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**Institutt for energi- og prosessteknikk**

**Bachelorutdanningen på Kalvskinnet**

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# Bachelor Thesis

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| **Group members:**<br>Magnus A. Wendelborg<br>Emil Oppegård | **Supervisor:**<br>Bruno G. Pollet<br>bruno.g.pollet@ntnu.no<br>92 48 93 16 |
| **Field of study:**<br>Renewable Energy Engineer | **Project number:**<br>FEN1807 |
| **Employer:**<br>NVES, Nasjonalt Vindenergisenter | **Contact info for employer:**<br>Thomas Bjørdal<br>thomas@nves.no<br>95 89 32 89 |

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PROJECT THESIS

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# Preface

This thesis is a part of a three-year bachelor's degree in Renewable Energy Engineer at the Department of Energy and Process Engineering at NTNU (*Norges teknisk-naturvitenskaplig universitet*) Trondheim. The contact between the bachelor group and NVES (*Norges Vindenergisenter*) was established on the 12th of September 2017 during the conference for Renewable Energy at NTNU Trondheim. The thesis statement was later defined based on NVES' desire to investigate the opportunity of a hybrid system with wind power on aquaculture plants.

The last three years have been educational with the highlight being this thesis, which gave us the opportunity to apply the acquired knowledge from the past two and a half years. The period working on this thesis have been fun, challenging, and sometimes frustrating. There are several people who have contributed to our work that we would like to thank.

Firstly, we would like to thank our supervisor, Bruno G. Pollet for valuable advice, guidance and feedback. Your quick responses have saved us from numbers of inefficient days and frustrations. You also have helped us meet deadlines.

We would also like to give a special thanks to our external supervisor in NVES, Thomas Bjørdal for guidance and useful information throughout the semester, as well as setting up a meeting with Nekton Havbruk AS, allowing us to get an idea of the scale and operation of an aquaculture plant. Additionally, we would like to thank Pål Preede Revheim for tips related to the wind analysis, and Erlend Hestad for gathering the energy data for us.

Further, a thank is aimed to John Arild Wiggen at NTNU for helping us find a solution to gather the energy data and acquire the necessary equipment, the thesis would not have been the same without it.

Lastly, we would like to thank the people at Nekton Havbruk AS to let us use their plant as an example, provide us with information, and allow us to gather essential energy data.

Trondheim 23.05.2018

Magnus A. Wendelborg

Emil Oppegård

Magnus A. Wendelborg

Emil Oppegård

# Abstract

As most of today’s aquaculture plants located off the power grid are being powered by diesel generator, NVES wants to investigate the opportunity of powering aquaculture plants by using a wind-diesel hybrid system with a battery storage. The main objective is to reduce emissions and contribute to making the aquaculture industry environmental friendly by utilizing the excellent wind conditions along the Norwegian coastline. As a basis, the thesis uses Nekton Havbruk’s plant at Gjelsøya as an example.

Based upon the analysis of the wind and energy data, four different proposed systems were simulated in a MATLAB® environment to determine the impact of the different components on performance and profitability. These simulations indicated that a wind-diesel hybrid system with battery storage was not a viable solution for an aquaculture plant at the same size as the one at Gjelsøya. However, the hybrid systems turned out to be a viable solution to cut the emissions with approximately 50% for larger plants if the systems were designed with a renewable penetration of 50-60%, given that the plant is operating 15 years or longer.

As the aquaculture industry is growing, it’s crucial to reduce its emissions to protect the wild life along the Norwegian coastline as well as contribute to meet Norway’s total share of emissions in reference to the Paris agreement. Should Norway be able to comply with the agreement, an important policy instrument is to remove the subsidies on the marine diesel used by the aquaculture industry to increase the interest in hybrid power solutions.

To further investigate the possibilities of a wind-diesel hybrid-based power solution, a small/full-scale should be initiated.

