# Limiting the carbon dioxide emission aboard an offshore salmon farm by introducing a wind and battery system.

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# Oppsummering

Oppgåva vil sjå på moglegheita til å bruke vindkraft og batteri til å avgrense bruken av dieselgenerator, og dermed kutte utslepp av karbondioksid med 80 % om bord dei planlagde offshore lakseoppdrettsanlegga til SalMar AS, kalla Ocean Farm 1. Dette blir gjort gjennom simulasjonar i kode-programmet Python. Ved å kombinere forbruksdata frå eit anlegg saman til forbruket frå seks anlegg, kan det bli laga eit teoretisk forbruk. Dette kan bli samanlikna med vinddata frå NORA-3WP [1], eit vindressursdatasett over Norden. Ved å hente ut data frå koordinatar foreslått av SalMar kan ein god indikasjon på kraftproduksjon frå vind bli skapa. Det blir brukt perturbasjonar som samanliknar resultat for fire konfigurasjonar av turbinar. Ein, to og tre av den vertikale typen SeaTwirl S2x [2] med 1 MW nominell effekt og ein turbin av den horisontale typen Siemens SWT-2.3-113 [3] som har 2.3 MW i nominell effekt. Dette blir samanlikna opp mot utan batteri og mot batteri med kapasitet på 1200, 1800 og 2400 kWh. Til slutt vil det ligge ein dieselgenerator på 4 MW i botn som reserve i lågproduksjons periodar. Desse scenarioa blir samanlikna opp mot eit grunntilfellet som berre bruker dieselgenerator for å dekkje straumbehov.

Resultata viser at det er mogleg å gå under 20 % av originalutslepp ved å bruke turbinen SWT-2.3-113, medan SeaTwirl sin vertikale turbin slit med å halde følgje. Dette er nok grunna forskjellane i høgde og kraftkurvene til turbinane. Det beste scenarioet blir rekna til å vere ein kombinasjon av SWT-2.3-113 turbinen, samt ein batterikapasitet på 1200 kWh. Dette er grunna at

utsleppet er under 20 % av grunntilfellet, og har ikkje eit større batteri enn det som trengs for å dekke det. Økonomisk sett er det forsett dyrt å kjøpe seg inn i offshore flytande vindkraft med høge installasjonskostnadar samt høg drift- og vedlikehaldskostnadar. Det er venta at levetidskostnadar vil gå frå 117 øre/kWh i 2021 til 68 øre/kWh i 2030 [4]. Ein djupare økonomisk analyse må gjennomførast før eit eventuelt system kan settast ut i praksis, men teoretiske utrekningar ved hjelp av vinddata tilseier at det er mogleg å avgrense utsleppa med 80 % ved hjelp av eit vind- og batterisystem.

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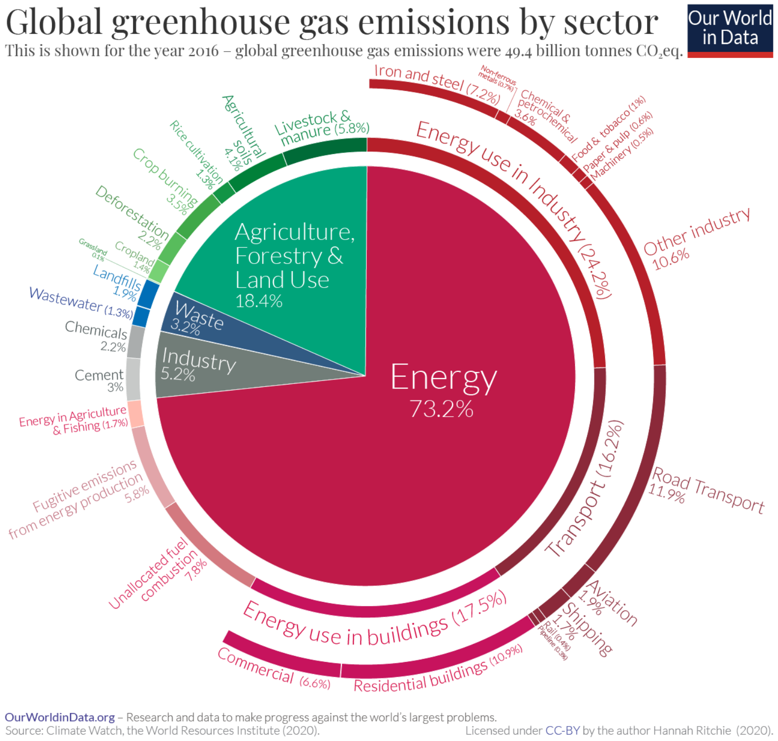
# Chapter 1

# Introduction

As climate change is a looming threat that becomes more urgent, the global community is starting to look towards how to brake the changes. One of the ways to do this is to limit what is considered one of the most important greenhouse gas [5], carbon dioxide. Norway decided after the UN Climate Change Conference 26 [6], or COP26 in Glasgow in 2021, to update their goals for 2030. This was revealed during COP27 in Egypt, where Norway issued a press release that the new goal was to reduce emissions by 55 % by 2030 compared to 1990 levels [7]. To reach this goal, a reduction of greenhouse gases must happen in many different sectors. According to OurWorldInData based on references such as the World Research Institute [8] and the 2014 AR5 IPCC report (The Intergovernmental Panel on Climate Change) [9], the agricultural sector stood for 18.4% of the global greenhouse gas emissions. While the livestock and manure emissions, a sub-sector within the agricultural sector, stood for 5.8% of the global emissions. Furthermore, 73.2% of the emissions is caused by the energy use in different sectors. The energy use in agriculture and fishing stands for 1.7% of the global greenhouse gas emissions.



Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes $CO_2$eq.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020).
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Figure 1.1: Global greenhouse gas emissions by sector in 2016. Gathered from OurWorldInData.org [10] under CC BY 4.0

The Norwegian Seafood Research Fund issued an environmental accounting of farmed salmon and other seafood in comparison to meat from chicken, pork, and cattle. This was done by SINTEF (The Foundation for Industrial and Technical Research), NTNU (Norwegian University of Science and Technology) and SIK (Swedish Institute for Food and Biotechnology) in 2009. The project resulted that for each produced edible kilo of fish sold in Paris, released a $CO_2$-equivalent of 2.5kilos [11]. The Swedish institute had numbers on the chicken, pork and cattle, which was at 2.5, 5.9, and 30 kilos respectively per kilo produced meat [11]. A later paper by SINTEF came with some different numbers based on where the fish is transported.

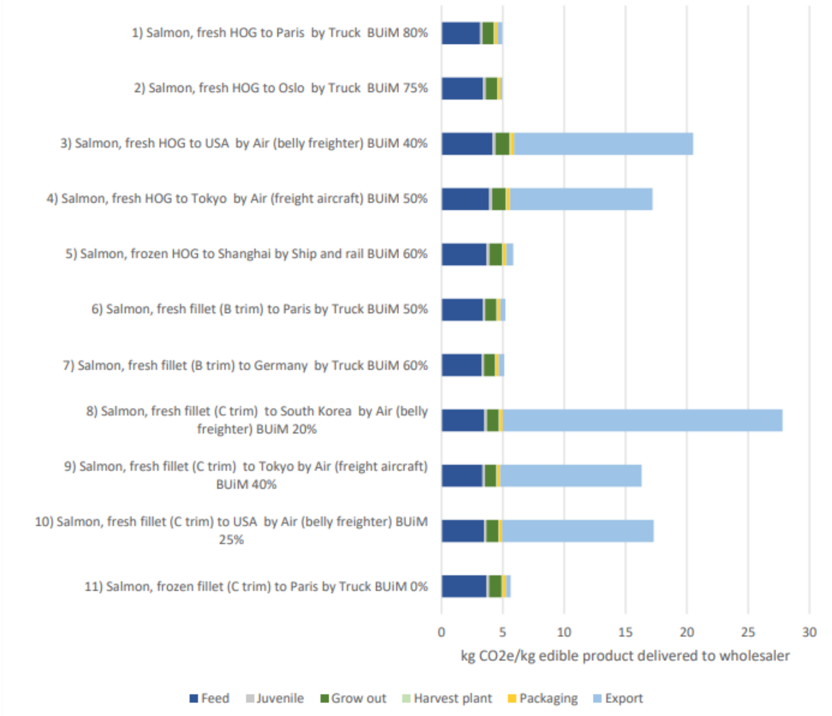


Figure 1.2: Greenhouse gas emissions per life cycle phase of all salmon products (kg $CO_2$e/kg edible product at wholesaler) BUiM = By-product use in market. Gathered from Sintef [12]. under CC BY-NC-ND 4.0

In this paper [12], the energy usage of the farms during production is regarded as quite low. The farms are close to shore and generally connected to the grid by cable. The emission of greenhouse gases would be higher if it was run by a diesel generator. By utilizing renewable energies, these emissions can be limited. This is what this thesis is looking into.

The research question is:

*How much is it possible to limit the emission by changing from diesel generator to a combination of wind energy, battery technology and diesel generator at an offshore salmon farm?.*

There are also several sub-questions that are sought to be answered:

- What configurations of turbine size and battery size is the most optimized towards limiting carbon dioxide?

- What configurations are the most economic?
- Is there a way to make it economically feasible?

This thesis is made using electricity consumption data provided by SalMar [13], a salmon farming company looking at the possibility to move the production and cultivation of salmon offshore. Currently the farms are in fjords and close to shore where the electricity is either supplied by land-cable or by diesel generators [14]. The option of land cable might not be viable when put offshore because of the distance and loss in power. The loss per kilometer is highly dependent on the cable length, cable diameter and frequency of the signal transmitted, but a cable of 200 km have a theoretical maximum efficiency of 94 % [15] and is generally lower. According to Professor Bjørn Gustavsen and research scientist Olve Mo, the loss in long cables can be optimized for efficiency by introducing a voltage control [15]. The loss can however, still amount to large economic costs. Then why move it offshore? Traditional fish farms have had problems with a build-up of faeces and waste at the sea bed, as well as diseases and the escaping of fish. This can be seen in the escape statistics from the Norwegian directorate of fisheries.

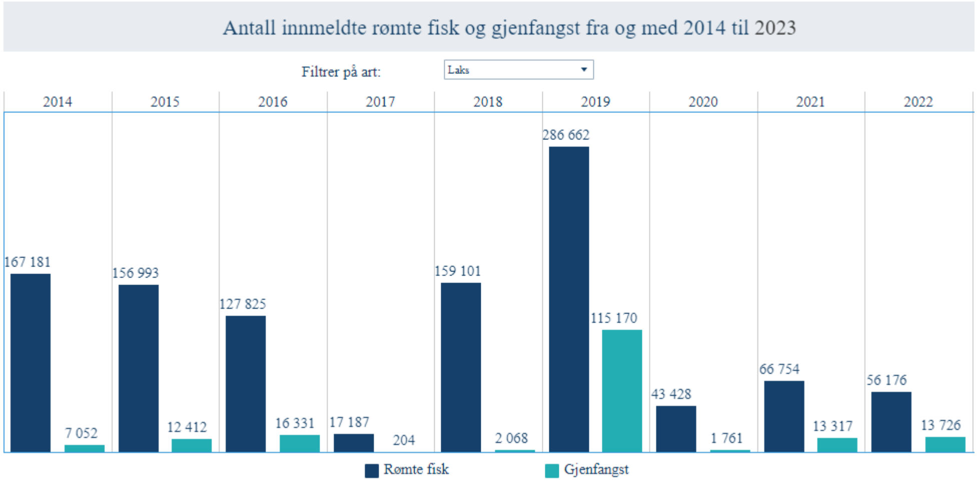


Figure 1.3: The columns show how many fish has escaped in dark blue and how many have been recaptured in light blue. These are reported numbers to the Directorate of Fisheries. It is expected that the real number of escaped fish are higher. Gathered from Directorate of Fisheries [16].

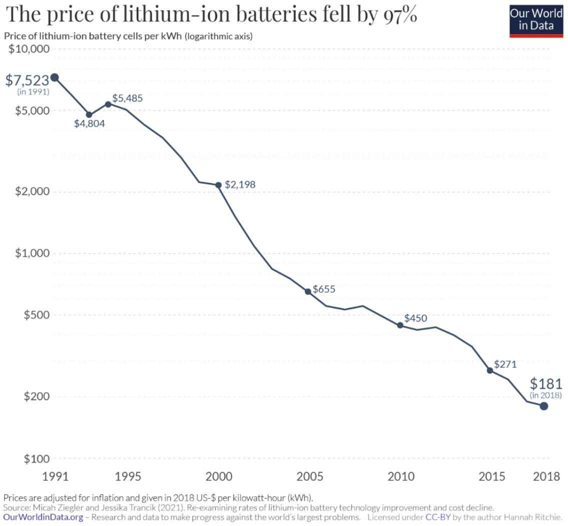
The numbers in figure 1.3 only consist of the amount of reported salmon escaped, it is believed that the number of escaped fish is even higher per year. The escaped fish goes up the rivers and spawns with the local wild salmon, changing the genetic makeup of the stock in that river [17]. This has caused controversy in the public eye and in several media outlets [18][19][20]. By moving it offshore, SalMar claims there will be a higher flow of water and the waste can be spread around rather than being concentrated in one area. This also applies for when fish escape. They will be diluted over many rivers and a larger area instead of taking over one river. SalMar is therefore developing a project called Ocean Farm, that aims at making it possible to move it offshore and out to sea [21]. They claim that during their two production cycles, there has been low mortality and disease [22]. There was no need for delousing treatments of the fish.

There is research that can be compared, although this is mostly towards salmon farms close to shore. Most of these are either running using diesel generators, or are connected to the grid using land cables. As seen in figure 1.2. The work in this paper is based an earlier master's thesis by Sindre Sandøy [13]. Sandøy looked at the same coordinates, with the same facility. Although Sandøy looked at the possibility of combining energy from wind power, combined with production and storage of hydrogen. The production of green hydrogen, hydrogen created using renewable energy or low-carbon power, is still a new field. The prices are therefore quite high and there is not really a market for buying hydrogen yet [23]. As hydrogen is volatile in contact with oxygen, storing it requires precaution. This makes it so that a lot of energy potential and production of hydrogen goes lost.

For this thesis, the focus of hydrogen will be shelved for the benefit of a battery system. This is done because of the general low prices of battery [24] as seen in figure 1.4. The three components in focus for this thesis, will therefore be wind energy, a battery system and a diesel generator as backup for low production hours. Perturbations of the amount of turbines and size of the battery capacity will be looked at. Different sizes on the battery capacity and the amount of turbines will indicate what can be more effective, towards both cost and to cover the needed consumption.

As the timeline is limited, the thesis will have some limitations. There are many other interesting renewable energy sources outside of wind power, such as solar, ocean, hydro and geothermal. Solar was especially interesting seeing as it produces the most in the summer, when the sun shines the most in both the North Sea and the Norwegian Sea. This corresponds well with wind energy, seeing that it produces less energy during the summer as the ocean and the wind is generally quieter. It would therefore have been interesting to look at a combination of these, but the thesis had to be limited and solar power at sea is still a largely unexplored project that is mostly in the concept and testing phase.

The paper will look at some relevant theory, mainly that of wind energy, battery technology and how a diesel generator works. Secondly the method



Prices are adjusted for inflation and given in 2018 US-$ per kilowatt-hour (kWh).
Source: Micah Ziegler and Jessika Trancik (2021). Re-examining rates of lithium-ion battery technology improvement and cost decline.
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the author Hannah Ritchie.

Figure 1.4: Shows the lithium-ion battery prices per kWh adjusted for inflation over the last three decades. Years from 1991 to 2018 on the x-axis and price on the y-axis. Gathered from OurWorldinData [24] under CC BY 4.0 based on data from [25].

section will look at the data, and how it is to be used. By utilizing the coding language Python, large amounts of data can be processed in what is called big data analysis. Through big data analysis it is possible to calculate and create scenarios that simulates how a potential facility of this size could benefit. By gathering information about relevant turbines and batteries, a picture of what can be used is created. Adding these to the python script and creating calculations on what is needed by comparing it to the consumption data from their test year, can create a valid picture of possible solutions. Then after creating some possible scenarios, putting them in an economic perspective can be beneficial for the company, and to see what are viable solutions.

The thesis, though mainly with a focus on energy is a master's thesis in sustainability. A central focus of the master's is the connectivity of disciplines and how they correlate to solve problems. How can we benefit from using different methods and concepts from other disciplines. Professor Gunilla Öberg wrote the book “Interdisciplinary environmental studies” [26], which investigates how to incorporate more than just one scientific discipline to projects. Depending on the project, it can be beneficial to contact local farmers or workers that are outside the scientific community but may sit on information that can be instrumental for the findings in the project. This is called interdiscplinarity and goes beyond the confines of the specific scientific discipline. For instance interviewing people who could be affected by the project would introduce a social science aspect. Further than this is transdisciplinarity, which is to go beyond the confines of the researches and invites for instance the local or fishermen into the research project as non-researching colleagues. For this thesis, no interviews will be conducted, and the thesis will be more towards a theoretical aspect. It can however be beneficial to use methods and concepts from different disciplines. Mainly the disciplines that will be used are from mathematics, physics, informatics and chemistry. The discussion chapter will broaden up the thesis somewhat from the narrow focus in the theory, method and result chapters. It will contain a broader look at the sustainability of what the thesis is trying to do and use concepts from Brian Wynne, Professor Emeritus of Science Studies, and Professor Gunilla Öberg.

The word sustainability has become a word that you see everywhere, but what really is sustainability? Sustainability is the ability to maintain or improve living conditions for current and future generations by preserving natural resources, protecting the environment, and promoting economic and social development. The concept of sustainability is based on the idea that the earth’s resources are finite and that human activity should be carried out in a way that does not deplete them or harm the environment. One of the more impactful report was the ”Our Common Future” report [27]. Written by the ”Brundtland commission”, it was lead by the then Prime Minister of Norway Gro Harlem Brundtland, on behalf of the United Nations.

The conclusion includes a definition of sustainable development which was popularized by the report:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. [27]

The report emphasized the need for international cooperation and the involvement of all sectors of society in achieving sustainable development. It also highlighted the urgency of addressing global environmental problems such as climate change, deforestation, and loss of biodiversity. Overall, the report called for a fundamental shift in the way we think about development and the environment, and it continues to be a significant influence on environmental policy and sustainable development efforts today.

A central aspect within sustainability is the precautionary principle. Originating from Germany, the principle has been included in countless treaties and policy documents regarding the protection and preservation of the environment [28]. One of the more prominent implementation is in the 1992 Rio Declaration [29]. Principle 15 states "*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*" [29]. The principle has also implicitly been added to the Norwegian constitution as article 112:

> Every person has the right to an environment that is conducive to health and to a natural environment whose productivity and diversity are maintained. Natural resources shall be managed on the basis of comprehensive long-term considerations which will safeguard this right for future generations as well.
>
> In order to safeguard their right in accordance with the foregoing paragraph, citizens are entitled to information on the state of the

> natural environment and on the effects of any encroachment on nature that is planned or carried out.
>
> The authorities of the state shall take measures for the implementation of these principles. [30]

The paragraph states that natural resources shall be managed on the basis of comprehensive long-term considerations. Conducting thorough impact assessment are a considerable part of this safeguard, and needed in the planning and execution of projects that can impact the environment. Environmental sustainability is but one aspect of sustainability.

Environmental sustainability involves protecting and preserving natural resources and ecosystems, reducing pollution and waste, and promoting conservation and biodiversity. Sustainability is more than just focused on the nature. Social sustainability is concerned with promoting social justice, equality, and human rights, and improving the well-being of communities. Economic sustainability involves promoting economic growth and development that is socially and environmentally responsible, and that meets the needs of current and future generations. Overall, sustainability aims to balance economic development, social equity, and environmental protection, in order to achieve a more equitable and sustainable future for all. This thesis will look more towards the environmental sustainability in regards to the emission of carbon dioxide and other equivalent greenhouse gases, and how to limit them. The UN created in 2015 the 17 sustainable development goals [31] adopted by all United Nations Member States. This thesis will focus on two of these 17 goals. Goal 7 is "Ensure access to affordable, reliable, sustainable and modern energy for all" and a target is to "By 2030, increase substantially the share of renewable energy in the global energy mix"[32]. The other sustainable development goal in focus in the thesis is goal 13. It says "Take urgent action to combat climate change and its impacts" and one of the target is target 13.2 which says "Integrate climate change measures into national policies, strategies and planning" [33]. One indicator for this is

13.2.2 which looks at the total greenhouse gas emissions per year.

