the addition of a battery, and of *Innlandet* and *Viken* the LOLP changes less.

Though wind turbines are beneficial and will reduce GHG emissions, there are issues related to them, where turbines can conflict with the SDGs. The material extraction where we will have to resort to deep-sea mining can disrupt the local ecosystem and the effects wind turbines have on local fauna.

Bibliography

ACCIONA. (n.d.). *Wind power storage plant*. Retrieved from Sustainability for all: https://www.activesustainability.com/renewable-energy/wind-power-storage-plant/?_adin=02021864894

Argolabe Ingeniería. (n.d.). *T100 100kW Wind turbine.* Retrieved from Argolabe: http://www.argolabe.es/pdf/Argolabe(en).pdf

Arvesen, A., & Hertwich, E. G. (2012, Aug 10). *Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs.* Retrieved from Elsevier: https://www.sciencedirect.com/science/article/pii/S1364032112004169?via%3Dihub

Baerwald, E. F., D'Amours, G. H., Klug, B. J., & Barclay, R. M. (2008, Aug 26). *Barotrauma is a significant cause of bat fatalities at wind turbines.* Retrieved from ScineceDirect: https://www.sciencedirect.com/science/article/pii/S0960982208007513

Bevanger, K., May, R., & Stokke, B. (2017, October). *Center for Environmental Design of Renewable Energy.* Retrieved from Landbasert vindkraft: Utfordringer for fugl, flaggermus og rein: https://brage.nina.no/nina-xmlui/bitstream/handle/11250/2419532/ninatemahefte66.pdf?sequence=6&isAllowed=y

Conserve Energy Furture. (n.d.). *Is Fiberglass Recyclable?* Retrieved from Conserve Energy Future: https://www.conserve-energy-future.com/is-fiberglass-recyclable.php#:~:text=Fiberglass%20is%20not%20recycled%20because,as%20recyclable%20as%20other%20plastics.

Energifakta Norge. (2022, May 13). *Kraftproduksjon.* Retrieved from Olje- og energidepartementet: https://energifaktanorge.no/norsk-energiforsyning/kraftforsyningen/#vindkraft

Energy.gov. (2022, Oct 17). *Carbon Rivers Makes Wind Turbine Blade Recycling and Upcycling a Reality With Support From DOE*. Retrieved from Energy Efficiency & Renewable Energy: https://www.energy.gov/eere/wind/articles/carbon-rivers-makes-wind-turbine-blade-recycling-and-upcycling-reality-support

Energysage. (2022, Mar 9). *Wind energy pros and cons*. Retrieved from U.S. Department of Energy: https://www.energysage.com/about-clean-energy/wind/pros-cons-wind-energy/#:~:text=On%20the%20cons%20side%2C%20wind,of%20generating%20electricity%2024%2F7.

Gjølstad, M. (2023, January 12). *Norges Bondelag.* Retrieved from Invisteringer i fornybar energi på gårdsbruk - valg av saldogruppe mv.: https://www.bondelaget.no/jus-og-okonomi/skatt-regnskap-og-trygd/fagartikler/skatt-og-avgift/investeringer-i-fornybar-energi-pa-gardsbruk-valg-av-saldogruppe-mv

Gourley, S. W., Or, T., & Chen, Z. (2020, Sep 25). *Breaking Free from Cobalt Reliance in Lithium-Ion Batteries*. Retrieved from ScienceDirect: https://www.sciencedirect.com/science/article/pii/S2589004220306970

Gregersen, T. (2022, Jan 26). *Folket vil ha havvind - delt på midten om vindkraft på land*. Retrieved from Energi og Klima: https://energiogklima.no/nyhet/folket-vil-ha-havvind-delt-pa-midten-om-vindkraft-pa-land/

Haakenstad, H., Breivik, Ø., Furevik, B. R., Reistad, M., Bohlinger, P., & Aarnes, O. J. (2021, Oct 06). *NORA3: A Nonhyfrostatic High-Resolution Hindcast of the North Sea, the Norwegian Sea, and the Barents Sea*. Retrieved from American Meteorological Society: https://journals.ametsoc.org/view/journals/apme/60/10/JAMC-D-21-0029.1.xml

Hayes, C. (2020, Sep 14). *What will happen whan the raw materials run out?* Retrieved from The Institution of Engineering and Technology: https://eandt.theiet.org/content/articles/2020/09/what-will-happen-when-the-raw-materials-run-out/#:~:text=The%20reserves%20of%20some%20rare,quantities%20in%20the%20Earth%27s%20crust.