# Sammendrag

Da de fleste av dagens oppdrettsanlegg som er plassert utenfor strømnettets rekkevidde drives av dieselgeneratorer, ønsker NVES å undersøke muligheten til å drive oppdrettsanlegg ved hjelp av et vind-diesel hybridsystem med batterilagring. Hovedmålet er å redusere utslippene og bidra til å gjøre oppdrettsindustrien mer miljøvennlig ved å utnytte de gode vindforholdene langs norskekysten. Som et grunnlag bruker rapporten Nekton Havbruks anlegg på Gjelsøya som et eksempel.

Basert på analysen av vind- og energidata, ble fire forskjellige foreslåtte systemer simulert i MATLAB® for å bestemme hvordan de ulike komponentene påvirket ytelsen og lønnsomheten i systemet. Disse simuleringene indikerte at et vind-diesel hybridsystem med batterilagring ikke var en fornuftig løsning for et oppdrettsanlegg på samme størrelse som det på Gjelsøya. Derimot viste hybridsystemene seg å kunne være en fornuftig løsning for å redusere utslippene med ca. 50% ved større anlegg dersom systemene ble dimensjonert med en fornybarandel på 50-60%, gitt at oppdrettsanlegget driftes i 15 år eller lenger.

Etter hvert som oppdrettsnæringen vokser, er det viktig å redusere næringens utslipp for å beskytte dyrelivet langs kystlinjen, samt bidra til å møte Norges totale utslippsandel i henhold til Paris-avtalen. Dersom Norge skal overholde avtalen, er et viktig politisk virkemiddel å kutte subsidiene på marine diesel som brukes av oppdrettsnæring for å øke interessen for hybridløsninger.

For å videre undersøke mulighetene ved en vind-diesel hybrid-basert kraftløsning, bør et små/full-skala pilotprosjekt iverksettes.

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# Nomenclature

| | |
|---|---|
| **Fluke 435-II** | *Power analyzer* |
| **MATLAB®** | *Computer program* |
| **Renewable penetration** | *The share of renewable energy in a system* |
| **Power curve** | *A curve showing how much power the turbine produces at different velocities* |
| **Cut-in-speed** | *Wind velocity when the turbine starts producing* |
| **Rated wind speed** | *The velocity of wind when the turbine produces at maximum power* |
| **Cut-out-wind speed** | *The wind velocity when the turbine is shutting down* |
| **Pitch** | *Angle of the blades* |
| **Pellets** | *Fish food* |
| **Inverter** | *Converts DC power to AC power and vice versa* |
| **Rectifier** | *Converts AC power to DC power or DC to AC* |
| **Main load** | *All electronic devices connected to the grid* |
| **Dump load** | *An electronic device to dump excess power* |
| **Harmonic frequency** | *Frequencies above operating frequency* |
| **Particulate emission** | *Microscopic solids or liquids* |
| **Oxidizer** | *A chemical which a fuel requires to burn* |
| **Flux** | *A quantity which passes through a surface* |

# Abbreviations

| | |
|---|---|
| **NVES** | *Norges Vindenergisenter* |
| **NTNU** | *Norges teknisk-naturvitenskaplige universitet* |
| **HAWT** | *Horizontal axis wind turbine* |
| **VAWT** | *Vertical axis wind turbine* |
| **UN** | *United Nations* |
| **Li-ion** | *Lithium-ion* |
| **NiCd** | *Nickel-cadmium* |
| **NiMH** | *Nickel metal-hydride* |
| **PM** | *Particulate matter* |
| $CO_2$ | *Carbon dioxide* |
| $N_2$ | *Nitrogen* |
| $O_2$ | *Oxygen* |
| $SO_x$ | *Sulfur oxide* |
| $C_{12}H_{23}$ | *Average formula of diesel* |
| $H_2O$ | *Water* |
| **CO** | *Carbon monoxide* |
| $NO_x$ | *Nitrogen oxide* |
| **Mgo** | *Marine gas oil* |
| **Mdo** | *Marine diesel oil* |
| **LCOE** | *Levelized cost of energy* |
| **E.D** | *Energy demand* |
| **O&M** | *Operating and maintenance cost* |
| **WES** | *Wind energy solutions* |
| **I** | *Investment cost* |
| **CF** | *Cash flow* |
| **r** | *Discount rate* |
| **PV** | *Photovoltaic* |