The thesis is split up in six chapters. In the second chapter I will explain the main theory about wind power, how a battery and diesel generator is functioning. In chapter three I will introduce the data used and the methods used for processing and utilizing the data. The fourth chapter will present results from the coding part of the thesis. During chapter five, the results will be discussed and there will be a wider look at the sustainability aspect of the thesis. Chapter six will round out the thesis and include a conclusion.

# Chapter 2

# Theory

## 2.1 Mechanical Energy

Energy is a broad concept that involve much theory and ideas. Energy, in regards to movement is called kinetic energy. Together with potential energy which is dependent on the position of the system, add up to become mechanical energy. In this thesis, mainly kinetic energy is relevant and will be explained. Kinetic energy is the energy of a moving object or body. The most known formula for this is:

$$E_k = \frac{1}{2}mv^2 \tag{2.1}$$

The kinetic energy equals a half times the mass of the object times the velocity raised to the power of two. The energy of the object is therefore connected to the movement speed of the object and the mass.

The formula 2.1 explained above is a part of what is called classic mechanics or Newtonian mechanics. The mechanics are a representation of the real world and provide acceptable calculations for simpler problems. If more accurate calculations or more advanced objects and scenarios are to be calculated, there could be a need to go into the more advanced version of the mechanics. These are Lagrangian mechanics and Hamiltonian mechanics. A more mathematical view of the formulas makes difficult problems easier to compute, but are beyond what is needed in this thesis.

We are able to harness this energy and convert it into electricity in different ways. Photovoltaic cells directly creating energy from solar rays. Wind turbines uses the kinetic energy of the wind to turn a generator to generate electricity. Nuclear and coal plants that warm water into vapor turns a similar generator as in a wind turbine.

## 2.2 Wind energy

Harnessing the wind has been done for several millennia with sails on ships. The first wind turbine created to produce electricity was placed in Cleveland, Ohio in 1888 [34]. Since then the turbines have grown a lot in size. Today there are offshore turbines created that have a wing diameter of 220 meters, that can produce up to 12MW [35]. There are concepts of turbines that can range up to 40MW. The wind is created by the energy from the sun and the rotation of the earth. The thermal energy is unequally distributed around the globe. This creates different pressures, which causes the air to move which creates wind. The spin of the earth also affects the wind and creates movement. This is called the Coriolis effect.

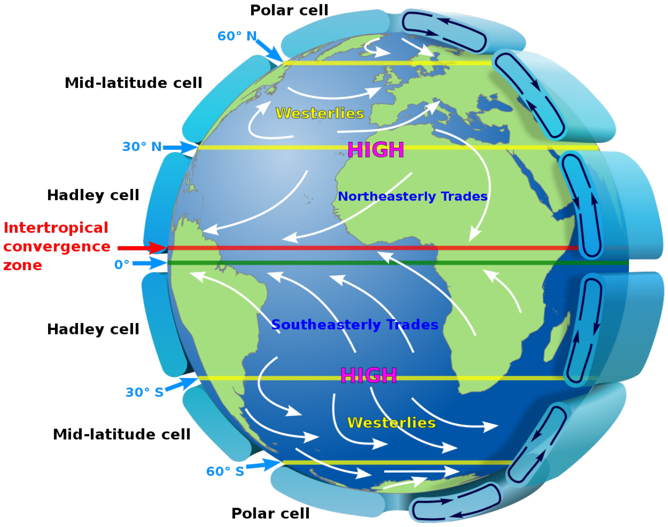


Figure 2.1: Shows the prevailing winds and the different cells on the globe. It also shows where the main high pressure gathers. Figure gathered from WikiMedia [36] under CC BY-SA 3.0

The trade winds created by the Coriolis effect can be seen close to the equator, while the westerlies are mainly what hits the coast of Norway. The three cells in each hemisphere can be seen on the figure 2.1. They are created by the differential heating hitting the earth from the sun. Because of our atmosphere, the tilt, the curvature and different parts are covered in clouds, snow and ice, the Earth warms up in different speeds [37]. As the air gets warmer, it expands, becomes less dense and rises. Since the equator takes the largest concentration of heat an area of low pressure exists of the equator. The air that rises then moves towards the poles. Because of the rotation of the earth some of the warm air sinks at around 30° degrees north and south causing high pressure. This then gets pushed north and south. The wind going towards the equator completes the Hadley cell as seen in figure 2.1. The same goes for the Mid-latitude cell and the Polar cell [37]. As Bergen and the coast outside Bergen is sitting at about 60° North, the westerlies are the prevailing winds in the area. In the summer the weather will vary between weak low pressure and weak high pressure relative to the latitude. In the autumn the activity of low pressure will ramp up and a lower pressure than the standard will occur in the Nordic Seas. A build up of the Icelandic low pressure and the Siberian high pressure will start and only build up during the autumn and winter, and lessen in the spring [37]. When the Icelandic Low is at its strongest during the winter, we can look at the North Atlantic Oscillation-index (NAO-index) which compares the strength of the Icelandic Low with the Azores high, and determines the strength and direction of the Westerlies. The azores is an island group 1500 kilometers west of Portugal [38]. NAO is a statistical description that explains the low and high pressure activity during a period of three to six months. A high NAO indicates a larger low pressure activity over Iceland or smaller high pressure activity over the Azores [37]. When there is a larger difference in the two permanent pressure systems, it indicates a larger NAO and a higher strength in the Westerlies. A higher index gives a warmer and wetter winter, while lower gives a colder and dryer winter. The winter will therefore generate more wind than the summer.

### 2.2.1 Harnessing the wind

Wind energy can be harnessed as kinetic energy. To find volume of air flowing through a cross-sectional area A normal on the wind, we use the formula:

$$P = \frac{1}{2} A \rho u^3. \tag{2.2}$$

$\rho$ is air density. P is power of wind, measured in watts, which will be heavily affected by the change in $u$ (wind speed). As the wind power is proportional to the third power of the wind speed, doubling the wind speed will increase the available wind power with multiple of eight. A wind turbine cannot transform all of the kinetic energy of the wind into mechanical energy. There still need to be air flow going through the area of the turbine. If the wind turbine would harness all the energy from the wind inside the designated area, the flow of the wind would stop. If the flow would stop, the turbine would no longer gather energy and the production would stop. Therefore there is a theoretical maximum of what can be harnessed. This theoretical upper limit is called the Betz limit and sits at 59 %. As the wind passes the area created by the turbine, there is a drop in wind speed which according to Bernoulli's principle increases the pressure [39]. To be able to rotate the wind turbine, two different points of pressure needs to be made. This is done in a similar way as a plane wing. When the wind has to spread below and above the wing, it has to travel a different distance and therefore with different speeds. This makes it so there is a difference in pressure, and creates a lift on the wing as shown in figure 2.2.

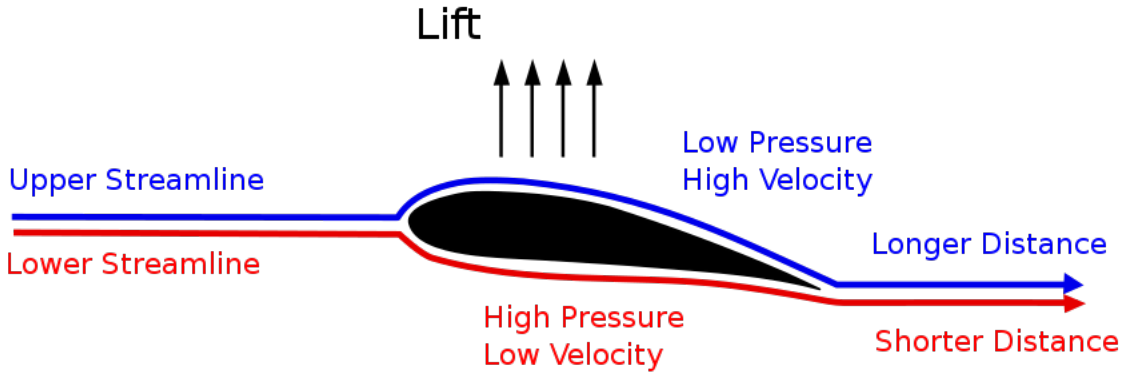


Figure 2.2: Figure of an airfoil, showing the distance and difference in pressure above and below the wind. Gathered from WikiMedia [40] under CC BY-SA 4.0

The teardrop shape of the wing encourages this behaviour and makes it so the turbine blades spin. In most modern turbines, the wings can be angled differently so that the speed can be regulated and stopped at higher wind speeds [41]. When the turbine spins, it spins the shaft which in turn can spin gears that magnify the rotations, this then spins a shaft with higher speed inside a generator. What happens within the generator is explained in the

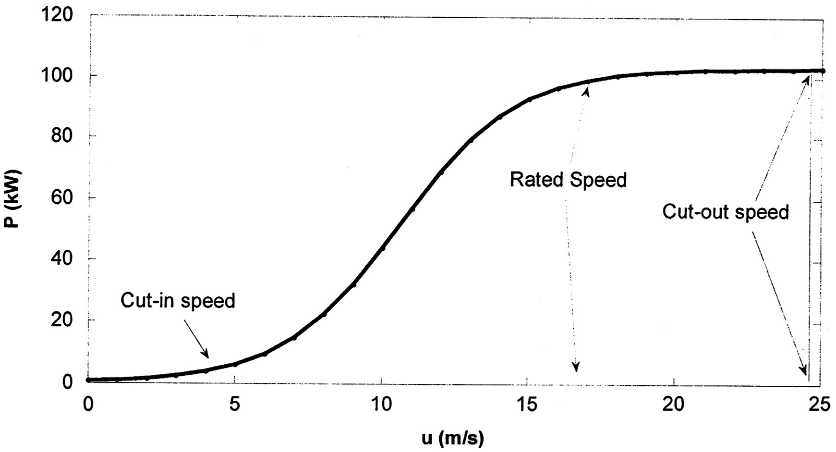


Figure 2.3: A typical power curve for a HAWT turbine. The x-axis contains the wind speeds, while the y-axis shows the power output in kW, as a function of wind speed. It also shows at what speeds the cut-in, rated and cut-out occur. Gathered from [43] under CC BY 4.0

subsection 2.4.2.

### 2.2.2 Power curve

The power curve is an important aspect of a wind turbine. It is a graphic representation of the turbines electrical power output as a function of wind speeds [42]. It has several variables that determine how it looks. Within the cut-in speed and cut-out speed is where the wind turbine can utilize the air to transform it into energy. This can be seen in figure 2.3

Furthermore the rated speed is where the rated power is reached. This is the maximum output from the wind turbine. Higher wind speeds will keep the same rotation on the turbine since a higher rotational speed on the turbine might be harmful and decrease its length of function. If the speed continues upwards towards the cut-out speed it will stay at the rated power until the cut-out speed is reached. Above the cut-out speed, the wind speeds are too high and braking the turbine to get the rated power might

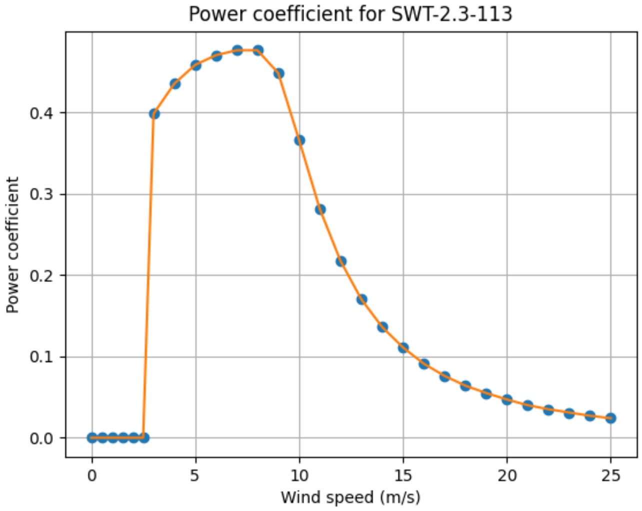


Figure 2.4: The power coefficient of a Siemens SWT-2.3-113 wind turbine. Wind speeds at the x-axis and the power coefficient or the ratio between actual to ideal extracted power. Created in Python with data gathered from [44]

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decrease the life expectancy. The turbine then completely shuts down and stops transforming energy. The power coefficient is how much of the kinetic energy is transformed into electrical energy. The theoretical upper limit is the Betz limit of 59 % as discussed earlier.

### 2.2.3 Power production

As we have looked into both the wind energy and the efficiency of the wind turbine, they can be combined to look at how the power gets produced or rather transformed into usable energy. The power output from the wind turbine can be calculated in several ways. Either through the formula $P_{out} = Cp * P_{rated}$ Where $Cp$ is the power coefficient and $P_{rated}$ is the power from the function 2.2. This gives the power output from the turbine. If the power curve is available for the turbine, it can be used as a function. Inserting wind

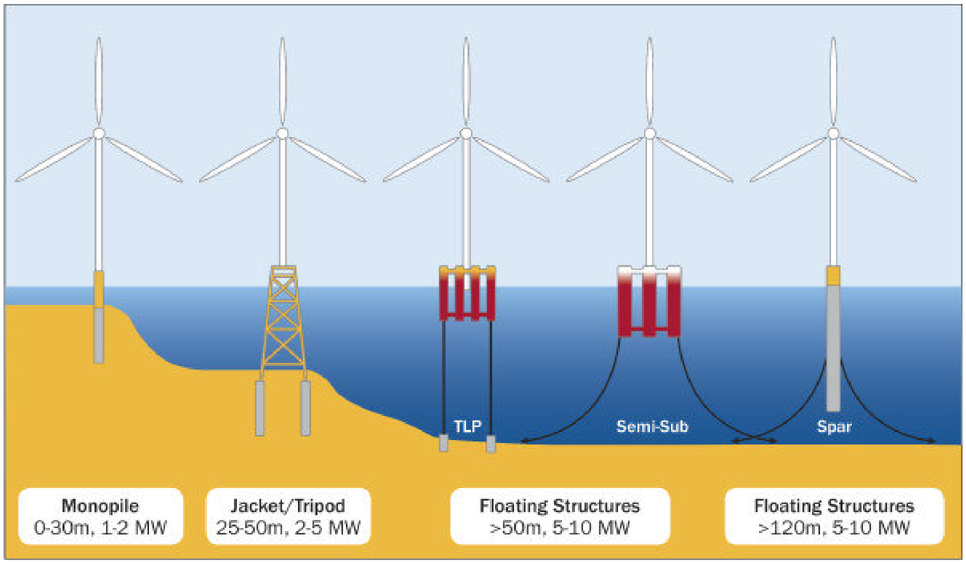


Figure 2.5: Different types of anchoring for turbines. Shows the need for floating when depth increases. Gathered from [46] under CC BY 4.0

speeds into the function will give the power output in return.

### 2.2.4 Offshore

The ocean has generally higher wind speeds and therefore more energy. This contributes to making the ocean a optimal place for harnessing wind through turbines [45]. Producing larger wind turbines and moving them out to sea is also less of a logistical challenge than moving the long wings across the land to where the wind farm is located. There are however several problems with installing turbines at sea. The installation and operational cost of offshore wind parks are generally higher than onshore [45]. This is because of several components. As the depth increases, the systems for anchoring changes. At low depths close to shore, there are several types of foundations that are bolted and fastened to the seabed floor in different ways. Mono pile, Tripod, Jacket, Suction bucket and Gravity base are some of the foundations that are possible if it is inside the given meter difference.

As the depth gets higher, there is a need to implement and install floating turbines. These are currently in development and new technology emerges. Some different types can be seen in figure 2.5. As of 2021, there were only three floating farms. Hywind Scotland, Kincardine and Windfloat Atlantic according to "A review of modelling techniques for floating offshore wind turbines" [47]. The paper goes on to say that "... the costs associated with floating wind are still significantly higher than for fixed offshore energy." With the development it is expected that the prices will drop. A trend that can be seen with most renewable energy resources. The opportunity that comes with offshore wind parks is however beneficial so the market is currently being broadened by funding and new technology.

### 2.2.5 HAWT VS VAWT

There are two main variants of the wind turbine. The most common and widespread is the HAWT (Horizontal Axis Wind Turbine). It has the signature look of what most think of when they hear of a wind turbine. It usually has three wings and operates upwind [48]. Meaning that the generator housing is behind the turbine blades in regards to the wind direction. The VAWT (Vertical Axis Wind Turbine) sits with its blades perpendicular to the ground. The designs differ, but are mainly the Savonius turbine that utilizes drag to rotate and the Darrieus turbine that uses aerodynamic blades to generate lift and turn the turbine [49]. As the VAWT is created with blades perpendicular to the ground, it is omnidirectional, meaning it can take in the wind from any direction. Horizontal turbines need to have a yaw system to rotate into the wind [49]. Additionally the vertical turbine can benefit from having the gearbox and generator placed lower in the turbine. Decreasing the operational and maintenance cost. Johari et. al [49] states that the vertical turbine is the best choice in the slow and more turbulent wind environment, found in urban areas. Being the more quiet of the two designs also benefits the urban environment. On the other side, the paper goes explains that the horizontal axis wind turbine is the more ideal choice for wind environment with more consistent and less turbulent wind [49]. This corresponds well with the wind found offshore.

## 2.3 Battery

There are several different types of batteries, but they all benefit from a reduction-oxidation reaction. This is a spontaneous reaction that turns chemical energy into electrical energy by forcing the electrons to travel through a wire. Several of these electrochemical cells are connected into a battery. An electrochemical cell ha four main components: Cathode, anode, electrolyte and separator [50].

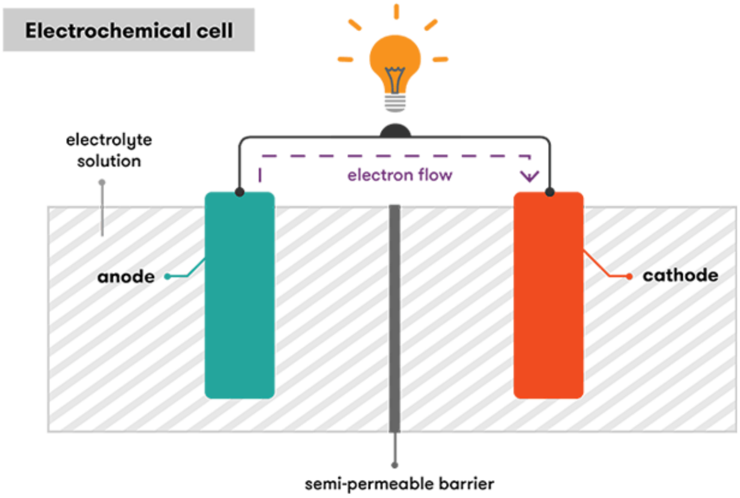


Figure 2.6: Picture of an electrochemical cell. Gathered from [51] under CC BY-NC-SA 4.0.

The cell shown in the figure 2.6 is a crude representation of the workings of a battery. When hooked up, there is a flow of electrons going from the anode to the cathode. The movement of these electrons is what we call electricity. What element or chemical compound chosen for the anode and cathode is done by looking at their standard potential for half-reactions [51]. It is a table of calculated reactions. For instance, the best cathode would be the $Li^+(aq)+e^- \longleftrightarrow Li(s)$ which has a $E^0 = -3.040$. The arrow going both directions is used in chemistry and indicates that the reaction moves towards an equilibrium between the two reactants. This number is measured in volt and found by comparing it to the half-reaction $2H^+(aq) + 2e^- \longleftrightarrow H_2(g)$, which is chosen as the standard. On the other side of the table, there is for instance $F_2(g) + 2e^- \longleftrightarrow 2F^-(aq)$ which has an $E^0 = 2.87$. Calculating the difference between the two $E^0$ you get the electrochemical potential of the cell. Which is the voltage of the cell [51]. To rise the voltage of the battery, one can either choose different electrodes to get a higher electrochemical potential, or stack several cells together in a series. The electrolyte in the cell allows charged ions to move. When the anode produces electrons to go through the wire, an equal number of charged ions are moved into the electrolyte to keep the electrode in a charge-balanced state [51]. The semi-permeable barrier stops the electrons from going straight to the cathode, but instead be moved through the wire.