Honsberg, C., & Bowden, S. (2019). *Photovoltaics Education Website*. Retrieved from https://www.pveducation.org

Kelly, L. (2023, Feb 23). *Top 10 Cobalt Producers by Country (Updated 2023)*. Retrieved from Investing News Network: https://investingnews.com/where-is-cobalt-mined/

Klipping, A., & Trømborg, E. (2015, Oct 22). *Hourly electricity consumption in Norwegian housholds - Assessing the impacts of different heating systems.* Retrieved from Elsevier: https://www.sciencedirect.com/science/article/pii/S0360544215012050

Klipping, A., & Trømborg, E. (2016, Feb 23). *Modeling and disaggregating hourly electricity consumption in Norwegian dwellings based on smart meter data.* Retrieved from ScianceDirect: https://www.sciencedirect.com/science/article/pii/S0378778816301001?via%3Dihub

Kommunal- og distriktsdepartementet. (2019, 12 19). *Fylkessammenslåinger i regionreformen*. Retrieved from Regjeringen.no: https://www.regjeringen.no/no/tema/kommuner-og-regioner/regionreform/regionreform/nye-fylker/id2548426/

Korthauer, R. (2018). *Lithium-Ion Batteries: Basics and Applicatons.* Germany, Kriftel: Springer.

Leloudas, G., Zhu, W. J., Sørensen, J. N., Shen, Z. W., & Hjort, S. (2007). *Prediction and Reductio of Noise from a 2.3 MW Wind Turbine.* Retrieved from IOPscience: https://iopscience.iop.org/article/10.1088/1742-6596/75/1/012083

Mai, T., Wiser, R., Sandor, D., Brinkman, G., Heath, G., Denholm, P., . . . Strzepek, K. (2012). *Exploration of High-Penetration Renewable Electricity Futures.* Retrieved from National Renewable Energy Laboratory: https://www.nrel.gov/docs/fy12osti/52409-1.pdf

Mendecka, B., & Lombardi, L. (2019, May 24). *Life cycle environmental impacts of wind energy technologies: A review of simplified models and harmonization of the results.* Retrieved from Elsevier: https://www.sciencedirect.com/science/article/pii/S1364032119303259

NASA. (2023, Apr 20). *Global climate change*. Retrieved from NASA: https://climate.nasa.gov/

National Academies of Sciences, Engineering, and Medicine. (2005). *Facilitating Interdiciplinary Research.* Retrieved from The National Academies Press: https://doi.org/10.17226/11153

Nilsen, K. L. (2021, Nov 21). *Denne gården drives med sol, vind og hydrogen*. Retrieved from Teknisk Ukeblad: https://www.tu.no/artikler/denne-garden-drives-med-sol-vind-og-hydrogen/515059

Noregs vassdrag- og energidirektorat. (n.d.). *Saksgang for konsesjonsbehandling av vindkraft*. Retrieved from NVE: https://www.nve.no/konsesjon/konsesjonsbehandling-og-oppfoelging-av-vindkraft-paa-land/konsesjonsbehandling-av-vindkraftverk-paa-land/

Noregs vassdrags- og energidirektorat. (n.d.). *Anleggskonsesjon for vinkraft med installert effekt ≤ 10 MW.* Retrieved from NVE: https://www.nve.no/media/2247/veileder-vindkraftverk-tom-10-mw.pdf

Norges vassdrags- og energidirektorat. (2023, January 18). *NVE.* Retrieved from Plusskunder: https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/nettleie/tariffer-for-produksjon/plusskunder/

Norgesvel. (n.d.). *Norgesvei*. Retrieved from Vindturbin på Lundal gård i Undheim: https://www.norgesvel.no/fornybart-paa-garden/lundal-gard

NORSUS. (n.d.). *Norwegian insitute for Sustainable Research*. Retrieved from About Life Cycle Assessment (LCA): https://norsus.no/en/om-livslopsvurdering/

Nyhus, H. (2022, Sep 27). *Ny rapport talfestar kor mykje ekstra straum Noreg treng til klimatiltak*. Retrieved from NRK: https://www.nrk.no/vestland/ny-rapport-talfestar-kor-mykje-ekstra-straum-noreg-treng-til-klimatiltak-1.16117234

Öberg, G. (2011). *Interdisciplinary Environmental Studies: A Primer.* Chichester, West Sussex, UK: Wiley-Blackwell.