# List of Symbols

| **Symbol** | **Unit** | **Description** |
|---|---|---|
| $E_k$ | J | Kinetic Energy |
| m | kg | Mass |
| V | m/s | Velocity |
| A | $m^2$ | Cross-section |
| P | W | Power |
| S | VA | Apparent power |
| U | V | Voltage |
| I | A | Current |
| cosφ | | Power-factor |
| x | | An unknown variable |
| e | | Euler’s number |
| k | | Shape parameter |
| b | | Scale parameter |
| μ | | Expectation |
| σ | | Standard deviation |
| π | | Mathematical number, pi |
| $CI_{95}$ | | 95% confidences interval |
| n | | A given number |

# 1. Introduction

## 1.1 Background

As the aquaculture industry has grown significantly along with a focus on the global environment over the last decade, it is important to find new renewable energy solutions to cut the $CO_2$ – emissions [1]. In collaboration with NTNU, NVES wants to investigate the possibility of using a wind-diesel hybrid system with battery storage to power aquaculture plants. A group of two students from NTNU will perform the required research as part of their bachelor's degree in renewable energy.

The aquaculture plants have high energy consumption due to feeding, lights, control devices and service facilities for workers. Most of the today's plants are powered by diesel generators, which results in high $CO_2$ and particulate emissions. With the excepted growth in the aquaculture industry and modern plants located further off the Norwegian coastline, it is expected that the emissions and cost will further increase [1, 2]. For facilities located near the coast, the most reasonable option would be electrification with low voltage line (1 kV). However, facilities located further off the coast need high voltage installations (22 kV) due to voltage losses. High voltage installations are not only complicated and costly, but also require concession, access control and expertise. An on-site wind-diesel system with battery storage could potentially reduce the $CO_2$-emissions and costs significantly for plants isolated from the electricity grid as the wind conditions along the Norwegian coastal line is ideal for wind power.

The purpose of this project is to design a system that can help establish collaboration with research and development work and relevant industry, and in the future, carry out a small/full-scale prototype. This project used a specific plant located off the coast of Hitra (Norway) as basis but may prove valuable for other plants. If the project is successful, a wind-diesel hybrid system could potentially become the main power source for aquaculture plants in the future.

## 1.2 Thesis Statement

The objective of the thesis is to examine whether a wind-diesel hybrid system with a battery package is a reasonable solution to reduce the $CO_2$ and particulate emissions. To make the system interesting for the market, it must come at a reasonable price.

Energy from renewable sources is free of charge but can’t be produced at all time like a diesel generator due to weather conditions. To sustain the aquaculture plant with enough power during periods without energy production, the plant must draw the power required from an on-off power source. A battery package can function as an on-off power source, as it enables the plant to store renewable energy during periods when the energy production is higher than the consumption. However, a diesel generator is required as a back-up system if the periods without energy production last longer than the energy stored in the battery.

The idea is to combine wind power with a battery storage system to reduce $CO_2$ and particulate emissions and cost by reducing the usage of diesel generators. The problem of the thesis can be summarized as follows:

***“Is a wind-diesel hybrid system with battery storage a viable solution to cut $CO_2$ and particulate emissions at an aquaculture plant?”***

## 1.3 Methodology

The process of validating the most reasonable and functioning system will consists of various aspects. To begin with, the thesis presents general theory about different technologies used in this thesis; wind energy, batteries and diesel generators. This provides useful information on how the different technologies work and how the cuts in $CO_2$ and particulate emissions are determined.