In this thesis batteries are used to deliver energy when wind is not sufficient or limit the use of the generator. Batteries can also be used to shave of high and lows so that the power-grid gets a more steady stream of electricity.

### 2.3.1 Secondary batteries

Secondary batteries have the same reaction as explained above. The main difference between primary and secondary batteries is that secondary batteries can use electrical energy and reverse the reaction so that the battery gets charged up again. They are called ”wet” batteries, seeing that they use a liquid electrolyte, while the primary batteries use a ”dry” paste [52]. By sending an electric charge through the wire, the electrons from the cathode are sent back towards the anode, and the charged ions are also moved back into the anode. When charging however, the electrode does not return to the exact way it was, and there is some degradation on the electrode. This degradation is larger if the charging and discharging speed is higher. Making the life expectancy of the battery lower.

### 2.3.2 Why Lithium?

Lithium is the third element in the periodic table. This makes it the lightest density of all solid elements at room temperature, as well as having the smallest ionic radius of the alkali metals. Furthermore it has the highest specific heat capacity for solids and the highest electrochemical potential [50]. As explained above. This makes lithium very compatible to be used in batteries as the cathode.

Lithium is a highly reactive element, therefore it is not easy to locate in larger quantities around the world. The largest concentration of it is found in brine salt flats and in a granitic type of rock called pegmatite. Over 50 per cent of the lithium reserves are within what is called the "lithium triangle", which consist of the countries: Argentina, Bolivia and Chile [53]. Both China and the US are also major brine producers. In these brine mixtures there is between 0.01 and 0.2 per cent lithium. Therefore there is work to process the lithium from the brine after it has been extracted from the ground. The main way to concentrate the lithium is to use large evaporation ponds, that utilizes the natural evaporation from the sun and wind. When the concentration of lithium reaches the chosen parts per million, 6000, according to the book Lithium Process Chemistry [50], it gets moved on to a treatment plant for further processing. The time it takes between the brine is pumped up until the lithium is a ready product is usually between one and two years.

## 2.4 Diesel generator

Diesel generator uses the combination of an electric generator and a diesel engine to produce electricity by burning diesel fuel. They are commonly used as a backup system or as the main power source, typically in rural places [54].

### 2.4.1 Diesel engine

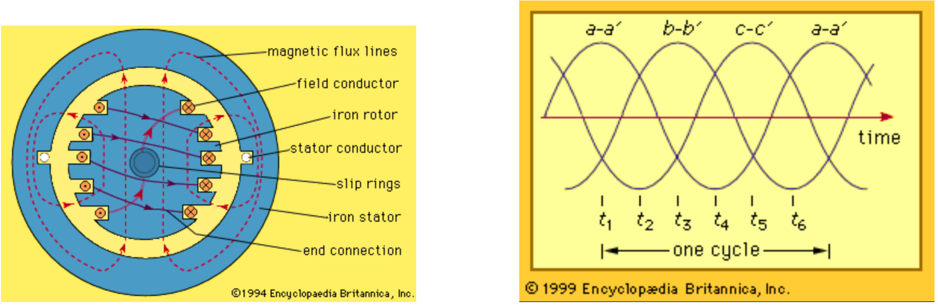
The diesel engine uses the concept of the ideal gas law.

$$p = \frac{nRT}{V} \tag{2.3}$$

Where p is pressure, V is volume, n is amount of mol, T is temperature in Kelvin and R is a constant that equals $8.3145 Jmol^{-1}K^{-1}$ or $0.08206\frac{L*atm}{mol*K}$ Dependent on what unit the pressure is calculated at. In standard SI units 8.31 is used. The air gets pumped into a piston, and the volume is decreased, which increases the pressure and rises the temperature. When it is heated inside the piston the diesel fuel is injected. This causes ignition which converts chemical energy into higher temperature, that pushes the piston back again. The pistons moving rotates a crankshaft that sends the now rotating energy into a drive axle for a car or in this case into the electric generator part [54].

### 2.4.2 Electric generator

The electric generator transform mechanical or kinetic energy into electric potential difference or voltage [54]. By having a part that rotates, as we have from 2.4.1. The rotating crankshaft goes into the electric generator and spins the shaft. This turns a rotor which has a magnetic field in a sinusoidal distribution. The magnetic field will be strongest at two points, and weakest at the two points perpendicular to these as shown in figure 2.7a. So when the rotor spins, it creates a sinusoidal wave that goes between the maximum to minimum and back again. The standard sinusoidal wave is a motion that goes from a positive maximum to a negative maximum in a wavelike motion. The waveform can be seen in figure 2.7b and it is this wave that the stator conductor while rotating creates within the magnetic flux lines. The coils on the stator then oscillates with the difference in magnetic flux in a sinusoidal distribution, and then converts the magnetism into an alternating current.



(a) Synchronous generator (b) Waveforms system

Figure 2.7: a) shows the different parts inside the electric generator. b) shows the waveform of the stator conductor while rotating inside the magnetic flux lines. Figures gathered from Britannica [55] under CC BY 4.0

### 2.4.3 Emission

According to *The Physics of Energy* [54], a typical diesel generator emits 2.6kg $CO_2$ per liter diesel burned. This can be calculated by backwards calculation. Starting out with kWh, it is possible to calculate the amount of diesel used. The amount of diesel burned can be then converted into $CO_2$ emitted. Other gases and particulate matter are also emitted, however it will not be heavily focused on in this thesis. A liter of diesel contains 0.73 kg pure carbon that when burned is turned into 2.6 kg of carbon dioxide [54]. Depending on the quality and mix of the diesel, the answers can vary. that it is "The emission factor considered for a diesel generator was 1.27 kg $CO_2$/kWh, 3.15 kg$CO_2$/l and 3.50 kg$CO_2$/l. " [56]. The conversion of one liter of bio-diesel contains 38 MJ of energy, while diesel contains 43MJ per kilo or liter [52]. Since the diesel generator does not operate at a 100 per cent efficiency and can therefore not extract all of the energy from within the diesel. We look at an efficiency curve of the diesel generator, which depends on the machine, but contains the same structure. In a paper by Peralta et. al. [57], we see one such efficiency curve in figure 2.8

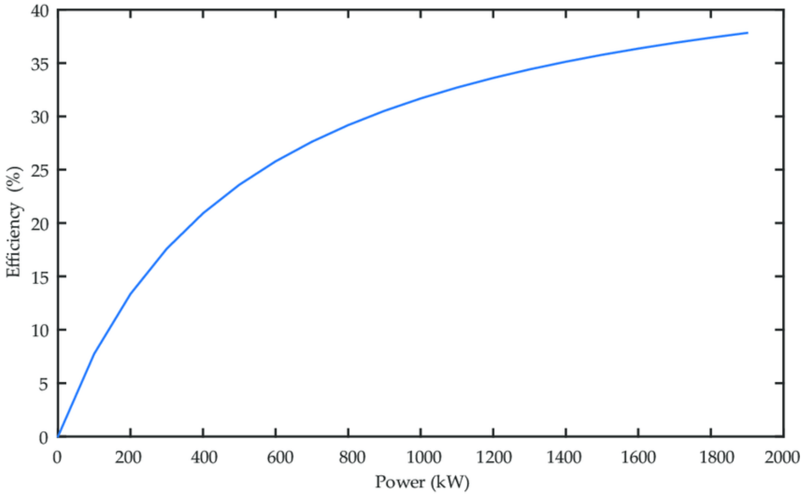


Figure 2.8: Figure of an efficiency curve for a diesel generator. X-axis shows the power input in kW, and the y-axis shows the efficiency in %. Gathered from Peralta et. al. [57] under CC BY 4.0

On the x-axis, power can be replaced with percentage of the output, in this instance, the maximum output is somewhere between 1800 and 2000 kW. As the engine runs on a higher percentage, it is able to extract more energy from the diesel. This makes it so the engine creates more energy from less diesel when it is running on a higher frequency or percentage power output.

# Chapter 3

# Methods

In this chapter the approach to the thesis will be explained. The data used will be first, and then it will be explained how this data is used and calculated to create scenarios. Lastly the outputs and how they are calculated will be shown. This is done with the goal of the research question in mind. How to best limit the emission of the Ocean Farm 1 to below 20% by utilizing a wind and battery system, with additional help from a generator as backup. The planned energy system can be seen in figure 3.1. The primary energy comes from wind and oil. This is converted into electrical energy by wind turbines and diesel generators. Energy goes into the salmon farm and the battery. Any surplus energy then goes either to waste or be used for something else. The surplus of energy will be looked at in the discussion.

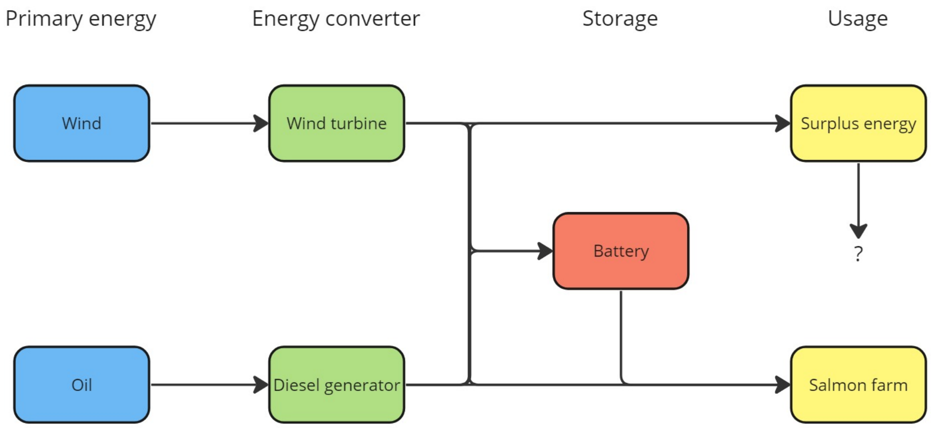


Figure 3.1: Shows the planned energy system. The primary energy comes from wind and oil. Energy converter by wind turbines and diesel generators. Battery as storage. Surplus into salmon farm or wasted. Created in miro

The setup for the method section is shown in figure 3.2. Explanation of the primary data used in the code. Then an explanation of the code, with the packages used can be found in the appendix A.1, the main concepts and calculation will be presented later in the chapter. The output from the code and how it was calculated, will be looked towards the end of the method chapter.

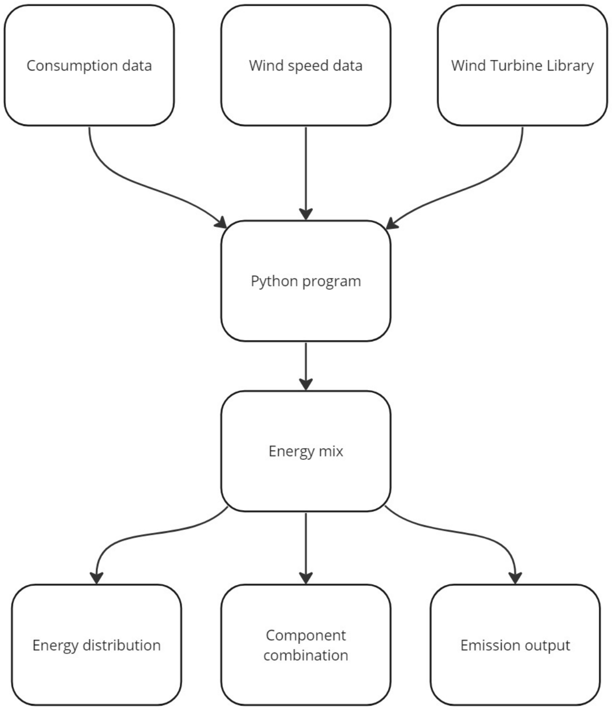


Figure 3.2: Shows the method flowchart. Starting with the data, then into the code. From the code comes the energy mix, how much energy is from the wind and how much is from diesel. Lastly we get outputs such as the energy distribution, what different combinations was used and how much emission the scenario emits. Created in miro

## 3.1 Data

Most of the data collection was done by my predecessor Sindre Sandøy [13], and I could build upon the data he was given. The main data used in this thesis is from the wind collection NORA3-WP [1], consumption data of the Ocean Farm 1 given by SalMar, and the open database: Wind Turbine Library [44].

### 3.1.1 NORA3-WP

The NORwegian hindcast Archives Wind Power data set, or NORA3-WP is a new high resolution wind resource and wind power data set [1]. Created by Ida Marie Solbrekke and Asgeir Sorteberg, it has as a goal to be open access for use in research, governmental management and for other stakeholders. It is based on the original NORA3 data set, which itself is a reanalysis of ERA-5 by the Norwegian Meterological Institute. It covers the North Sea, the Baltic Sea, and parts of the Norwegian and Barents Sea as seen in figure 3.3 below. It has a grid resolution of 3 x 3 kilometers. The data set contains hourly data from three different heights, 101, 119, and 159 meters above sea level. In this thesis the height of 101 meters above sea level is used.

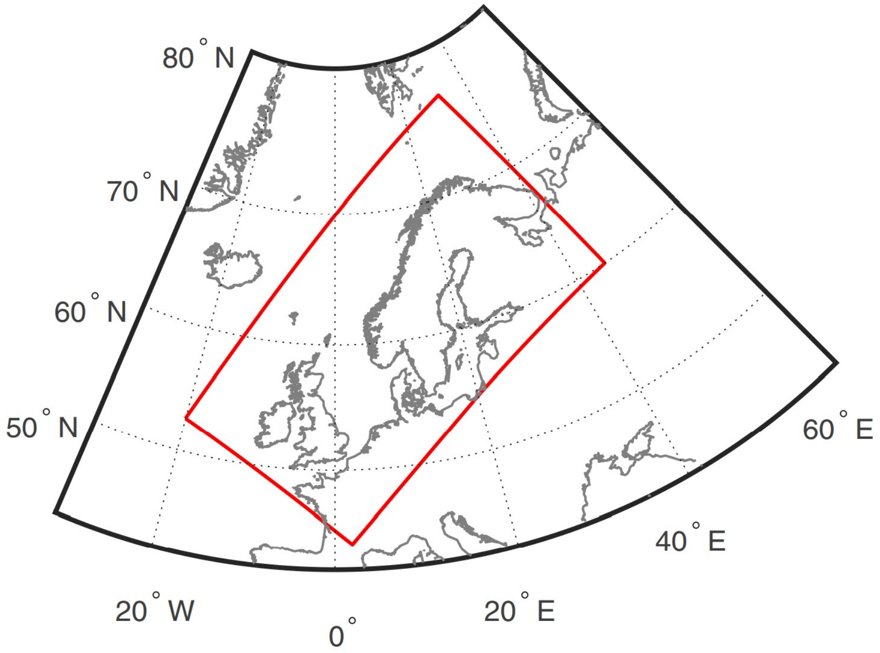


Figure 3.3: Map of Northern Europe. The data set NORA3-WP covers the area within the red rectangle [1] under CC BY 4.0.

The data set will be the main input for the thesis and information is extracted at the closest data-point to the location shown in figure 3.4. The year that are extracted are 1996-2019. For a 20 year period, the years 1996-2015 are chosen. The wind speeds for this period is shown in the figure 3.5. There are 175320 data points or 20 years of hourly data.

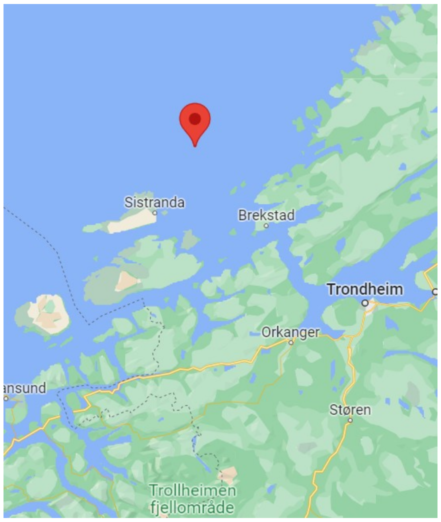


Figure 3.4: Location of Ocean Farm 1. 63.94203N, 9.133442E. Coordinates from [13]. Screenshot taken of Google Maps [58].

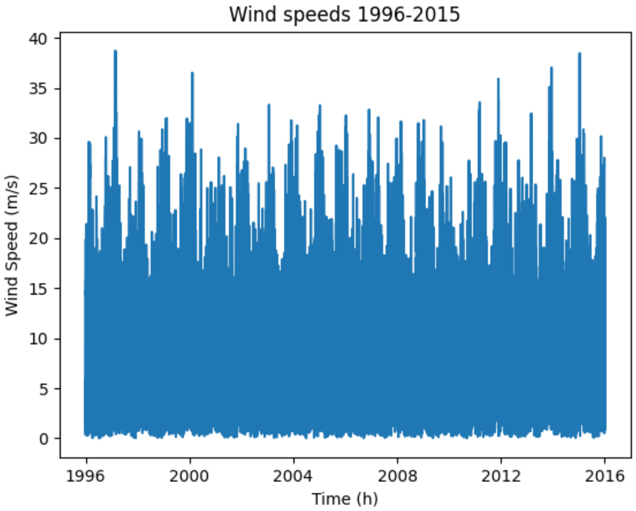


Figure 3.5: Shows the wind speeds from 1996-2015. Time in years on the x-axis and wind speed in m/s on the y-axis.

### 3.1.2 Consumption data

SalMar, one of the worlds largest salmon farming companies started a strategic partnership with Aker ASA, an industrial investment company, to create SalMar Aker Ocean [59]. The company has as a goal that by 2030 they will produce 150 000 tons of farmed salmon from offshore installations [21]. This is done through the installation of Ocean Farm 1. With a diameter of 110 meters and height of 69 meters, it has a volume of $250000m^3$ and can hold over 1 million salmon simultaneously [13].

Figure 3.6: Photo of the Ocean Farm 1 [60].

The production facility has had two successful production cycles. The consumption data to both of these production cycles was given to Sandøy, they occurred in the year 2019 and 2020. Consumption data with resolution of both 10 minutes and of hourly was given. Since the NORA3-WP data set was hourly, Sandøy chose to use the hourly consumption data. The most energy-demanding process of the facility is to feed the fish, there was fish in the facility between 22 October 2019 and 15 September 2020 [13]. Sandøy therefore chose to use the first and last five months of power consumption data where the fish was present. The last two months used data where there were no fish in the facility. This can be seen in the data and in figure 3.7, as it is generally lower than the rest. The modified consumption had a yearly power demand of 771.4 MWh, slightly more than the raw data of 696.8 MWh and 767.3 MWh for 2019 and 2020 respectively [13]. In April 2022 it was moved to a shipyard to receive upgrades before it is meant to produce again in April 2023 [61].

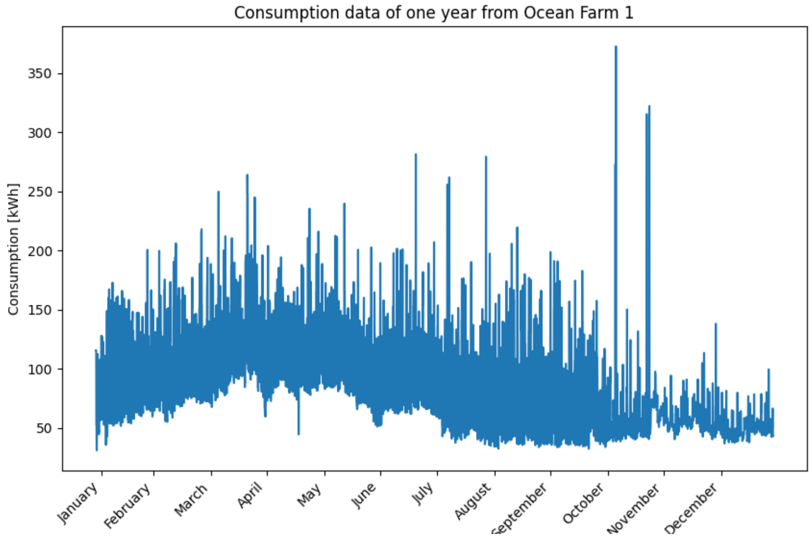


Figure 3.7: Hourly data of one years consumption from the Ocean Farm. The x-axis shows the corresponding months, while the y-axis shows consumption in kWh. Created in Python based on information from SalMar AS.