Olje- og energidepartementet, kommunal- og moderniseringsdepartementet. (2015, May). *Veileder for kommunal behendling av minder vindkaftanlegg.* Retrieved from NVE: https://www.nve.no/media/2248/veilder-mindre-vindkraftanlegg.pdf

Podmore, L. (2022, February 24). *AZO Materials.* Retrieved from What Materials are Used to Make Wind Turbines?: https://www.azom.com/article.aspx?ArticleID=21371

Regjeringen. (2022, Nov 03). *Nytt norsk klimamål på minst 55 prosent*. Retrieved from Regjeringen.no: https://www.regjeringen.no/no/aktuelt/nytt-norsk-klimamal-pa-minst-55-prosent/id2944876/

REUK.co.uk. (n.d.). *Betz Limit*. Retrieved from The Renewable Energy Website: http://www.reuk.co.uk/wordpress/wind/betz-limit/

Ritchie, H., Roser, M., & Rosado, P. (2022). *Energy*. Retrieved from OurWorldInData.org: https://ourworldindata.org/electricity-mix

Rittel, H. W., & Webber, M. M. (1973, June). *Dialemmas in a general theory of planning.* Retrieved from Springer: https://doi.org/10.1007/BF01405730

Sæter, L. J., & Kvande, I. (2021, Feb 19). *Energiforbruk i melkefjøs - Forbruksmønster og mulighet for energisparing.* Retrieved from NORSØK: https://orgprints.org/id/eprint/39419/

Sayed, E. T., Wilberforce, T., Elsaid, K., Rabaia, M. H., Abdelkareem, M. A., Chae, K.-J., & Olabi, A. G. (2020, Dec 14). *A critical review on environmental impacts of renewable energy systems and mitigation stratagies: Wind, hydro, biomass and geothermal*. Retrieved from Elsevier: https://www.sciencedirect.com/science/article/pii/S0048969720380360?via%3Dihub

Solbrekke, I. M., Sorteberg, A., & Haakenstad, H. (2021, Nov 30). *The 3km Norwegian reanalysis (NORA3) - a validation of offshore wind resources in the North Sea and the Norwegian Sea.*

Retrieved from European Academy of Wind Energy: https://wes.copernicus.org/articles/6/1501/2021/

Solvind Prosjekt AS. (n.d.). *Åsen 2 - på Åsen gård*. Retrieved from Solwind: https://solvind.no/prosjekter/asen-2-pa-asen-gard/

SSB. (2023, Feb 08). *Statistisk sentralbyrå.* Retrieved from Gardsbruk, jordbruksareal og husdyr: https://www.ssb.no/jord-skog-jakt-og-fiskeri/jordbruk/statistikk/gardsbruk-jordbruksareal-og-husdyr

SSB. (2023, Mar 14). *Statistisk sentralbyrå.* Retrieved from Elektrisitet: https://www.ssb.no/energi-og-industri/energi/statistikk/elektrisitet

Statistisk sentralbyrå. (2020, April 16). *SSB*. Retrieved from Kart og geodata fra SSB: https://www.ssb.no/natur-og-miljo/geodata#Nedlasting_av_rutenettsstatistikk

Tabassum-Abbasi, Premalatha, M., Abbasi, T., & Abbasi, S. A. (2013, Dec 18). *Wind energy: Increasing deplyment, rising environmental concerns*. Retrieved from Elsevier: https://www.sciencedirect.com/science/article/pii/S1364032113007685?via%3Dihub

Tummala, A., Velamati, R. K., Sinha, D. K., Indraja, V., & Krishna, V. H. (2015, Dec 30). *Elsevies.* Retrieved from A review on small scale wind turbines: https://www.sciencedirect.com/science/article/abs/pii/S1364032115014100?via%3Dihub

U.S. Department of Energy. (2015, Mar 12). *Wind Vision: A New Era for Wind Power in the United States.* Retrieved from Energy.gov: https://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf

UN. (n.d.). *Sustainable Development Goals*. Retrieved from United Nations Development Progamme: https://www.undp.org/sustainable-development-goals

Watson, D. E. (2015). *Wind Turbine Efficiency*. Retrieved from FT Exploring: https://www.ftexploring.com/wind-energy/wind-turbine-efficiency.htm

Wind Turbine Models. (2017, Aug 16). *Vestas V39*. Retrieved from wind-tubine-models.com: https://en.wind-turbine-models.com/turbines/383-vestas-v39

Wind Turbine Models. (2022, Jan 30). *ACSA A27/225*. Retrieved from wind-turbine-models.com: https://en.wind-turbine-models.com/turbines/817-acsa-a27-225