To obtain a detailed picture of the energy consumption at the plant, energy data will be gathered at the plant using a Fluke 435-II. Along with analysis of the wind data provided by NVES, this will be used to purpose four different wind-diesel hybrid systems with battery storage. Furthermore, simulations carried out in MATLAB® for each system will yield renewable penetration, cost efficiency and cuts in $CO_2$ and particulate emissions. The performance and profitability of the systems will also be simulated for two, three and four times the energy demand at Gjelsøya in an attempt to replicate a larger aquaculture plant.

By comparing the data with today’s costs and emissions, the thesis assesses whether a wind-diesel hybrid system with battery storage is a viable solution to reduce $CO_2$ and particulate emissions.

### 1.4 The Aquaculture Industry in Norway

The concept of fish farming is an old idea which dates back 4000 – 5000 years. Back then, the Chinese bred cyprinid in dams with artificial fertilization, a method also used by the European priests in the middle age[3]. Today, dams have been replaced with large plants located at sea as shown in Figure 1.1. As for the Norwegian aquaculture industry, the cyprinid has been replaced with salmon and several other species.

The Norwegian aquaculture industry has experienced a significant growth in the last two decades. With the production for 2016 being worth 64 billion NOKs, the aquaculture industry is one of Norway’s most important sources of income. The industry now plays a key role in keeping job opportunities along the coast of Norway as the number of employees has increased from 3 353 in 2006 to 7 237 in 2016. In coherence with the declining activity in the Norwegian oil industry, the salmon has been announced by many as the new oil. [4]

With the marine resources Norway has, the aquaculture industry can potentially replace the oil industry in the future. However, as the industries have expanded rapidly in the last two decades, a lack of focus of the environmental consequences have resulted in the industry having to deal with major problems as fish lice or escaping fish. Solutions to these problems are being developed[5].

*Figure 1.1: An aquaculture plant at the coast of Norway[6].*

### 1.5 Nekton Havbruk AS

Nekton Havbruk AS was founded in 2001 and is an aquaculture company located at Smøla in Møre og Romsdal. Nekton Havbruk have concession for production of salmon as well as a view licence for food fish. Nekton Havbruk AS currently has 11 employees with Rune Iversen being the CEO of the company. The company is owned by Smølen handelkompani AS. [7]

The plant at Hitra is the plant this thesis uses as basis for the research. The plant consists of six net cages, where only three of them are currently in use. A barge contains all necessary equipment for operating and storing. Figure 1.2 is a picture taken at the plant with the barge.

*Figure 1.2: Picture taken from at the Nekton Havbruk's plant at Gjelsøya (Hitra) with the barge at back.*

### 1.5.1 Today’s System

With a feeding consumption of about two tons pellets a day, Nekton Havbruk’s facility at Gjelsøya is a small plant compared to the majority in the aquaculture industry. Along with six net cages, the plant consists of a barge which houses the feeding system, two diesel generators and a control room. The diesel generators (165 kVA and 88 kVA), which powers the entire plant, are placed in an engine room below deck. An integrated control system in the generators switches between the 88 kVA and 165 kVA aggregates depending on the required power. The feeding system at the plant is delivered by Akvasmart (Figure 1.3), allowing the crew to control the feeding, and monitor the temperature as well as the oxygen level of the water along with sea currents. Described in the simplest manner; the feeding system works by blowing the pellets from the barge to the net cages through pipelines. The feed blower compresses the air, raising the pressure enough to let the air carry the pellets through the pipelines. At Nekton Havbruk’s plant, two feed blowers (at 22 kW each) and feeding lines are sufficient to distribute enough food. Figure 1.4 illustrates today’s system at the plant, with the load being the feeding system and any other load requiring power at the plant. As of now, this will be referred to as the main load.