The spikes shown in the figure are possibly anomalies but are kept. For this thesis it was chosen to look at a time-frame of 20 years. Mainly because this can give an idea of how it will look after operating for an extended time. SalMar has planned to have six facilities on the same energy system [13]. The consumption data for one year is repeated over 20 years of wind data to create 175320 hours. To create consumption data that consist of six facilities with different timelines on the production cycle, it was chosen to shift the production cycle for each facility with 1440 hours or 60 days. This was done by merging six different consumption timeseries with a shift of i*1440 hours, where "i" was the variable in a for loop for 0-5. All six consumption lists where then added on top of each other, creating the data shown in figure 3.8. The final 20 year dataset consisting of wind, wind production and total consumption from the six facilities has been denoted to go from 2024 till 2044. This is entirely fictional and only done because of the date_range function from Pandas (see Appendix A.1) that allows for an easy reference. For instance, it can be used to extract a specific month or week of data. The year 2024 was chosen as it is a leap year and lies in the future. 2024 is a leap year so that it matches the wind data that starts in 1996, a leap year. The years were put in the "future" and not in 1996 for instance, because the facilities are not yet up and running and were planned for April 2023, November 2024 and so on until the sixth is supposed to be operational in September 2027 [13].

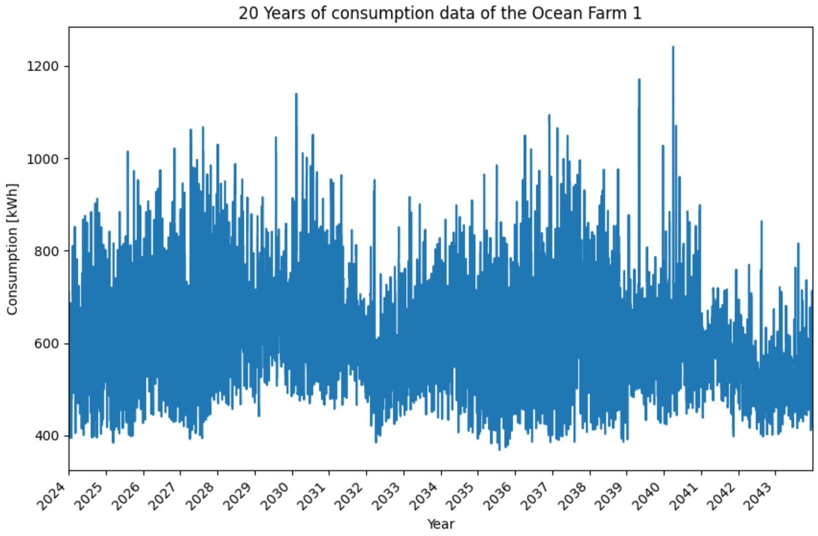


Figure 3.8: Hourly data of 20 years consumption for six Ocean Farm facilities. The years on the x-axis are created for my own benefit, but does not have an impact on the data. Y-axis shows the consumption measured in kWh. Created in Python based on data in figure 3.7.

### 3.1.3 Turbines

The download of the open database Wind Turbine Library [44] made it easier to code the turbines. The database contains plentiful of turbines to choose from and a setup that is possible to add my own turbines to as well. It contains many variables that can be useful, however the power curve wind speeds, power curve values and hub heights were mainly used. The SeaTwirl S2x turbine was not in this library and was manually added, based on information from several sources [2] [62] [63]. Furthermore, comparing the SeaTwirl S2x to another turbine seems beneficial. Finding another turbine that is offshore based and has a rated production between 1MW and 3MW was not easy. As explained in 2.2.4, scaling up the size and production of wind turbines offshore is easier with the transport and the amount of available space. The turbine chosen was therefore an older onshore wind turbine that matches the needs of the system. The SWT 2.3-113 turbine created by Siemens was already in the Wind Turbine Library, along with a functioning power curve. The basic data for the two turbines can be seen in table 3.1.

| Turbine data | | |
|---|---|---|
| | **S2x** | **SWT-2.3-113** |
| **Rated power (MW)** | 1 MW | 2.3 MW |
| **Hub height (m.a.s.l.)** | 50 m.a.s.l. | 99.5 m.a.s.l. |
| **Cut-in speed (m/s)** | 3 m/s | 3 m/s |
| **Rated wind speed (m/s)** | 12 m/s | 11 m/s |
| **Cut-out speed (m/s)** | 25 m/s | 25 m/s |
| **Type** | VAWT | HAWT |

Table 3.1: Shows the data for the two turbines that are planned to be used. The data consist of the rated power, hub height, cut-in, rated and cut-out wind speeds. As well as the type of turbine. Either Vertical - or Horizontal Axis Wind Turbine. Created with data from [2] [62] [63] and [44].

### SeaTwirl S2x

One type of wind turbine that has been interesting to look at for this project is the SeaTwirl S2x. It is unlike most others a VAWT. SeaTwirl states that it produces one megawatt of energy, and requires a lower operating cost [2]. It is made to be used offshore and can take in wind from all sides. It has a low height of 55 meters above and 80 meters below sea level. According to the company, this will lower the operation cost because the essential parts of the wind turbine, such as the generator, are close to the sea level instead of in the top, as in the normal horizontal turbines. This lower center of mass also helps with the stability claims the company [2]. The promise of a lower cost and suitability for wind farms, islands, remote locations and fish farms make the product interesting in this project. In the code, the hub height set for the turbine is 50 m.a.s.l. (meters above sea level), which is a generous height seeing that the turbine in itself is only 55 meters high. The design of the turbine can be seen in figure 3.9. The turbine has a consession to be tested at "Marin energi testsenter" north of Stavanger [64].

### Siemens SWT-2.3-113

The Siemens SWT-2.3-113 got its name because it has a rated power of 2.3 MW and a rotor diameter of 113 meters [3]. It is a HAWT, but not an offshore turbine. It was chosen as a reference for this thesis, because its rated power is close to what Sandøy ended up with in his thesis [13]. He had three 750 kW turbine, that add up to 2.25 MW in effect. It can also be compared to two S2x turbines. The turbine has a hub height of 99.5 m.a.s.l.

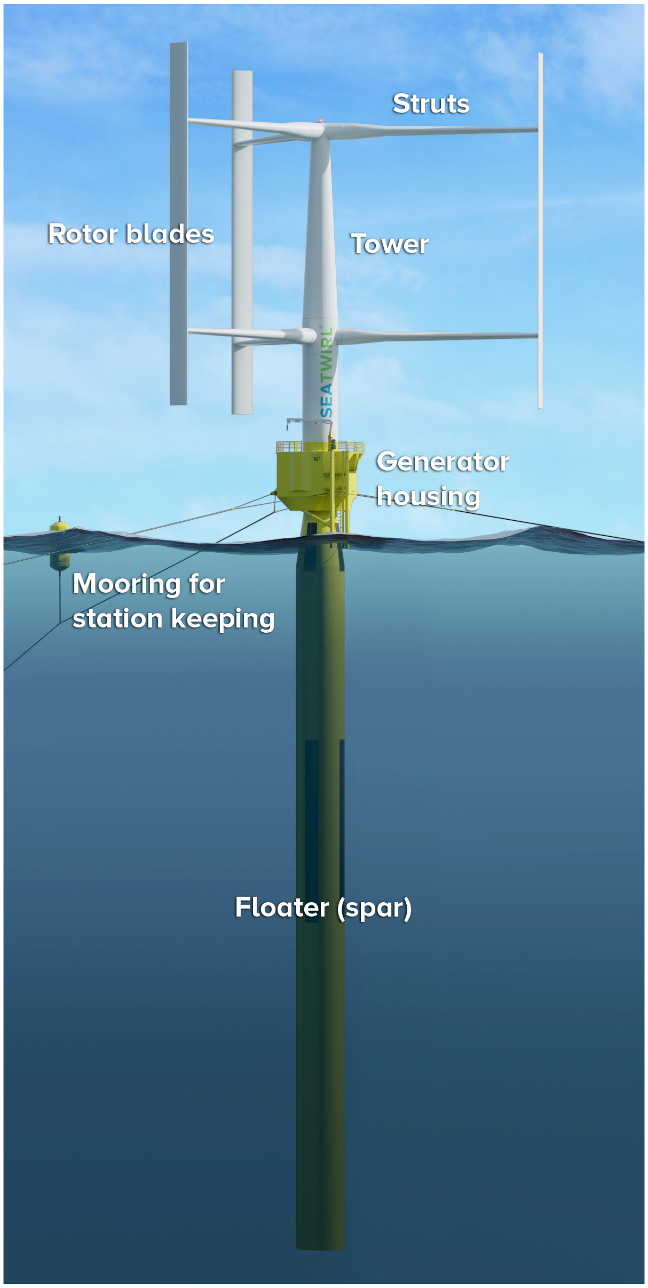


Figure 3.9: Overview of the SeaTwirl S2x concept, including position of generator. It is 55 meters above sea level and 80 meters below. Gathered from SeaTwirl.com [2]

## 3.2 Approach

As a lot of calculation was needed to generate a result, using a coding software was obligatory. The choice then became to use Python as it is commonly used within computer science and can be useful to understand for future work. During the thesis there has been a steep learning curve, but using packages with good documentation helped. Whether a change in the turbine, battery or diesel generator, the program is supposed to be able to facilitate these changes. This is done with different modules.

### 3.2.1 Assumptions

Firstly some assumptions are made that simplifies the system and code. The NORA3 wind data set generally gives an underestimation of the wind speeds of around 5% or 0.5 m/s [1]. Since the consumption data has been created by merging six facilities of the already manufactured one year data, it is hard to determine how large the inaccuracies might be. The code does not deal with energy loss through charging, discharging, and has no battery self-discharge rate. The diesel generator does not have a startup penalty, but if it is on, it does not turn off unless it has been on for a minimum of three hours, or the battery is charged more than 50 %. This creates a somewhat more realistic generator that does not turn on or off every other hour. The wind turbine also does not have a startup penalty. Lastly, there has been a assumed that there is no downtime for the different systems, although this will occur for both maintenance and eventual failures.

### 3.2.2 Power production

To get the correct wind speeds for each turbine, the data has to be transformed into the height of the hub height for the turbine. This is done by using the wind gradient equation:

$$v(z) = v_{ref} \frac{ln(z/z_0)}{ln(z_{ref}/z_0)} \tag{3.1}$$

Where $z_0$ is the roughness of the surface, over rough ocean it is set to 0.001. z is hub height and $z_{ref}$ is height of the data. $v_{ref}$ is the wind data. The new wind speeds are then calculated to be the corresponding wind speeds according to their current heights. The power output from the wind turbine is then calculated by using an interpolation of the data from the power curves. By using the "Interp1d" function in Python, the wind speed can be used as input and the power output will be returned. As the power production of the wind turbine is not dependent on the battery system, nor the generator, it can be calculated before the main calculation. The figure 3.10 show the power curve for their respected turbine. It can be seen that the SWT-2.3-113 reaches its rated power on a lower wind speed than that of the S2x.

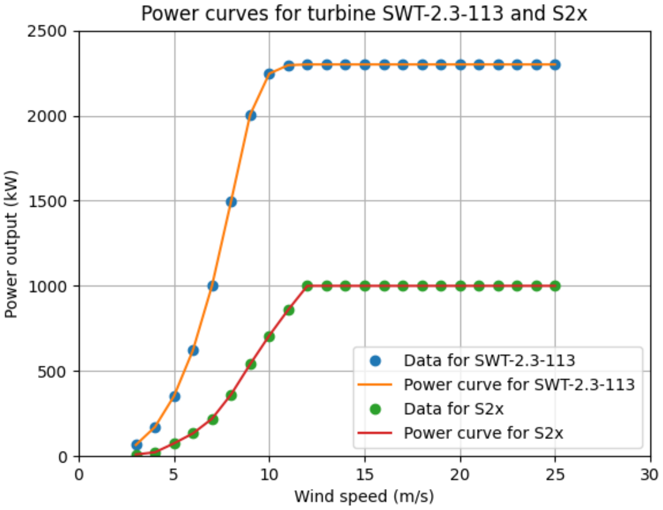


Figure 3.10: Shows the power curves for the two turbines used in this thesis. The SeaTwirl S2x has a rated power of 1 MW, while the SWT-2.3-113 has a rated power of 2.3 MW. X-axis shows wind speed, while y-axis shows the power output.

### 3.2.3 Battery

The battery module bases its action on the incoming value of $E_{deficit}$ seen in equation 3.2. By calculating the difference between the consumption and the power output from the wind turbine or turbines, it shows if there is a surplus or deficiency in energy.

$$E_{deficit}(t) = E_{consumption}(t) - E_{windoutput}(t) \tag{3.2}$$

The size of the battery is dependent on the scenario but is a multiple on packs of 60 kWh ($E_{pack}$). The scenarios use 0, 20, 30, and 40 $N_{packs}$ as values. This gives the nominal capacity of:

$$E_{nominal} = N_{packs} * E_{pack} \tag{3.3}$$

#### Charging

When $E_{deficit}$ is less than zero, the battery is set to charge. The available energy surplus is limited by the maximum charging value ($E_{maxcharge}$) during the time interval (t) of an hour. The value of $E_{maxcharge}$ is set to be 25 % of $E_{nominal}$. The battery can not exceed the upper capacity ($E_{uppercapacity}$) of the battery. Which is determined as 80 % of the nominal capacity, which again is dependent on the current scenario explained in 3.3.3.

$$E_{bat}(t) = min[E_{bat}(t-1) + min[abs(E_{deficit}(t)), E_{maxcharge}], E_{uppercapacity}] \tag{3.4}$$

### Discharging

When $E_{deficit}$ is larger than zero, the battery is set to discharge or drain. The energy deficit is limited by $E_{maxdischarge}$, which is the same value as $E_{maxcharge}$. The battery can not exceed the lower capacity ($E_{lowercapacity}$) of the battery. Which is determined as 20 % of the nominal capacity.

$$E_{bat}(t) = max[E_{bat}(t-1) - min[E_{deficit}(t), E_{maxdischarge}], E_{lowercapacity}] \quad (3.5)$$

The battery having a lower capacity at 20 % and upper capacity at 80 % makes it so the useful part of the battery is only 60 %. This can be overly cautious for the lifetime of the battery even though fully charging and discharging a battery lowers its lifetime. This over cautiousness is somewhat justified with the high value for the maximum charge of 25 %. The charge and discharge rate of batteries can vary and depends on what they are used for. The usage of batteries in storing renewable energies often need a higher DOD (Depth of Discharge), because the energy is intermittent. In the paper *A Multi-Factor Battery Cycle Life Prediction Methodology for Optimal Battery Management* [65] the charge is set to a maximum of 0.5C and the discharge to 1C. This corresponds to 50 % and 100 % of the capacity per hour. This was meant for a 5 kWh battery interacting in a home with a photovoltaic cell. The normal charge and discharge rate is generally closer to 10 % of capacity. The battery does not have a self-discharge rate. The battery is set to start at the lower capacity.

| Battery | | |
|---|---|---|
| Description | Value | Unit |
| $E_{pack}$ | 60 | kWh |
| $E_{lowercapacity}$ | 20 | % |
| $E_{uppercapacity}$ | 80 | % |
| $E_{maxcharge}/E_{maxdischarge}$ | 25 | % |
| $\epsilon_{charge/discharge}$ | 100 | % |

Table 3.2: Shows the variables and values for the battery in the code. The battery consist of $E_{pack}$ of 60 kWh each, and range between 0 and 40 of these packs for the scenarios. The battery has a $E_{lowercapacity}$ of 20 % and $E_{uppercapacity}$ of 80 % to prevent damage. The battery has a $E_{maxcharge}/E_{maxdischarge}$ of 25 % of its maximum capacity per hour. The $\epsilon_{charge/discharge}$ is the charge/discharge efficiency is at 100 %, meaning that no energy goes lost as it charges.

### 3.2.4 Diesel generator

The diesel generator only turns on if the power output from the wind and the battery does not cover the consumption of the facilities.

$$E_{gen}(t) = E_{consumption}(t) - E_{windoutput}(t) - min[E_{bat}(t-1) - E_{bat}(t), 0] \quad (3.6)$$

As explained in assumptions 3.2.1, the diesel generator does not have a start up penalty and produces the amount needed to cover the energy deficit that is left after the wind and battery have covered what they can. The energy deficit is seen in the equation 3.6. It can be covered as long as it does not go beyond the set maximum of 1200 kW ($G_{max}$), or 30 % efficiency ($G_{eff}$) of the 4 MW diesel generator ($G_{nom}$).

$$G_{max} = G_{eff} * G_{nom} \quad (3.7)$$

The size of diesel generator was chosen by what Sandøy had in his thesis [13], while also being able to cover most of the consumption, except some abnormal large spikes that can be seen in the figure 3.8. The emission from the diesel generator will be explained in section 3.3.2. The diesel generator is not used to charge the battery in the different scenarios, except in the final section where an analysis of the result to this assumption is conducted.

### Letting the diesel generator charge the battery

This is only done in a special scenario and done by utilizing the maximum charge value of 25 % of the battery capacity. In the code, the battery is either drained or charged based on the energy deficit value that is based on the power output of the wind turbine as mentioned in the equation 3.2. The batteries maximum charging/discharge value ($E_{maxcharge}/E_{maxdischarge}$) is then decreased by how much it is charged or drained by the energy deficit:

$$G_{maxcharge}(t) = E_{maxcharge} - abs(E_{bat}(t) - E_{bat}(t-1)) \tag{3.8}$$

$$G_{avail,charge}(t) = min[G_{max} - E_{gen}(t), G_{maxcharge}] \tag{3.9}$$

This is then moved into the diesel generator, which uses the remainder ($G_{avail,charge}$) after covering the needed energy to charge the battery. This will be compared in section 4.5.2 in the results.

## 3.3 Output

The output of the code is what will be analyzed in the result chapter. As there is a lot of data, the primary output will make it easier to gather an understanding of the possible solutions.

### 3.3.1 Energy distribution

The energy distribution is some of the most interesting to look at in the thesis. How much of the energy was produced? How much was used to cover the consumption of the facility. At what percentage of the consumption did the diesel generator have to cover? And how much of this produced energy was wasted? np.sum() is a function in the NumPy library (see Appendix A.1) that sums up all data points in a list.

$$E_{prod} = E_{windoutput} + E_{gen} \tag{3.10}$$

The wasted energy ($E_{wasted}$) is then calculated by looking at how much of this total energy ($E_{prod}$) was not used to cover the consumption ($E_{consumption}$) or change in battery. Calculated as the difference between the last and first iteration as seen in 3.11.

$$\Delta_{bat} = E_{bat}(t_{max}) - E_{bat}(t_0) \tag{3.11}$$

$$E_{wasted} = E_{prod} - E_{consumption} - max[\Delta_{bat}, 0] \tag{3.12}$$

The change in battery is easy to forget to add in the equation, because it is neither wasted nor used in the consumption.

### 3.3.2 Emission

The emissions are calculated based on the amount of energy transformed by the diesel generator. As shown in equation 3.7, the maximum output of the diesel generator was set to 30 % ($G_{eff}$) of the 4 MW. The total electricity from the generator in kWh ($E_{gen}$) is multiplied with the efficiency $G_{eff}$ and the constant $C_{kWh/l}$ set to 10.56 kWh/l. This is found by looking at the energy in a liter of diesel, which was presented as 38 MJ/l in 2.4.3. This is converted into kWh per liter: $38MJ/l = \frac{38*10^6}{3600*1000} = 10.56kWh/l$.

$$G_{diesel} = E_{gen} * \frac{1}{G_{eff}} * \frac{1}{C_{kWh/l}} \tag{3.13}$$

This gives the amount of consumed diesel in liters. This is then multiplied with the value of 2.67 $kgCO_2/l$ ($C_{kgCO_2/l}$)[56], which is how much carbon dioxide each liter of diesel emits.

$$C_{CO_2} = G_{diesel} * C_{kgCO_2/l} \tag{3.14}$$

$C_{CO_2}$ is how much carbon dioxide the system emits over the 20 year period. Which is equal to the electricity produced by the diesel generator multiplied with 0.844 $kgCO_2$. This constant can be found by calculating the equation 3.13 and 3.14 for 1 kWh. This gives:

$$\begin{gathered} 1kWh * \frac{1}{0.3} * \frac{1}{10.56} = 0.316liter(G_{diesel}) \\ 0.316liter * 2.67kgCO_2/l = 0.844kgCO_2 \end{gathered} \tag{3.15}$$

### 3.3.3 Component combination

Looking at different combinations for the energy system was always central in the thesis. How it was to be implemented was however changed a multiple times. In the end, it was chosen to cycle through a different amount of the S2x turbines, from one to three turbines. Or a rated power of 1 MW to 3 MW. This was done to see how much of a role the size of the wind turbine had to say. The way to implement this was to multiply the power production of the SeaTwirl S2x turbine by the amount of turbines chosen. Since the number of turbines are so few, the wake effect of the turbines was not considered. The addition of the Siemens SWT-2.3-113 was also added towards the end, because it was interesting to see how a horizontal axis wind turbine would influence the energy system. The battery capacity is then also changed by changing the amount of battery packs. The amount was chosen to be zero, 20, 30, and 40 packs. Giving a battery capacity of 0, 1200, 1800, and 2400 kWh respectively. This can be seen as a very simple Monte Carlo simulation. Monte Carlo simulations covers a lot, but in essence it is modeling a system as a series of probability density functions. When changing either the wind turbine size or the battery capacity, it creates several samplings of a single event [66]. This creates 16 scenarios with different turbines and battery sizes as seen in table 3.3, and including the base case of only the diesel generator without wind power, it adds up to become 17 scenarios.

| Scenarios | | | | |
|---|---|---|---|---|
| **Battery capacity/ Turbine** | **1S2x** | **2S2x** | **3S2x** | **1SWT-2.3-113** |
| **0 kWh** | 1S2x/0 | 2S2x/0 | 3S2x/0 | 1SWT/0 |
| **1200 kWh** | 1S2x/1200 | 2S2x/1200 | 3S2x/0 | 1SWT/1200 |
| **1800 kWh** | 1S2x/1800 | 2S2x/1800 | 3S2x/1800 | 1SWT/1800 |
| **2400 kWh** | 1S2x/2400 | 2S2x/2400 | 3S2x/2400 | 1SWT/2400 |

Table 3.3: Shows a table with the 16 different scenarios and their names.

### 3.3.4 SSR and SCR

Some key indicators of a system is the self-sufficiency ratio (SSR) and supply cover ratio (SCR). The SSR is the fraction of the on-site electrical demand ($E_{demand}$) covered by the on-site electricity generation ($E_{avail}$). In this case either the production of energy from the wind turbine or a combination of electricity from the wind and electricity from the diesel generator.

$$\text{SSR} = \frac{\Sigma_{t=1}^{N} min[E_{avail}, E_{demand}]}{\Sigma_{t=1}^{N} E_{demand}} \tag{3.16}$$

While the SCR is the self-consumption factor and defined as the fraction of the produced electricity from the in-house energy system that is used for the in-house consumption. Calculating the SCR is done using the equation:

$$\text{SCR} = \frac{\Sigma_{t=1}^{N} min[E_{avail}, E_{demand}]}{\Sigma_{t=1}^{N} E_{prod}} \tag{3.17}$$

Where $E_{avail}$ is available energy, $E_{demand}$ is the energy demand and $E_{prod}$ is the energy produced.

### 3.3.5 LOLP

The loss of load probability (LOLP) is defined as the fraction of time that the on-site electricity generation system does not cover the electricity demand. It is meant to show how much is needed to be supplied of a grid, but can be used here to see how often the generator needs to cover the demand. It is calculated with the equation:

$$N_{g>d} = \sum_{t=1}^{N} f(t) \begin{cases} f(t) = 1 E_{avail} < E_{demand} \\ f(t) = 0 E_{avail} >= E_{demand} \end{cases} \tag{3.18}$$

LOLP is then found by dividing $N_{g>d}$ with N. N being the total number of iterations or hours. The energy autonomy is calculated by $E_{autonomy} = 1 - LOLP$. It is the fraction of the time that 100 % of the demand can be matched by on-site generation.

$$\begin{aligned} E_{avail} &= E_{windoutput} + max[\Delta_{bat}, 0] (\text{Without diesel generator}) \\ E_{avail} &= E_{windoutput} + E_{gen} + max[\Delta_{bat}, 0] (\text{With diesel generator}) \end{aligned} \tag{3.19}$$

The difference in the available energy with and without the diesel generator will be looked at in the discussion 5.1.

# Chapter 4

# Results

This chapter will present the results of the thesis, along with analysing the data. The calculation were explained in the method chapter 3 and will be referenced throughout. The chapter will follow a similar setup to the method chapter, as it starts with looking at the input data. Below the consumption data, wind data and power production will be presented. Before the base case, and different scenarios are presented. The implications of the scenarios will be discussed in the next chapter.

## 4.1 Consumption

The consumption was set up as shown in 3.1.2. Looking at what a 20 year timeline with all six facilities in different phases of the production would be affected by the simulations. The consumption data was set up as a 20 year time series to match the 20 year of wind data as explained in 3.1.1 and 3.1.2. The figure 4.1 shows the calculated mean and standard deviation for the consumption data on an hourly basis for each year used in the simulations. This coincides with the fact that the consumption data was created by combining six facilities and for this to repeat over the 20 years. As explained in the consumption section in the method chapter 3.1.2, the years chosen are

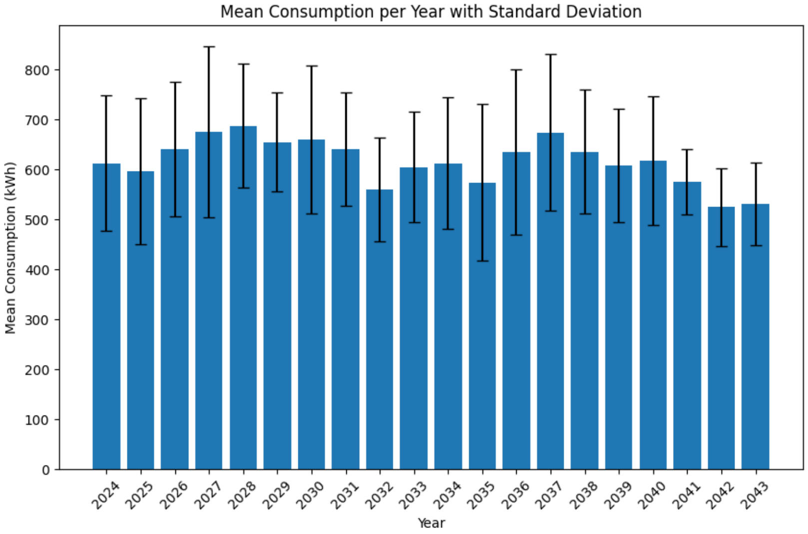


Figure 4.1: Shows the hourly mean and standard deviation for every year of the consumption data. X-axis shows the year, while the y-axis shows the consumption in kWh.

arbitrary, but starts at a leap year to match the wind data. The seasonal variations for the consumption data are presented in figure 4.2. The figure shows that the consumption largely hold itself within the same mean values, although the month of April and May seem to have a higher mean than the rest. This does however match the one year data, where the months of April and May are 39 % and 29 % higher than the mean respectively. The consumption frequency plot 4.3, shows the frequency for the different values in the consumption data. By analysing the data used to create the plot, it can be seen that the consumption is above 1000 kWh only 0.71 % of the time, and above 800 kWh for 10.32 % of the time.

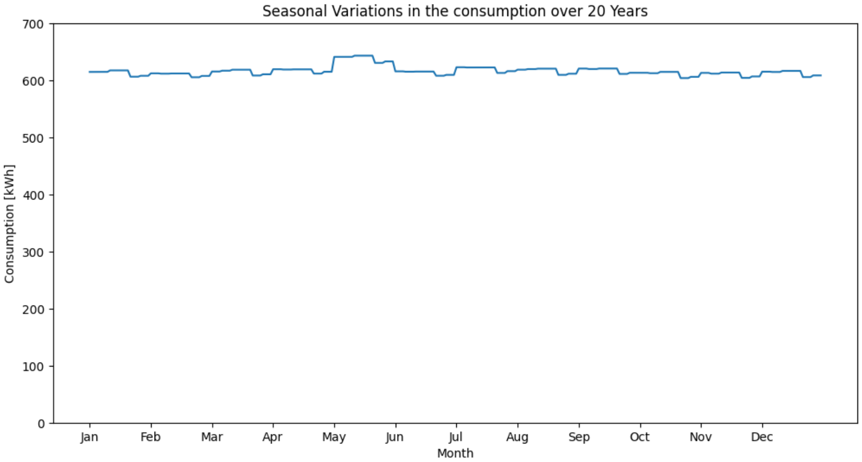


Figure 4.2: Shows the seasonal variation for consumption over the 20 years. Calculated the mean per hour for each month. The months on the x-axis and consumption in kWh on the y-axis.

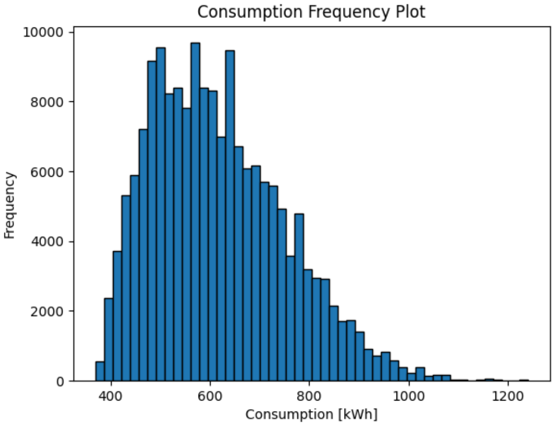


Figure 4.3: Shows the frequency plot of the consumption data. Consumption in kWh is shown on the x-axis and the frequency of these values are shown on the y-axis. Bin width is set to 50.

## 4.2 Wind data

The data has a maximum wind speed of 38.7 m/s, and a minimum of 0.005 m/s. The mean for the data set at 101 meters is 9.69 m/s and the standard deviation is 5.36 m/s. A year by year mean and standard deviation plot can be seen in figure 4.4. It shows that the mean values for the wind speeds are close. The high standard deviation for each year indicates a large spread in the wind speed. This can be seen in the seasonal variation of the wind speeds in figure 4.6. Generally higher wind speeds in the winter and autumn months compared to the summer. This correlates with the aforementioned changes is pressure on the coast from the Icelandic low and Azores high during the different seasons. The heights compared to each other can be seen in the figure 4.5. 101 and 995 m.a.s.l. are close to identical, which matches with the small difference in height. For 50 m.a.s.l. the mean is 9.08 m/s and a standard deviation of 5.02 m/s. This is 93.78 % of the mean at 101 meters.
As both turbines have a cut-in speed of 3 m/s, it is relevant to see how long the wind speeds can continuously stay below this limit. In the figure 4.7, it shows the frequency of how many hours in a row the wind speed is below 3 m/s. The two highest being 67 and 63 hours, while the third comes in at 47.

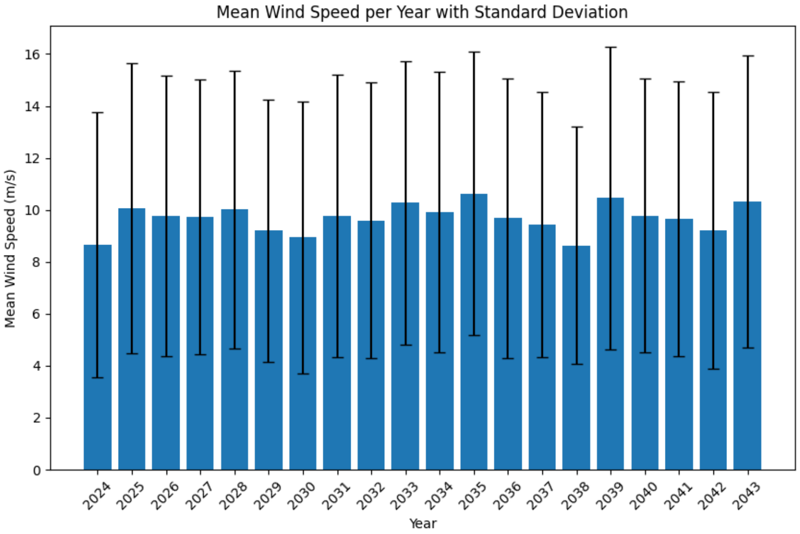


Figure 4.4: Shows the hourly mean and standard deviation per year for the wind data. X-axis is the years in focus, and y-axis is the wind speed in m/s. At 101 meters above sea level

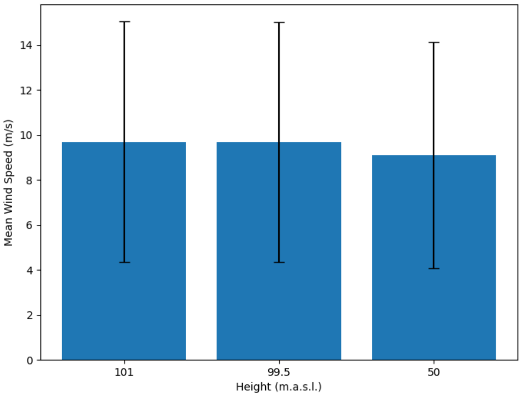


Figure 4.5: Shows the mean and standard deviation for the wind data at the three heights 101, 99.5 and 50 m.a.s.l. X-axis is the height of the wind data, while the y-axis is the mean wind speed in m/s.

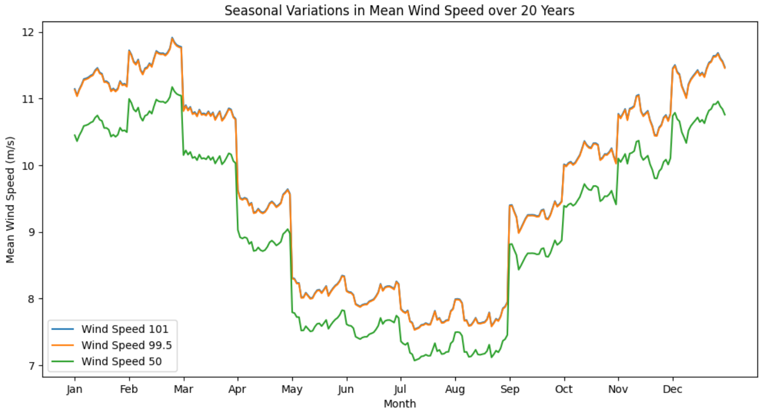


Figure 4.6: Shows the seasonal variation for the as the mean for each month over the 20 years of data. The months on the x-axis and the wind speed in m/s on the y-axis. Three heights have been measured as blue, orange and green. The heights are 101, 99.5 and 50 meters above sea level respectively.

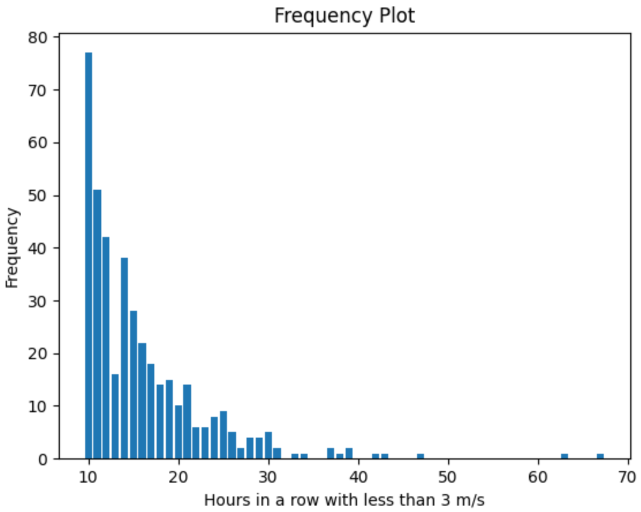


Figure 4.7: Shows the frequency plot for for events where the consecutive number of hours the wind is below 3 m/s exceeds 10 hours. 3 m/s was selected because the cut-in speed of 3 m/s for both turbines. Frequency (number of events) on the y-axis and hours in a row on the x-axis.

## 4.3 Power production

When looking at the production of the SeaTwirl S2x, there are some notable differences that occurs when using a VAWT instead of a horizontal one. If we compare the use of the S2x to the SWT-2.3-113 by Siemens, some key differences can be seen. The two most important are the hub height and the power curve of the two turbines. The S2x is a VAWT so the hub height is much lower than that of the SWT-2.3-113. They are set to 50 m.a.s.l. and 99.5 m.a.s.l. respectively. This can be seen in the wind speed frequency distribution in figure 4.8. The difference is small, but over 20 years it can amount up to 5 % power production loss. For the power curves, the main difference is that the power curve for SeaTwirl S2x needs a higher wind speed to reach its rated power. This can be seen in the figure 2.2.2

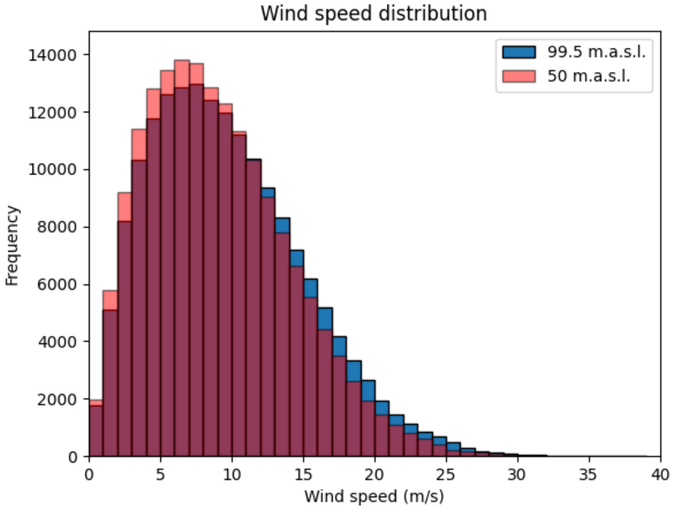


Figure 4.8: Frequency distribution for both hub heights. 99.5 m.a.s.l. can be seen is somewhat higher in the wind distribution.

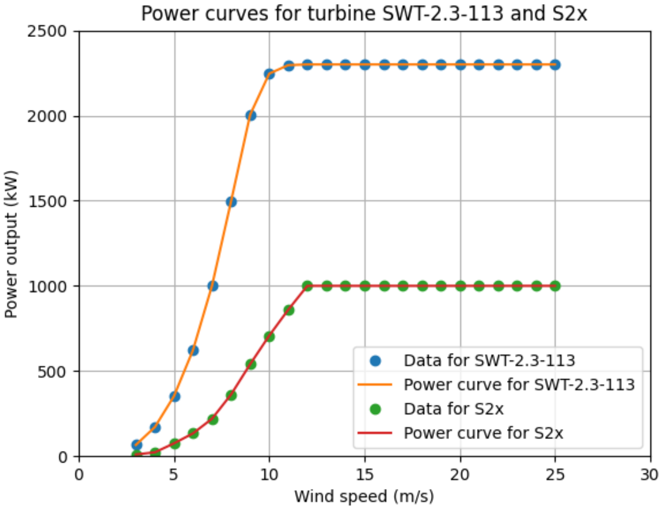


Figure 4.9: Shows the power curves for the two turbines used in this thesis. The SeaTwirl S2x has a rated power of 1 MW, while the SWT-2.3-113 has a rated power of 2.3 MW. X-axis shows wind speed, while y-axis shows the power output.