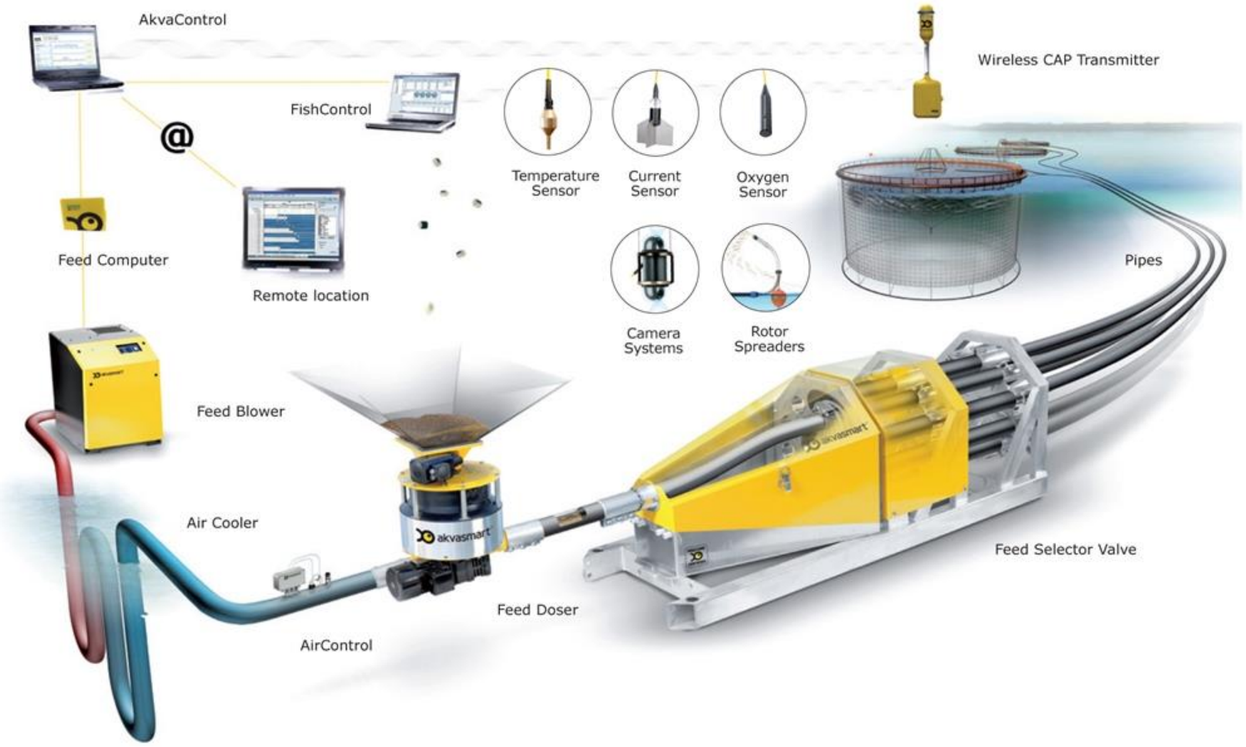

*Figure 1.3: Feeding system[8].*

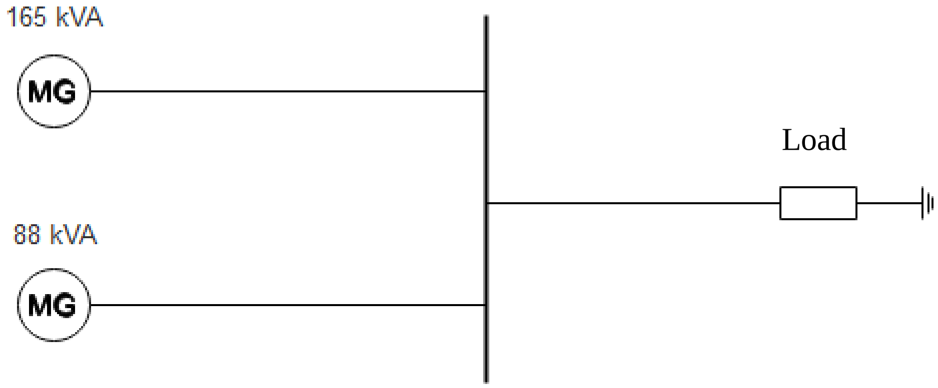

*Figure 1.4: Schematic drawing of today's system.*

### 1.6 NVES

Nasjonalt Vindenergisenter (*NVES*) is one of three centres of expertise in renewable energy owned by the Møre og Romsdal county, localized in the middle of the largest wind farm in Norway at Smøla (Norway). NVES develops and supports innovative and creative solutions for renewable energy for both industry and private individual. Their main focus is to utilize the local energy resources for every project. NVES also holds educational events for schools. Currently NVES has three employees, Thomas Bjørdal (manager), Pål Preede Revheim (project manager) and Erlend Hestad (Research associate).

# 2. Wind Energy

## 2.1 Basic Wind Energy Theory

As light from the sun heats up the Earth's surface the temperature of the air near the ground increases, thus reducing the density of the air. Due to being less dense than the air above, the air at the ground will rise leaving an area with low pressure. To equalize the pressure differences, cold air from above descends to fill the space created by the hot air. This creates a flow of air as illustrated in Figure 2.1, or better known as wind. This process happens continuously all around the planet, creating calm gusts, devastating storms and even shaping the environment.