By looking at the power distribution for one S2x turbine 4.10, the turbine does not produce power for 10.05 % of the time. It produces at rated power (1MW) of energy 14.51 % of the time, and produces above 98 % of rated power 27.35 % of the time. By looking at the same for the SWT-2.3-113, it does not produce power 9.36 % of the time. It produces at rated power 16.47 % of the time. For 42.00 % of the time it produces more than 2250 kW an hour or above 97.83 % of rated power. This can be seen in the power distribution plot 4.11.

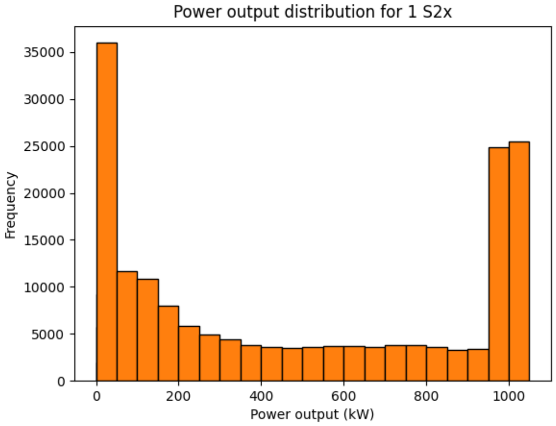


Figure 4.10: The power output distribution for 1 S2x turbine. Bin width of 50.

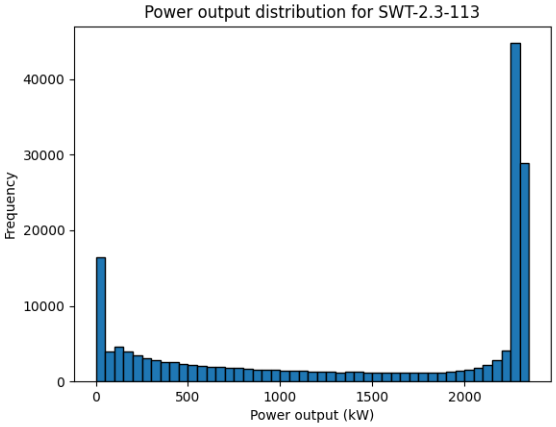


Figure 4.11: The power output distribution for 1 SWT-2.3-113 turbine. Bin width of 50

The seasonal variation of wind speed is used to find the seasonal variation of the power production, we can see the impact of the difference in wind speed. It is clear the difference between the months of May-August versus the rest of the year. The difference the height of the wind data has to say, can be seen in the figure 4.12 and 4.13. 101 and 99.5 are almost identical, while 50 meters above sea level has a mean of 93.24 % to that of 99.5 m.a.s.l.

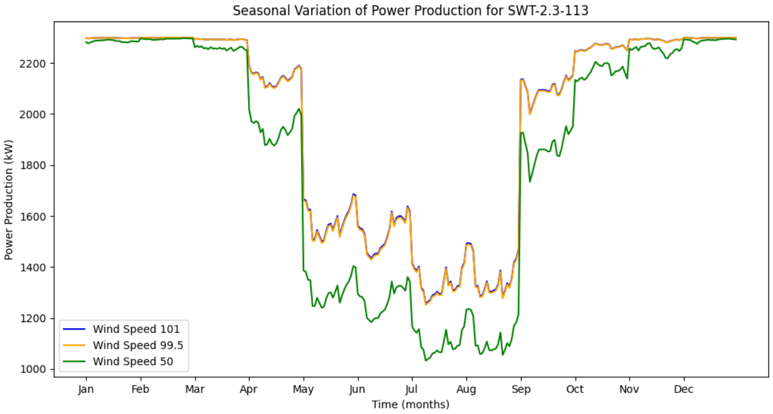


Figure 4.12: Shows the seasonal variation for power production for the SWT-2.3-113 turbine over a year. The x-axis shows the months, while the y-axis shows the power production in kW. The three different heights of 101, 99.5 and 50 meters above sea level are represented.

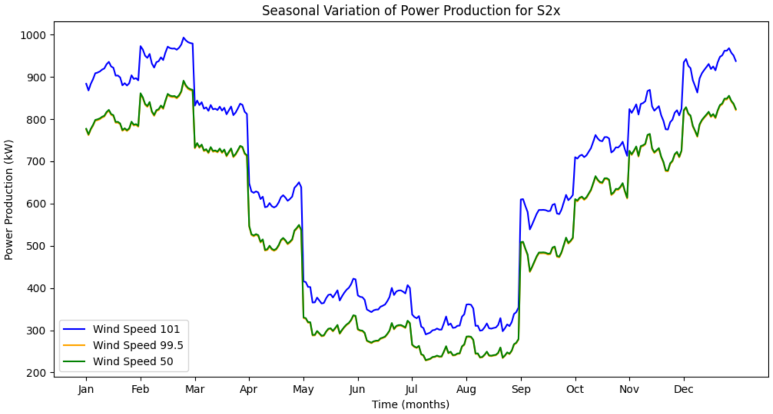


Figure 4.13: Shows the seasonal variation for power production for the S2x turbine over a year. The x-axis shows the months, while the y-axis shows the power production in kW. The three different heights of 101, 99.5 and 50 meters above sea level are represented.

## 4.4 Scenario

In the scenario section, the results for different scenarios created and simulated will be presented. The first is the base case, which the primary scenarios that are shown after will be compared against. Lastly, some extreme event scenarios will be presented.

### 4.4.1 Base Case

The base case is the use of only diesel generator to produce the needed energy to cover the consumption. By doing this, it is possible to see and compare to what a fully diesel generator driven scenario will produce in emission and if it is able to cover the consumption by itself. The diesel generator covers the needed consumption but cannot cover energy tops that goes beyond the maximum efficiency of 1200kW as explained in 3.2.4. As seen in figure 4.14, there are some peaks in the consumption that goes beyond 1 200kW. This leads to a deficiency in these hours. This happens during 40 hours, and sums up for a total of 1 651 kWh. The $CO_2$ emission module 3.3.2 calculates that the mean emission from this scenario is 4554.33 tons of $CO_2$ per year in the 20 year period. The table 4.1 is created so that it can be compared to by the other scenarios.

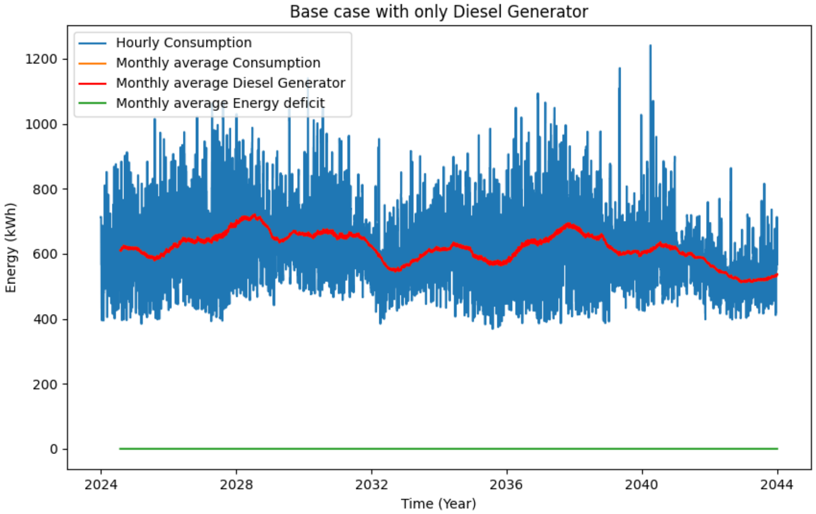


Figure 4.14: Shows the energy production for the base case. The monthly average consumption in orange is hidden by the monthly average diesel generator in red. The monthly average energy deficit is close to zero for the whole period.

| | **Base case** |
|---|---|
| **Electricity generated (GWh)** | 108.08 |
| **Electricity used (GWh)** | 108.08 |
| **Energy wasted (GWh)** | 0 |
| **Energy deficiency (kWh)** | 1651.44 |
| **Hours with deficiency (h)** | 40 |
| **Electricity from generator (GWh)** | 108.08 |
| **Electricity from generator (%)** | 100 |
| **Yearly emission (tons $CO_2$)** | 4554.33 |
| **Hours generator is on (%)** | 100 |

Table 4.1: Table of result for the base case. Shows the energy generated and wasted. While looking at the amount of energy not covered and for how many hours. The last part of the table is how much energy is coming from the diesel generator, how much of the time it is on and how much $CO_2$ is emitted.

### 4.4.2 Primary scenarios

The primary scenarios were created by looking at different combinations of battery capacity sizes and amount of the SeaTwirl S2x turbine and the SWT-2.3-113 turbine. By looking at the change in how much of the energy is from the diesel generator, it is possible to see how effective the different scenarios are in limiting the carbon dioxide emissions. The battery capacity was chosen to have the sizes of 0 kWh, 1200 kWh, 1800 kWh and 2400 kWh as seen in 3.3.3, and the diesel generator was not allowed to charge the batteries.

#### One S2x turbine

|  | **Base case** | **0 kWh** | **1200 kWh** | **1800 kWh** | **2400 kWh** |
|---|---|---|---|---|---|
| **Electricity generated (GWh)** | 108.08 | 131.77 | 129.62 | 128.80 | 128.10 |
| **Electricity wind (GWh)** | 0 | 86.34 | 86.34 | 86.34 | 86.34 |
| **Wasted wind energy (GWh)** | 0 | 23.70 | 21.54 | 20.73 | 20.02 |
| **Wasted wind energy (%)** | 0 | 27.5 | 24.95 | 24.01 | 23.19 |
| **Energy Deficiency (kWh)** | 1651.44 | 41.29 | 41.29 | 41.29 | 41.29 |
| **Hours with deficiency (h)** | 40 | 1 | 1 | 1 | 1 |
| **Electricity from generator (GWh)** | 108.08 | 45.44 | 43.28 | 42.47 | 41.76 |
| **Electricity from generator (%)** | 100 | 42.04 | 40.05 | 39.29 | 38.63 |
| **Yearly emission (tons $CO_2$)** | 4554.33 | 1914.63 | 1823.79 | 1789.58 | 1759.59 |
| **Hours generator is on (%)** | 100 | 58.00 | 53.83 | 53.76 | 53.74 |

Table 4.2: Result for one S2x turbine. Results consist of four sizes of battery capacity compared to the base case. It shows the electricity generated and wasted, the energy deficiency in kWh and hours as well as electricity and hours from the diesel generator and yearly emissions in tons $CO_2$.

### Two S2x turbines

| | **Base case** | **0 kWh** | **1200 kWh** | **1800 kWh** | **2400 kWh** |
|---|---|---|---|---|---|
| **Electricity generated (GWh)** | 108.08 | 207.24 | 204.75 | 203.76 | 202.87 |
| **Electricity wind (GWh)** | 0 | 172.68 | 172.68 | 172.68 | 172.68 |
| **Wasted wind energy (GWh)** | 0 | 99.16 | 96.67 | 95.68 | 94.80 |
| **Wasted wind energy (%)** | 0 | 57.42 | 55.98 | 55.41 | 54.90 |
| **Energy deficiency (kWh)** | 1651.44 | 41.29 | 41.29 | 41.29 | 41.29 |
| **Hours with deficiency (h)** | 40 | 1 | 1 | 1 | 1 |
| **Electricity from generator (GWh)** | 108.08 | 34.56 | 32.08 | 31.09 | 30.20 |
| **Electricity from generator (%)** | 100 | 31.98 | 29.68 | 28.76 | 27.94 |
| **Yearly emission (tons $CO_2$)** | 4554.33 | 1456.48 | 1351.64 | 1309.91 | 1272.62 |
| **Hours generator is on (%)** | 100 | 44.35 | 40.42 | 39.78 | 39.17 |

Table 4.3: Result for two S2x turbines. Results consist of four sizes of battery capacity compared to the base case. It shows the electricity generated and wasted, the energy deficiency in kWh and hours as well as electricity and hours from the diesel generator and yearly emissions in tons $CO_2$.

### Three S2x turbines

| | **Base case** | **0 kWh** | **1200 kWh** | **1800 kWh** | **2400 kWh** |
|---|---|---|---|---|---|
| **Electricity generated (GWh)** | 108.08 | 288.23 | 285.76 | 284.76 | 283.86 |
| **Electricity wind (GWh)** | 0 | 259.01 | 259.01 | 259.01 | 259.01 |
| **Wasted wind energy (GWh)** | 0 | 180.15 | 177.69 | 176.68 | 175.78 |
| **Wasted wind energy (%)** | 0 | 69.55 | 68.60 | 68.21 | 67.87 |
| **Energy deficiency (kWh)** | 1651.44 | 41.29 | 0 | 0 | 0 |
| **Hours with deficiency (h)** | 40 | 1 | 0 | 0 | 0 |
| **Electricity from generator (GWh)** | 108.08 | 29.22 | 26.75 | 25.74 | 24.84 |
| **Electricity from generator (%)** | 100 | 27.03 | 24.75 | 23.82 | 22.99 |
| **Yearly emission (tons $CO_2$)** | 4554.33 | 1231.10 | 1127.19 | 1084.85 | 1046.87 |
| **Hours generator is on (%)** | 100 | 37.92 | 34.12 | 33.47 | 32.76 |

Table 4.4: Result for three S2x turbine. Results consist of four sizes of battery capacity compared to the base case. It shows the electricity generated and wasted, the energy deficiency in kWh and hours as well as electricity and hours from the diesel generator and yearly emissions in tons $CO_2$.

**SWT-2.3-113**

| | **Base case** | **0 kWh** | **1200 kWh** | **1800 kWh** | **2400 kWh** |
|---|---|---|---|---|---|
| **Electricity generated (GWh)** | 108.08 | 275.73 | 273.33 | 272.35 | 271.47 |
| **Electricity wind (GWh)** | 0 | 254.28 | 254.28 | 254.28 | 254.28 |
| **Wasted wind energy (GWh)** | 0 | 167.66 | 165.26 | 164.27 | 163.39 |
| **Wasted wind energy (%)** | 0 | 65.94 | 64.99 | 64.60 | 64.26 |
| **Energy deficiency (kWh)** | 1651.44 | 41.29 | 0 | 0 | 0 |
| **Hours with deficiency (h)** | 40 | 1 | 0 | 0 | 0 |
| **Electricity from generator (GWh)** | 108.08 | 21.45 | 19.05 | 18.07 | 17.19 |
| **Electricity from generator (%)** | 100 | 19.85 | 17.62 | 16.72 | 15.90 |
| **Yearly emission (tons $CO_2$)** | 4554.33 | 903.88 | 802.67 | 761.33 | 724.21 |
| **Hours generator is on (%)** | 100 | 28.75 | 25.47 | 24.85 | 24.09 |

Table 4.5: Result for one SWT-2.3-113 turbine. Results consist of four sizes of battery capacity compared to the base case. It shows the electricity generated and wasted, the energy deficiency in kWh and hours as well as electricity and hours from the diesel generator and yearly emissions in tons $CO_2$.

The tables 4.2, 4.3, 4.4, and 4.5 shows the results for the primary scenarios. The tables show the total electricity generated, as well as the electricity from the wind and the diesel generator. The amount of wind energy wasted and the energy deficiency. From the tables it can be seen that increasing the rated power of the turbines decreases the electricity provided by the diesel generator and by that decrease the emissions. Doing this however increases

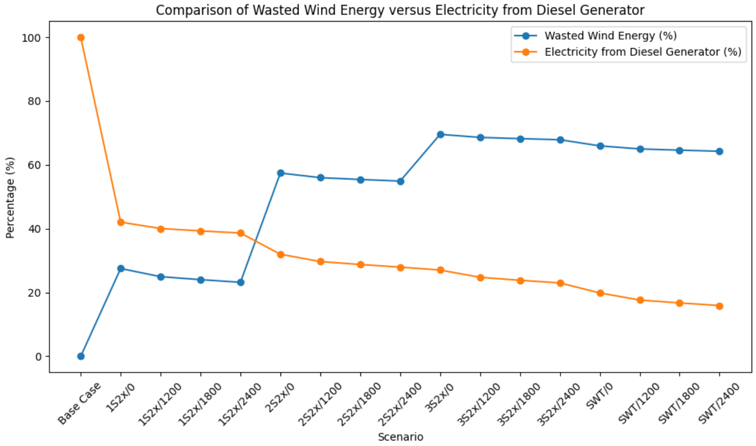


Figure 4.15: Shows a comparison between the wasted wind energy as a percentage of the and electricity from the diesel generator. The electricity from diesel generator is the same as percentage of emissions compared to the base case. The scenarios on the x-axis and the percentage on the y-axis.

the amount of wind energy the system fails to utilize and goes to waste. This leads to a over dimensioning of the turbines can quickly become costly. This comparison can be seen in figure 4.15. It is apparent that increasing the turbines have less of an impact on the electricity from the diesel generator as the available rated power increases. All scenarios cover all the energy demands, except for one hour that will be looked at more in the discussion.

### 4.4.3 Worst case scenario

An interesting scenario to look at is what will happen when we compare the worst wind month, i.e. the month with the lowest mean value, up against the month of consumption with the highest mean value. This is done to look at the possible strain on the diesel generator should the available wind be low. The month with the lowest wind speed is May 2010 according to the wind data in the 1996-2015 timeline. The month with the highest consumption would be June 2028, if the data starts at January 1. 2024. The scenarios chosen are the SWT/1200 and the 1S2x/1200 scenarios that combines the single wind turbines with a battery capacity of 1200 kWh. They were chosen as they both only require one turbine, and is combined with the smallest battery. This creates the more economic combination that can benefit from being analysed during a stress-test of the system. The scenario looks at how high the percentage of the diesel generator needs to be at a worst case scenario with low wind, but still with production. The result for the scenario is shown in the table 4.6. All consumption is covered by either wind, battery or the diesel generator. As seen in the table, both turbines struggle coping with low wind speeds. Especially the S2x turbine produces only 21.38 % of the energy needed in the consumption. This leads to the high emission of 78.62 %. The SWT turbine, even with the low wind energy, has not utilized 38.22 % of it.

| **Worst case scenario** | | |
|---|---|---|
| **Turbine** | **SWT** | **S2x** |
| **Electricity generated (MWh)** | 765 | 559.7 |
| **Wind turbine production (MWh)** | 525.3 | 124.6 |
| **Wasted wind energy (MWh)** | 211.5 | 6.3 |
| **Consumption (MWh)** | 553.4 | 553.4 |
| **Energy from generator (MWh)** | 239.6 | 435.1 |
| **Emission (tons $CO_2$)** | 201.97 | 366.72 |
| **Emission (% $CO_2$ )** | 43.30 | 78.62 |
| **Time generator is on (%)** | 58.06 | 92.22 |

Table 4.6: Table of result for the lowest mean wind speed month versus the mean highest consumption month. Turbine used is the SWT-2.3-113 and the S2x. Both use a battery capacity of 1200 kWh.

### 4.4.4 Least effective wind power usage scenario

Similar to the last section; what will happen if we compare the highest mean wind speed, to the lowest mean consumption month? This scenario is looked at to determine how much of the energy can be utilized if there is a period with high wind speeds, but low consumption. It also gives an indication of what the lowest possible emission can be for a month. The month with the highest mean wind speed in the data is December 2013 and the month with the lowest mean consumption data is October 2042. The same combinations of SWT/1200 and 1S2x/1200 are chosen. The table 4.7 shows the result in simulating the two months of data. All consumption is covered by either wind, battery or the diesel generator. The table shows that with high wind speeds the SWT turbine struggles with wasted wind energy. Since the consumption is so low, the turbine is not able to use 76.76 % of the energy it produces. As only 3.33 % of the electricity mix is from the diesel generator, in this scenario the SWT turbine is over dimensioned. The S2x turbine has only 23.4 % of the wasted wind energy as the SWT turbine has. Although it also only have 40.29 % of the production. 44.59 % of this production is wasted and not used to cover the consumption. For a scenario like this, even the smallest turbine of 1 MW rated power will be more than needed and lead to waste. A better and larger battery or storage system might mitigate this wasted wind energy.

| **Least effective wind power usage** | | |
|---|---|---|
| **Turbine** | **SWT** | **S2x** |
| **Electricity generated (MWh)** | 1 546.2 | 643.8 |
| **Wind turbine production (MWh)** | 1 534.6 | 618.2 |
| **Wasted wind energy (MWh)** | 1 178.0 | 275.7 |
| **Consumption (MWh)** | 368.9 | 368.9 |
| **Energy from generator (MWh)** | 12.3 | 26.4 |
| **Emission (tons $CO_2$)** | 10.35 | 22.24 |
| **Emission (% $CO_2$)** | 3.33 | 7.15 |
| **Time generator is on (%)** | 5.24 | 12.23 |

Table 4.7: Table of result for the highest wind versus the lowest consumption month. Turbine used is the SWT-2.3-113 and the S2x. Both use a battery capacity of 1200 kWh.

## 4.5 Emission

The $CO_2$ emission of the scenarios can be seen in the table 4.8. The base case of 4554.33 tons of $CO_2$ on average per year. Down to 724.21 tons per year or 15.90 % of the base case emitted for the scenario of one SWT-2.3-113 and a battery capacity of 2400 kWh. This can be seen in figure 4.16 along with the scenarios that are below 20 % of the base case. The table 4.9 shows the amount of energy from the diesel generator is used to cover the consumption. It can also be seen as the amount of energy the wind and battery system is not able to cover. The percentages in the two tables are the same, this is because the emission as explained in 3.3.2 is calculated with constants so that the relation between base case and scenarios are the same for the emission as it is for the percentage of electricity delivered from the diesel generator. This makes it so the figure 4.15 shows the connection between lowering emissions, but at the cost of an increase in wasted wind energy.

| Yearly emission (tons $CO_2$) by Scenario | | | | |
|---|---|---|---|---|
| | Battery capacity | | | |
| **Turbine(s)** | 0 kWh | 1200 kWh | 1800 kWh | 2400 kWh |
| **1 S2x** | 1914.63 (42.04%) | 1823.79 (40.05%) | 1789.58 (39.29%) | 1759.59 (38.64%) |
| **2 S2x** | 1456.48 (31.98%) | 1351.64 (29.68%) | 1309.91 (28.76%) | 1272.62 (27.94%) |
| **3 S2x** | 1231.10 (27.03%) | 1127.19 (24.75%) | 1084.85 (23.82%) | 1046.87 (22.99%) |
| **SWT-2.3-113** | 903.88 (19.85%) | 802.67 (17.62%) | 761.33 (16.72%) | 724.21 (15.90%) |

Table 4.8: Table of the result for scenarios. Emphasizing the yearly emission of $CO_2$ from the diesel generator used to cover the consumption. Percentage in relation to the base case shown in parentheses.

The diesel generator frequency plot for the scenario SWT/1200 shows that the mean, when the diesel generator is on, is at 426.50 kWh. This means that the diesel generator on average operates with a 22.49 % efficiency. Compared

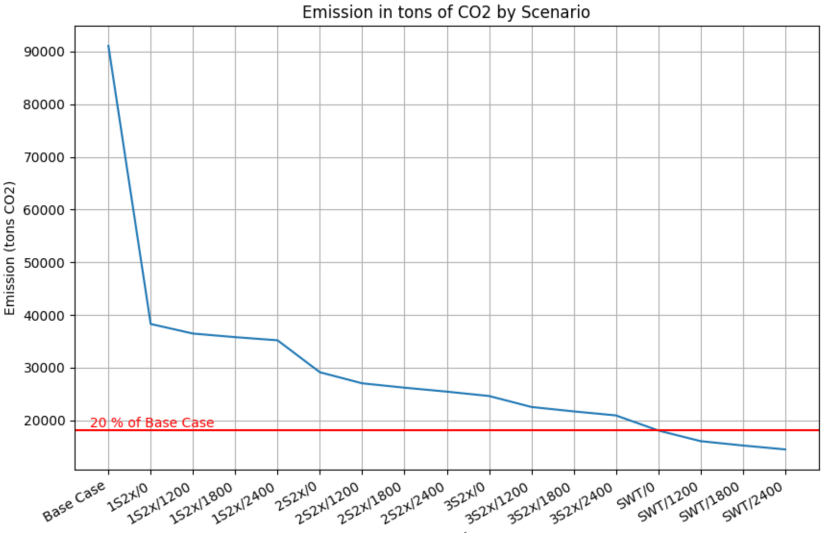


Figure 4.16: The blue line is the emission per scenario, while the red is 20 % of the emission of the base case. Scenarios are shown on the x-axis and emission in tons of $CO_2$ is shown on the y-axis.

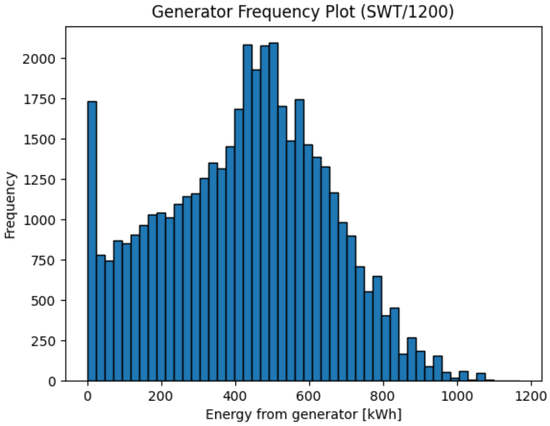


Figure 4.17: Shows the frequency plot for the energy from the generator for the scenario of one SWT-2.3-113 and battery capacity of 1200 kWh. X-axis shows the energy from the generator in kWh, and y-axis shows the frequency. Values of zero have been removed.

| Percentage of electricity from diesel generator to cover consumption | | | | |
|---|---|---|---|---|
| | Battery capacity | | | |
| **Turbine(s)** | 0 kWh | 1200 kWh | 1800 kWh | 2400 kWh |
| **1 S2x** | 42.04 | 40.05 | 39.29 | 38.64 |
| **2 S2x** | 31.98 | 29.68 | 28.76 | 27.94 |
| **3 S2x** | 27.03 | 24.75 | 23.82 | 22.99 |
| **SWT-2.3-113** | 19.82 | 17.62 | 16.72 | 15.90 |

Table 4.9: Table of the result for scenarios. Emphasizing the percentage of electricity from the generator used to cover the consumption. A comparison for all 16 primary scenarios.

to that of the base case, which has an average operating efficiency of 28.46 %, the diesel generator is less effective on turning diesel into electricity, and more emission per liter diesel is emitted.

### 4.5.1 Size of diesel storage

An important factor in this is how much is diesel is needed to keep "at hand" during low wind events. By summing up the amount of diesel used each month by scenario, a maximum, minimum and mean of the needed diesel can be found. The result can be seen in figure 4.18. It ranges from a top of 175 000 liters a month at max for the base case, and goes as low as 2 090 liters for the SWT/2400 combination. The trend of the scenarios for the diesel consumption is the same as the emission, which coincides with the fact that emission is just a multiple of the diesel consumption. This figure does however show how high the diesel consumption still can be during a low wind month.

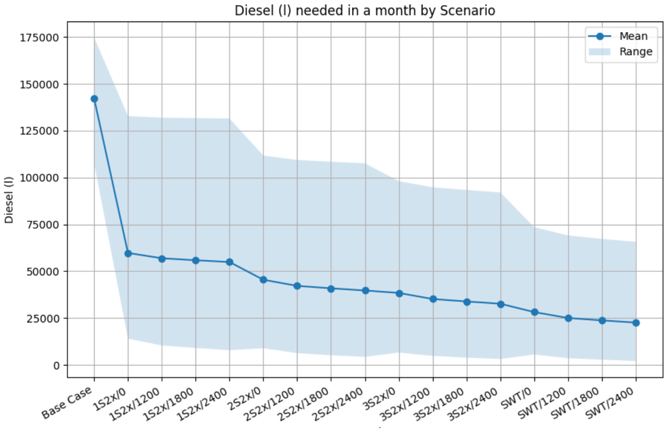


Figure 4.18: Shows the diesel used per month per scenario. The blue line is the mean value per month, while the colored area is filled between the maximum and minimum of the month in scenario. X-axis shows scenarios, while the y-axis shows the amount of diesel in liters.

### 4.5.2 Generator charge battery

The diesel generator does not charge the battery for the scenarios above. In this section it will be looked at if the diesel generator is allowed to charge the battery. The method section 3.2.4 explains how the diesel generator charges the battery. The result for the test can be seen in table 4.10. When it is enabled the emission of the scenarios using the S2x turbine increases by 4.15 %. The wasted wind energy increases by 0.70 % and the diesel generator is on 1.57 % of the time. The diesel generator does however operate on a higher efficiency which is increased by 3.80 %. The same can be seen for the scenarios using the SWT-2.3-113 turbine. The increase in emission is higher than for the S2x turbine and increases with 6.11 %. If the last scenario (SWT/2400) is compared towards each other, the increase in emissions is 12 %. The diesel generator operates at a higher efficiency here as well, an increase of 6.56 %. In a more accurate simulation, the amount of electricity one would gain from a liter of diesel would rise. The reasons for this scenario having more negative aspects than positive will be disussed in the discussion chapter.

| **Generator used for charging battery** | | |
|---|---|---|
| **Turbine(s)** | **S2x** | **SWT-2.3-113** |
| **Emission increase (%)** | 4.15 | 6.11 |
| **Wasted wind energy increase (%)** | 0.70 | 0.67 |
| **Time generator is on (%)** | 1.57 | 1.92 |
| **Generator efficiency (%)** | 3.80 | 6.56 |

Table 4.10: Table of the result for scenarios when diesel generator is allowed to charge battery. The calculation is the sum for every scenario with a battery capacity with diesel generator charging, compared to the same scenarios without charging.

# Chapter 5

# Discussion

## 5.1 Interpretation of result

The research question is to see if it is possible to limit the emission of greenhouse gases by introducing the system to a wind and battery combination, with the diesel generator in reserve. By looking at the result, we can see that with only installing one 1 MW S2x wind turbine, the facility can decrease its emission output with 60 %. By adding one more turbine, the $CO_2$ emissions by the generator is decreased by 70 %, and a third lowers it to between 73-77 % decreased. Increasing the amount of turbines more than these three given in the result, will not affect the amount of emitted carbon dioxide in a large degree. Likely one reason is because the battery cannot charge more than the maximum charge in an hour, so increasing the power output from the turbine does not help in covering the consumption or recharging the battery. When the wind speed is too low for the turbines to produce it does not matter how many turbines are installed.

This can be seen in several of the scenarios, that there is one peak of the consumption data that is 1241 kWh. There are 40 instances of values above 1200 kW for the consumption data that occurs back to back, which test the simulations ability to cover the consumption. Most scenarios have this as the only time there is a energy deficiency. For that one hour that is in deficiency, the battery is at its lowest capacity and the wind turbine does not produce any energy. The generator then tries to cover everything, but since the generator has a max of 1200 kW, it will lead to a deficiency of 41 kW. As the production and battery capacity increases the deficiency is covered. As shown in the figure 4.7, the longest period where the turbine produces no power are two instances of above 60 hours. In this period, the battery will quickly be drained and the generator will have to produce all of the needed energy. During this period, the size and amount of rated power does not play a role. Since the battery has been set with the high maximum value for charge and discharge of 25 % of the nominal capacity and the battery has a useful capacity of 60 %, between 20 % and 80 %, the battery can be discharged from full capacity to empty as fast as in three hours. With a higher useful capacity or a lower maximum discharge this would take more time.

The seasonal variation of the wind speed play an important role in the power production during the year. As the speeds vary from a mean value of about 8 m/s during the months May to August, the availability for power production is lower than that of November to March where the speed is between 11 and 12 m/s. As seen in figures 4.6, 4.12 and 4.13 the hub height plays a key role in the power production of the turbine. By going from 99.5 m.a.s.l. to 50 m.a.s.l. the loss in power production can be considerable. This will be looked at further in section discussing the differences of HAWT vs VAWT.

The scenarios all limit the emissions. The S2x scenarios as explained lowers it by 60 %, 70 %, and 75 % for the combination of one, two, and three turbines respectively. The SWT-2.3-113 scenarios limit the emissions with over 80 % of the base case. Whether the economic, the emission or the ability to use what is produced is in focus, the best combination might differ. The best combination therefore depends on several factors, which will be discussed later.

### Worst and best case scenarios

Two special scenarios have been calculated in the result section. The lowest mean month of wind data versus the highest mean month of consumption data 4.4.3, along with the highest mean month of wind data versus the lowest mean month of consumption data 4.4.4. These extremes are created to highlight the possible situations that can occur to the facility. Either that the power production is too low, and the generator has to cover most of the consumption for that month. Or that the power production is way higher than what is needed, so the battery gets a maximum charge and the wasted energy is high. We can see in the scenario that there are no hours with deficiency in energy. The production from the turbine is almost three times as much for the high wind speed scenario versus the low, while the high consumption is an increase of 50 % to the low consumption. This shows the high variance in wind speed from month to month, while the consumption is more homogeneous. As the generator ranges from covering 3.3 % to 43.3 %, the spread in what the generator needs to cover is large. For the low wind versus high consumption there is 38.2 % wasted wind energy of consumption, while the opposite scenario, this number is as high as 319.3 %.

### Wasted wind energy

The wasted wind energy is a problem throughout the scenarios. Energy from wind is highly intermittent and the battery has a maximum charge in an hour of 25 % of its nominal capacity. When the energy production is high, the battery cannot take all the surplus energy into its system, causing energy to go lost. For the scenarios that use three SeaTwirl S2x turbines, the power produced is almost three times the consumption. This leads to a lot of wasted energy, as the battery cannot store the amount of energy being produced. What is not calculated in this thesis is what this energy can be used for. SalMar has launched the first electric wellboat [67], which can potentially use some of the wasted power to charge. Other solutions like this is a possibility to reduce the amount of wasted energy. There is also the possibility to connect to the grid to sell surplus energy, although this somewhat defeats the purpose of the thesis as it aims to be self-sufficient outside of the grid. Creating a more in-depth battery simulation could fix some of the issues of the wasted power. If the possibility to acquire more of the wasted power to the battery, the generator would also need to be less used and the emission would go down even more.

### Efficiency of the system

The efficiency of the system can be calculated using some different variables. Explained in 3.3.4 and 3.3.5 the calculations for the self-sufficiency ratio (SSR 3.16), the supply cover ratio (SCR 3.17), and the loss of load probability (LOLP 3.18), all help give an indication of how effective a system is in using the on-site electric generation, as well as covering the demand. As seen in the

| **The SSR, SCR and LOLP (%) without diesel generator** | | | | | | |
|---|---|---|---|---|---|---|
| | **Battery capacity** | | | | | |
| **Turbine(s)** | **0 kWh** | | | **1200 kWh** | | |
| | SSR | SCR | LOLP | SSR | SCR | LOLP |
| **1 S2x** | 57.96 | 72.55 | 58.00 | 59.96 | 73.22 | 53.57 |
| **2 S2x** | 68.02 | 42.57 | 44.35 | 70.32 | 43.39 | 40.19 |
| **3 S2x** | 72.97 | 30.45 | 37.92 | 75.25 | 31.10 | 33.87 |
| **SWT-2.3-113** | 80.15 | 34.07 | 28.75 | 82.38 | 34.68 | 25.27 |
| | **1800 kWh** | | | **2400 kWh** | | |
| | SSR | SCR | LOLP | SSR | SCR | LOLP |
| **1 S2x** | 60.71 | 73.47 | 52.69 | 61.37 | 73.68 | 51.83 |
| **2 S2x** | 71.24 | 43.71 | 39.09 | 72.06 | 43.99 | 38.03 |
| **3 S2x** | 76.18 | 31.37 | 32.83 | 77.01 | 31.60 | 31.74 |
| **SWT-2.3-113** | 83.28 | 34.93 | 24.29 | 84.10 | 35.15 | 23.19 |

Table 5.1: Table showing the SSR, SCR and the LOLP of the different turbine configurations without calculating the diesel generator.

| **The SSR, SCR and LOLP (%) with diesel generator** | | | | | | |
|---|---|---|---|---|---|---|
| | **Battery capacity** | | | | | |
| **Turbine(s)** | **0 kWh** | | | **1200 kWh** | | |
| | SSR | SCR | LOLP | SSR | SCR | LOLP |
| **1 S2x** | 100.00 | 82.02 | 0.87 | 100.00 | 82.02 | 0.90 |
| **2 S2x** | 100.00 | 52.15 | 0.62 | 100.00 | 52.15 | 0.65 |
| **3 S2x** | 100.00 | 37.50 | 0.44 | 100.00 | 37.50 | 0.48 |
| **SWT-2.3-113** | 100.00 | 39.20 | 0.34 | 100.00 | 39.20 | 0.35 |
| | **1800 kWh** | | | **2400 kWh** | | |
| | SSR | SCR | LOLP | SSR | SCR | LOLP |
| **1 S2x** | 100.00 | 82.02 | 0.90 | 100.00 | 82.02 | 0.88 |
| **2 S2x** | 100.00 | 52.15 | 0.65 | 100.00 | 52.15 | 0.63 |
| **3 S2x** | 100.00 | 37.50 | 0.49 | 100.00 | 37.50 | 0.46 |
| **SWT-2.3-113** | 100.00 | 39.20 | 0.36 | 100.00 | 39.20 | 0.34 |

Table 5.2: Table showing the SSR, SCR and the LOLP of the different turbine configurations with calculating the diesel generator.

tables 5.1 the SSR of the system ranges from 58 % to 84 % when calculated without the electricity from the diesel generator. With the generator this value reaches 100 % for all combinations. Which corresponds with the fact that the simulation is not on a larger electrical grid and has to be self-sufficient. Additionally that there are no calculated losses in the simulation as explained in 3.2.1. The amount of energy that goes unused can be seen in the SCR, ranging from 72.6 % to 30.4 % in the calculation without the diesel generator, and 82 % to 39 % with the diesel generator. This highlights the over dimensioning that has been a problem for a majority of the thesis. The size of the turbines do however show why they are important in the LOLP, ranging from 58 % for the S2x turbine without a battery, to 23.2 % for the SWT turbine with a battery of 2400 kWh. Calculating the LOLP with the diesel generator puts them all beneath 1 %.

The efficiency of the system with regards to the SSR, SCR and LOLP without the diesel generator shows the abilities of the wind and battery system to cover the demand of the facilities. To lower the loss of load probability, a higher power production and storage is required. However this leads to a lower supply cover ratio, meaning that the amount of wasted wind energy increases.

### HAWT VS VAWT

The differences of the HAWT and the VAWT can be seen quite clear in the results. The largest battery capacity of 2400 kWh combined with three S2x turbines giving a rated power production of 3 MW will cut the emission down to 23 % of the base case. While the same battery capacity and one SWT-2.3-113 turbine manages to limit the emission of $CO_2$ to 15.9 %. As looked at in the power production section 4.3, the horizontal axis turbine has the higher hub height as well as the more beneficial power curve, it can produce more energy with a lower rated power of 2.3 MW versus the 3 MW of the three S2x turbines. This is with the generous hub height of 50 meters above sea level, when the whole turbine is 55 meters high. Likely the hub height should have been set to around 35-40 meters. If the height is set to 35 meters, it creates a wind speed set with a mean of 8.8 m/s against the original mean of 9.7 m/s at 101 meters. Since the calculation of power output 2.2 from the turbine is a cube function in regards to wind, the amount of energy that can go lost increases fast. by looking at the two mean values above, 8.8 m/s is 90.72 % of 9.7 m/s. If the mean values are cubed: $8.8^3 = 681.5$ and $9.7^3 = 912.7$. The difference is now: $\frac{681.5}{912.7} * 100 = 74.7\%$. There is a loss of 25 % of the possible power from the turbines. The SWT/1200 kWh scenario that limited the energy from the generator to 17.6 % has a hub height of 99.5 meters above sea level. If this is changed to 50 meters to match the used hub height of the S2x turbine, the percentage of energy from the turbine is at 19.3 %. Or 20.3 % at 35 m.a.s.l. If the same is done in reverse, i.e. 2 S2x turbines at 99.5 m.a.s.l. with a battery capacity of 1200 kWh, the energy from diesel is down to 27.2 % from 29.6 %.