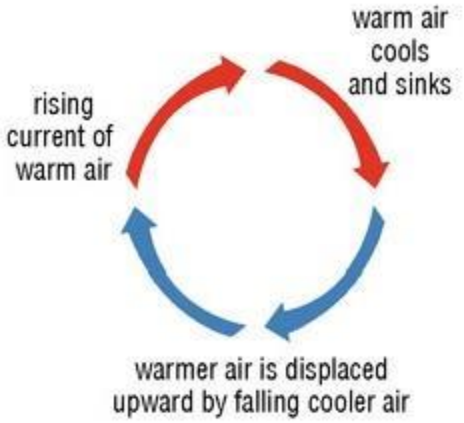

*Figure 2.1: Flow of air caused by temperature differences[9].*

The air flow is in fact a motion of mass, thus having a certain amount of kinetic energy. The kinetic energy of an object of mass m traveling at the speed v, is given by:

$$E_k = \frac{1}{2} m V^2 \qquad \mathbf{(2.1.)}$$

Because air is not a solid object like a rock or a ball, it is more convenient to consider a flux of air through a given cross-section, A, as shown in Figure 2.2. The mass m in Eq. 2.1 can then be replaced by:

$$m = \rho A V \qquad \mathbf{(2.2)}$$

ρ being the density of the air, A the area of the cross-section and V being the speed at which the air is moving. Substituting Eq. 2.2 for the mass m in Eq. 2.1 gives:

$$P = \frac{1}{2}\rho A V^3 \tag{2.3}$$

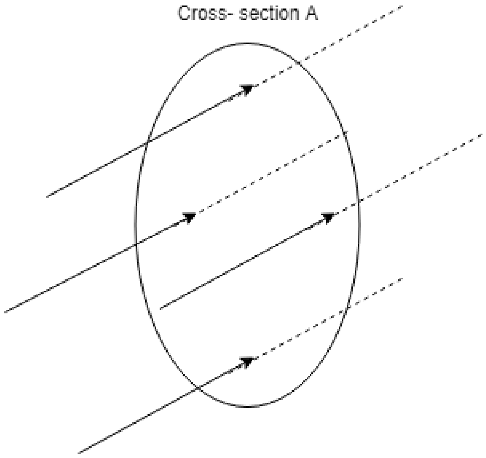

*Figure 2.2: Flow of air through cross-section A.*

By inserting the flux of air (mass per unit time), the equation now yields the power of the wind. The area of the cross-section and the velocity of the wind is the major factors affecting the power available in the wind. The density, as mentioned earlier, changes with temperature (and elevation). However, this variation is rather small (especially at a fixed elevation), and in most cases ρ is considered to be 1.225 kg/m$^3$ [10].