According to Doctor Pablo Ouro, the VAWT outperform HAWT when put in a farm of 25 10 MW turbines [63]. This is because the VAWT have a lower thrust coefficient and wake recovery time. Something the VAWT in this thesis draws no benefit from seeing that wake is disregarded. As there is a maximum of three VAWT turbines or one HAWT turbine there is little to no wake depending on the scenario. The most important difference between the HAWT and VAWT is the economic aspect, which will be looked at briefly in the economic section 5.2.

### Emission

The emissions of the scenarios can be seen in the table 4.8. The scenario with one SWT-2.3-113 and battery capacity of 2400 kWh, has the lowest yearly $CO_2$ emitted of the sixteen scenarios. It emits 724.2 tons, which is 15.9 % of the base case of 4554.3 tons. Looking at the result 4.5, we saw that in the base case the diesel generator operated with a mean efficiency of 28.5 %. While in the combination SWT/2400 the mean efficiency was 21.8 %. This is somewhat opposite of what was planned for in the thesis. The idea was that the generator should be operating less of the time, but with a higher efficiency. This is likely because it more often than not is providing energy for smaller values not covered by the wind energy or the battery. As it is set to not charging the battery for the scenarios it also lowers the efficiency of the generator.

One of the reasons a reduction of 80 % in emissions was chosen over 100 %, is that the cost for removing the last percentages often comes at a high economic cost. This can be seen in Sandøy's thesis [13]. His first case study tried to cover all consumption of the facility by a combination of wind and hydrogen. This showed itself to be very expensive. If the same where to be done here, an increase in the turbines rated power and the battery capacity would be needed. Having a diesel generator in backup can limit these expenditures and make it more economically feasible.

### Size of diesel storage

The size of the diesel storage is relevant for knowing how much diesel is needed in either an emergency or for general consumption. Figure 4.18 shows that for the base case, the maximum diesel used in a month is 175 000 liters. This decreases as the use of the generator also lowers. As explained in equation 3.14 in the method section, the amount of emission is proportional with the amount of diesel used. The emission is diesel used times $2.67CO_2$ per liter. For the results below 20 % emission of the base case, a diesel storage of 75 000 liters would be recommended. For the S2x turbines, the storage should be 150 000, 125 000 and 110 000 respectively for the amount of turbines, if it was not possible to fill the tanks more than once a month. For events where there are no production of power from the wind turbine, the base case should be followed. How much diesel is needed in the facility is dependent on how often it aims to be resupplied. Whether this is every year, month or week will determine the needed size of the storage.

### Generator charging battery

In the result chapter, there is a test where the generator is allowed to charge the battery. This leads to higher emissions and a small bump in the wasted energy. The increase in emission increases in tandem with the increase in the battery capacity. Likely the battery being charged by the generator decreases the amount of charging from the wind turbine. There is still the same deficiency even with the generator being able to charge. As written in the beginning of the discussion chapter, this is during the period of 40 hours that all have a consumption per hour of 1241 kW. The generator does not have the surplus to charge the battery during this period and fails to cover the hour where the energy is needed. For the scenario SWT/1200 looked at in section 4.5 in figure 4.17 the efficiency of the generator was at 22.5 %. With the charging from the generator on, this increases to 22.6 %. The results for this would vary based on the set rules for the charging of the battery in the code.

### Choosing the parameters

When choosing the parameters for the battery, which turbines and how the consumption was put together, it was influenced from several holds. One of the main influences was the thesis of Sandøy [13], which I have built upon. Reading other science papers that dealt with similar problems also helped. I stumbled upon the SeaTwirl S2x turbine that marketed the cheap operational cost because of its vertical axis build. They also marketed that the area of use was fish farms, which made me decide to focus the thesis on their turbine. Somewhere into the creation of the code, the interest in looking at the differences in energy output from a VAWT versus a HAWT was sparked. Searching for a HAWT that is offshore and less than 4 MW was not easy, so it was chosen to go for the Siemens SWT-2.3-113 turbine as explained in 3.1.3.

The battery having a useful capacity of 60 % of its nominal capacity, between 20 and 80 % was something chosen as the importance to lengthen the lifetime of the battery was in focus. In hindsight it could have been between 10 and 90 %. This is explained in 3.2.3, and there it is also explained that the high maximum charge of 25 % with the low useful capacity offsets each other. By using a 80 % useful capacity with a 10 % maximum charge an hour, the combination of SWT/2400 goes from 15.9 % emission to 15.6 %. The wasted wind energy for the 90/10 battery is 99.8 % to that of the 80/25 battery.

Having gotten the one year consumption data from Sandøy, it seemed logical to create the 20 year consumption data in a similar fashion that he had. Although moving away from the build up, and coding it in Python in a way it made sense for me. Since the data was supposed to be six facilities and I did not want to have large spikes, the shift of the production cycle of 1440 hours as explained in 3.1.2, seemed logical. Although in hindsight it could have been beneficial to look at how lining the production cycle up with the periods of higher wind speeds would be.

### Shifting the electricity consumption

To limit the amount of wasted wind energy and limit the emissions even more, there is the possibility to move the production of salmon so that the high energy consumption periods take place when the wind speeds are higher. As seen in the seasonal analysis, the seasonal variation gives higher wind speeds during the winter, autumn and spring months. In this thesis, the consumption for the facilities did not take this into consideration, and all facilities were placed together with a two month "delay" in the production. By shifting the main high energy periods out of the months between May and August when the energy production is at its lowest, as clearly visible in the figures 4.12 and 4.13. It could be possible to optimize the wind production, and decrease emission and wasted wind energy.

## 5.2 Economic

As explained has the Horizontal Axis Wind Turbine (HAWT) a higher efficiency, both in regards to wind speeds, because of the higher hub height, and the power curve. One HAWT turbine with a rated power of 2.3 MW produces almost the same as three Vertical Axis Wind Turbines (VAWT) with a rated power of 1 MW each. Why even look at the VAWT? SeaTwirl expects that the levelized cost of energy (LCOE) of their turbines will be "highly competitive" [68]. With their generator housing close to the sea level, the possibility for their operational cost to be lower than the HAWT's are high. Furthermore, since the vertical turbine can take in wind regardless of direction, there are several vital parts in a horizontal turbine that are not needed in the vertical. This can also help lowering the operational cost of the turbine. SeaTwirl has not provided or published the LCOE of their turbine as of yet, which makes making anything more than rough estimations difficult.

The price of floating offshore wind is expected to fall in the coming years. Equinor has set the LCOE of their wind park "Hywind Tampen" to about 130 €/MWh, while expecting this price to drop to 50 €/MWh by 2030 [69] for new wind parks. There are several sources that agree on this price for the floating offshore wind. The National Renewable Energy Laboratory calculated the LCOE of a 6.1 MW floating offshore turbine to be 132 $/MWh [70]. Projecting 25 years, the price of the turbine stood for 17.2 % of the cost, while operation & maintenance (O&M) stood for 29.5 % of the cost. For comparison, the LCOE for already established energy systems, such as onshore wind and solar photovoltaic cells, are between 30 and 50 $/MWh [71] [72]. The Norwegian Water Resources and Energy Directorate has their own data on prices based on sources from their own analysis [73], Statistics Norway [74], and the Ministry of Finance [75]. On their page, it sets the LCOE of floating offshore wind energy to 117 øre/kWh. Which approximately is 117 €/MWh for reference. The investment cost is set to 84 øre/kWh, and the operational cost is 32 øre/kWh. They predict the price of floating to be at 68 øre/kWh by 2030.

Another facet that is important is that in this system, there is only between one and three turbines. If the company are supposed to handle all the operation and maintenance themselves the price can rise drastically. If however there was a market for "renting" a wind turbine, that also included personnel for operating and maintaining the turbine. It could become more viable. This is something that Odfjell Oceanwind is looking at [76]. The prices shown in the last paragraph were all prices for larger wind parks and it can be expected that the price per MWh would be higher for smaller systems. This is also affected by the high waste of wind energy in the simulated systems. Overproducing energy that is not used will increase the LCOE. As technology develops and the prices for offshore based energy systems gets lower, the viability of the system grows.

Therefore the prices of the combinations can be very different. The price for one S2x turbine, which reduces the emission by about 60 %, depending on the battery size, might be a much cheaper and viable option than the SWT-2.3-113. The cost of reducing the emissions by an extra 20 % will likely yield a much higher installation and operational cost. Especially if there is no possibility to draw advantage of all the wasted wind energy. It might be better to use the 1 S2x scenario, and limit the amount of emission by 60 %, than not doing it at all with the SWT-2.3-113.

## 5.3 Limitations

The reliability of this data is impacted by the uncertainty of the data set NORA-3. Which has been simulated and could have an error-margin of up to 0.5 meters per second [1]. This makes it so the code has not been written with the highest focus on accuracy, rather to look if there is a possibility to limit the emission. Furthermore the power curve is created for the SeaTwirl S2x based on the information given in two papers and a site ([2][62][63]), but is not given by the company themselves. The power curve could therefore have inaccuracies, which should be highlighted. The same goes for the efficiency curve of the generator. It has been created from data based on the figure in the theory chapter, taken from Peralta et. al. [57], but no specific information of a generator was used. It was used to calculate the mean efficiency of the diesel generator. Lastly there could be some errors in the code, the main concern towards the battery module as it has been the most problem getting to work as intended during the thesis, and the feeling that it should be having a larger impact on the result is still there. There is however an overview of the whole system that indicates that the conclusions drawn from the simulations can be trusted.

As the master's is an interdisciplinary programme with focus on using more than just a single discipline, the preference would be to be able to mindfully use as many disciplines as possible. As long as the addition of the discipline makes sense and is feasible. There is however a danger with confusing interdisciplinarity with ”everything” as explained by Gunilla Öberg [26]. As will be looked at in the next section 5.4, the need to choose to focus at some issues and not all. I chose in this thesis to focus on limiting the emission from the facility by utilizing a Python program to calculate and simulate scenarios. This is a direct link to one of the main sustainability issues that is to decrease the emission of greenhouse gases and lower the risk of global warming. As a consequence, the thesis has been mostly a multidisciplinary thesis, with a more interdisciplinary aspect in the introduction and discussion.

When looking at a system like this, other limitations have to be considered. How far out is it feasible to look for emission? The production of batteries? The mining of the lithium needed in the batteries? The problem needs to be limited so that an overview can be made. Brian Wynne looked at this.

## 5.4 Wider aspect of sustainability

Brian Wynne looked at how to limit a problem [77]. What should be addressed when discussing a problem. For instance, in this thesis, where should the line be drawn? Is it needed to look at the emission from producing a wind turbine? The emission from the mining and crafting of the raw materials needed in the production of wind turbines? The expensive and time consuming extraction of lithium from the salt lakes? Furthermore Wynne looked at different uncertainties within policy knowledge that also applies in studies like these. He explains that his four types of uncertainty is risk, uncertainty, ignorance and indeterminacy [77]. Risk is where the odds and system behaviour is well known and chances of different outcomes can be defined by structured analysis. In this thesis, we know that there is a chance that the wind speeds for a season will be lower than the years modeled by the NORA-3WP data set. If the system parameters is known, but not the probabilities, Wynne calls it uncertainties. The third uncertainty is ignorance, not knowing what isn't known. Either because of a lack of knowledge or understanding about a particular phenomenon or system. The last is indeterminacy which is explained as knowledge being molded or changed to fit a reality that does not exist to make it valid.

Wynne's four types of uncertainty can be seen in this thesis. As the thesis has made assumptions and limitations, they can be sources of both quantitative and qualitative uncertainties. Certain choices I have made in the simulations and calculation have been guided by the thesis and data set given to me. This has "framed the problem", which can be connected with indeterminacy. For instance, focusing on the energy loss in charging and discharging could influence the result and lead to a different conclusion. The issue is that there are many ways to define a system and a problem. This leads to different outcomes, based on what is in focus for the thesis. It is all connected with what the writer and researcher consider as important to include and what can be disregarded.

Something to consider is where and how the material and product used in the scenario have been produced. The production of lithium used in the batteries have been discussed for a long time because of the difficulty in procuring it as briefly explained in 2.3.2. According to Mia Romare and Lisbeth Dahllöf of the Swedish Environmental Research Institute, the greenhouse gas burden of the current battery production amounts up to 150-200 kg $CO_2$equivalent/kWh [78]. Although the emission from the excavation and production of lithium carbonate from brine amounts to only 1-2 kg$CO_2$equivalent/kWh [78]. The life cycle analysis for a onshore wind turbine with a rated power of 2 MW by Chaouki Ghenai from the Ocean and Mechanical Engineering Department at Florida Atlantic University, USA calculated that the turbine would achieve a net reduction of C02 emissions by

55.4 % if all material used were recycled after the lifetime of the turbine [79]. If all material was dumped in a landfill after end of life for the turbine, it would cost the same emissions to produce and process the material, as it saved by producing renewable energy [79]. There is a large difference in the findings of these life cycle analysis for both turbines and batteries. Likely this is because of the different limitations the researches uses for what they look at. By indication however, it seems likely that the emissions cut by the batteries and turbines will have a positive gain as long as the material is recycled at the end of the products lifetime. By utilizing the concept of circular economy to reduce the amount of waste, and reuse as much as possible of the metals and materials. Although a perfect circular economy is not possible [80], there are benefits that can be gained from the concept.

The integration of a transdisciplinary approach to a problem such as this, can be beneficial. As written by Wynne [77], not knowing things we don't know can be dangerous. By inviting in, in this case, either fishermen or locals to help create an impact assessment of the facility and the energy system, a more holistic picture of the problems that can occur can be made. This can limit the ignorance part and promote a more sustainable approach to the problems. Öberg explains that this can be dangerous as well, to confuse interdisciplinary with "Everything" [26]. With a holistic approach, no matter how much information you gather, it still won't be possible to predict or fully understand the behaviour of a complex system. When choosing to study something, it is important to choose some but not all issues, and limit the perspectives. For example an impact assessment, while utilizing the transdisciplinary approach, could lead to indecision and delays to the timeline, which could lead to other consequences.

In addition to economic considerations, installing offshore wind turbines can also face political and legal challenges regarding the environmental challenges. The environmental impact of offshore wind turbines still consist of large knowledge gaps. WWF Norway wrote in 2014 a literature overview [81] on the impact of offshore wind power production. They explained that there are both positives and negatives with offshore wind parks. In the overview, the wind parks in question are fixed-foundation turbines that generate more damaging noise during installation, but become the home for artificial reefs that fastens itself on the sub-structure [81]. A problem other than noise is the harm it can do to birds as they can impact with the turbine. The overview states that " *While some studies show that loss of birds due to collisions with offshore wind turbines do not have significant impacts on current populations, the cumulative impacts over time of such loss on bird populations is more uncertain*" [81]. To reduce the risk, wind parks should not be placed in migration corridor for vulnerable bird species. Lastly they look at the possibility to connecting the wind parks with aquaculture. The growth of mussels benefit from the generally higher water quality offshore. The overview highlights the need for in depth and thorough impact assessments [81].

The amount of money and technology needed to create this energy system is considerable. As explained in the intro, the energy use in agriculture and fishing stands for 1.7 % of the global greenhouse gas emissions. The smallest of the sectors within energy use. Would the money be better suited used in other sectors for limiting the emissions? This is not easy to answer, and without a full economic analysis it is hard to compare. There is also the possibility to limit the energy use at the facility to decrease the cost of the renewable system needed to run it. According to Andrea A. Nistad, current RAS (Recirculating Aquaculture System) facilities have the possibility to limit their energy use by 30 % [82]. The composition of energy use in the Ocean Farm 1 project differs from that of a closed facility due to its open design, but still share many similarities.

The ethics of the data can be argued as it is a thesis done primarily on the behalf of the company that provides the data. Contact with the company has however been minimal and the last meeting with representatives was done in

April of 2022. They have not influenced the thesis more than contributing with the consumption data from the facility. This was processed by my predecessor [13], where he created the consumption data used in this thesis by combining two different production cycles from the facility. The thesis would benefit from a more comprehensive and accurate data set of the consumption from the facility.

# Chapter 6

# Conclusion

The thesis focused on how to limit the carbon dioxde emission of six planned offshore salmon farming facilities. This was supposed to be done by utilizing a combination of wind energy, a battery and a diesel generator for backup power. The thesis simulated this in Python and looked at 16 scenarios, with consumption data from SalMar AS and the earlier work of Sandøy [13]. Combined with wind speed data from the NORA-3WP data set [1]. The scenarios combined four different sizes of the battery capacity ranging from 0 kWh to 2400 kWh, as well as four different turbine configurations. One, two and three of the vertical axis SeaTwirl S2x turbine [2], and one horizontal axis Siemens SWT-2.3-113 turbine [3]. Of these scenarios, the combination of the SWT turbine and a battery capacity of 2400 kWh lead to the highest cut in emission, reducing the amount to 15.9 % of the base case. While the scenario of a SWT-2.3-113 turbine combined with a battery capacity of 1200 kWh would suffice in cutting the emission by 80 % and could be the cheapest alternative depending on the comparison of O&M cost for the two different turbines. It is completely possible to decrease the emissions of the facility, but the economic aspect should be under further investigation. For all scenarios in the thesis, there were high values of wasted wind energy. The supply cover ratio (SCR) for the scenarios ranged from 72.6 % to 30.5 %. Meaning how much of the produced wind energy is actually used to cover the demand. For the low emission scenarios this SCR is around 30-35 %. If there is no way to benefit from this wasted wind energy, the LCOE will become very expensive and hard to work around. As LCOE prices for offshore floating wind are expected to drop in the coming years the project to decrease the emission of the facilities become more feasible. The thesis shows that it is possible to limit the emission of the facilities by introducing a system that utilizes a combination of wind, battery and diesel generator. There is however a need to go more in depth to see if it can be economically feasible.

Future studies within this field can benefit from adding another green energy source to the system. Seeing that solar energy is highest during the summer, when the wind is at its lowest, they could benefit well from each other. The combination of the two power sources could be interesting to investigate. Creating an in-depth calculation and comparison of the HAWT vs VAWT, when the data is available and published should provide a clearer image on the advantages of the vertical axis wind turbine. Furthermore, using more accurate code and data will lead to a clearer image of what is possible to accomplish using renewable energies on offshore facilities. The thesis could potentially benefit from a more in-depth code for the battery. This can be done by looking at the data when the facilities go up and create new and more accurate consumption data. Although the accuracy would still be limited by the quality of the wind data. As slightly touched upon is the possibility to move the high energy production periods in the months with the highest average wind speeds a possible solution to decrease the emissions, and warrants further study.

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# Appendix A

# Code

## A.1 Python packages

### A.1.1 NumPy

NumPy [83] is a package in Python that focus on computational calculation. It is useful for quick calculation of arrays and lists. The main functions used were:

- np.sum()
- np.max()
- np.min()
- np.mean()
- np.std()
- np.arange()

The functions are quite self-explanatory. They sum all values in the array together. Find the maximum and minimum value, and can calculate the mean and standard deviation. It was very useful for summing up the values in the power production and consumption. As well as creating plots that included the mean and standard deviation. The np.arange() function was useful in creating a list with numbers between start and stop of the consumption.

### A.1.2 Pandas

Pandas [84] is a package that is created for data analysis. It can read and write .xlsx and .csv files, and add them to DataFrames. These DataFrames can be given a timeline, and using the extension it is then easy to divide the values by month or year. The possibility to have several columns of data side by side and comparing this made the work easier. The package was instrumental in the thesis. As shown below, it also allowed for quickly calculating the mean of the sum of each month of data.

- pd.read_csv('Filename.csv')
- pd.date_range('2024-01-01 00:00', periods=len(consumption), freq='H')
- monthly_average = wind[name].resample('M').mean()

### A.1.3 SciPy

SciPy [85] was used for its interpolation function. The interp1d function takes the x- and y-values and interpolates them using a cubic spline. This was used for both power curves and the efficiency curve of the generator.

### A.1.4 matplotlib.pyplot

Lastly the matplotlib.pyplot library [86] was used to create all Python figures in the thesis. The ability to create bar plots and line plots was useful along with the ability to save them. Matplotlib was also very useful in the early part of the thesis when I had the ability to quickly see how the results changed based on changes in the code.