## 2.2 Wind Turbines

The harness of wind energy is not a new concept. Figure 2.3 shows a typical wind mill which was used in the past to grind grain and pump water. The remnants of the wind mills which dates all the way back to 644 A.D were found in Afghanistan in the region of Seistan [11]. Since then, wind turbines have been developed into sophisticated machines in different shapes and sizes. However, they all follow the same principal of converting the kinetic energy from the wind into mechanical energy. By creating different pressure on each side of the blade, the air forces itself to the side with the lowest pressure, thus creating a lift. The blades, which are attached to a shaft, will rotate as the wind blows by. This converts the kinetic energy from the wind into mechanical energy. A generator at the end of the shaft then converts the mechanical energy into electricity.

*Figure 2.3: Old wind mill used to grind grain[12].*

### 2.2.1 $C_p$-factor, Betz limit and Power curve

For wind turbines it is important to distinguish between the available power in the wind, $P_{\text{wind}}$, and the power produced by the turbine. The reason is that the blades only can extract some of the kinetic energy from the wind; the rest is carried away with the air leaving the back of the blades. The efficiency of a wind turbine is known as the power coefficient ($C_p$) and is defined as the power extracted by the turbine divided by the available power in the wind. Because of the losses mentioned above, a wind turbine can never extract 100% of the available power in the wind. In fact, the maximum power coefficient for an ideal wind turbine is 59.3%, also known as Betz limit, and was established in 1962 by the German physicist Albert Betz [10]. In addition, the $C_p$-factor is not fixed through the wind spectrum, making the performance of a wind turbine to alter with the wind velocity. Figure 2.4 shows a typical power curve of a pitched wind turbine. The power curve shows the power a turbine delivers at any given wind velocity, along with rated power, rated windspeed, cut-in speed and cut-out speed. The rated power is the maximum power a turbine can deliver and is reached at rated wind speed. For wind velocities above rated windspeed the blades are pitched (rotated around their own axis) to prevent any damage, thus keeps the power delivered at rated power. Cut-in speed is the windspeed (usually between 3 – 5 m/s) at which the turbine starts to deliver power, while cut-out speed (usually between 20 – 25 m/s) is the windspeed at which the turbine is brought to a stop due to safety [10, 11].

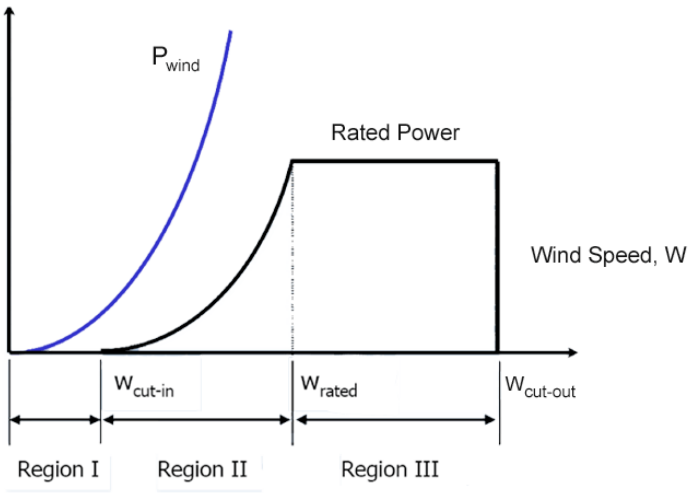

*Figure 2.4: Typical power curve for a pitched wind turbine[13].*

### 2.2.2 Horizontal axis wind turbine (HAWT)

The horizontal axis wind turbines (HAWT) are the most common type of wind turbine, mainly because of the commercial electricity producing which almost exclusively uses HAWT due to its high efficiency and power output [10]. The capacity of HAWT's ranges from several watts to 10 MW for offshore wind turbines and its further increasing as GE Renewable Energy is currently developing 12 MW turbines[14]. A HAWT have its blades rotating around a horizontal axis, making the rotation parallel to ground below. Figure 2.5 shows a schematic drawing of a HAWT with rotor and nacelle on top of the tower. The nacelle houses all the electronics and mechanical devices as the generator, gearbox and yaw system. The biggest advantage of a HAWT is the rotors blades which can be pitched and designed aerodynamically to maximize lift. The pitching system rotates the blades around their own axis, making them extract less or more power from the wind depending on the conditions.

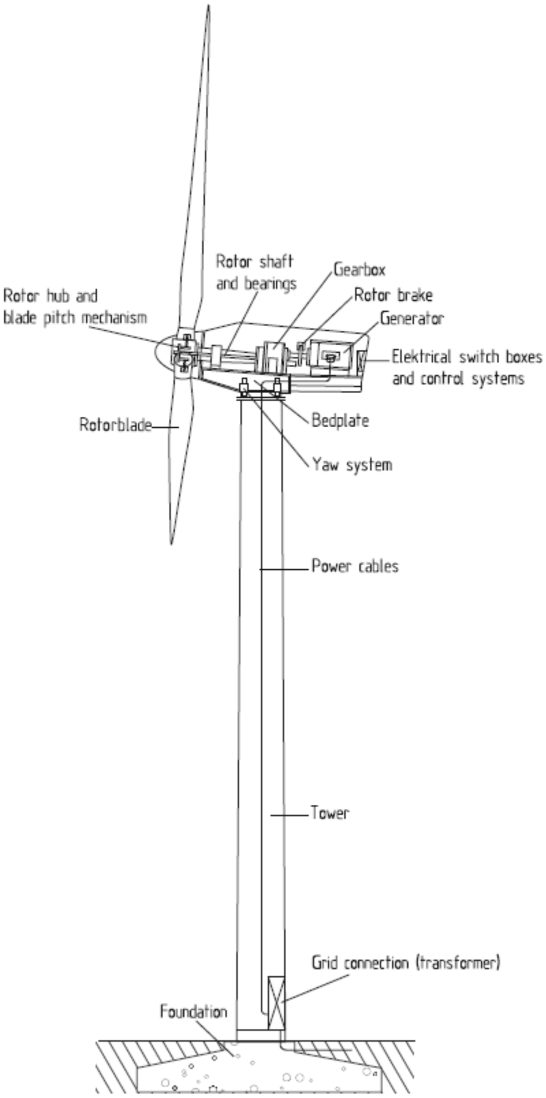

*Figure 2.5: Schematic's of a HAWT[11].*

### 2.2.3 Vertical axis wind turbine (VAWT)

Vertical axis wind turbines (VAWT) comes in many shapes and sizes and have a wide range of applications. A good example of a VAWT is an anemometer which is used to measure wind velocities. VAWT are mainly categorized in three different types; Darrius-rotor (shown in Figure 2.6), Savonius-rotor and H-rotor. What is common for all of them is the rotation around a vertical axis. The advantages of a VAWT is that it can extract power from any wind directions, along with a vertical shaft which allows the housing to be placed at ground level, making maintenance operation easy to execute. However, VAWT have some disadvantages of not having the possibility of pitching, in need of start-up help and higher price per kW compared to a HAWT. [10, 11]

*Figure 2.6: A Darrieus turbine[15].*

# 3. Battery

Used in everyday life, batteries are at the very centre of portable electronics. Laptops, mobile phones, flash lights and other portable gadgets all uses batteries as a power source. In the recent years, batteries have made a major impact in transportation with the possibility to power a vehicle based purely on electrical energy. As the technology is continuously developing, batteries' range of application widens.

A battery is a galvanic cell converting chemical energy into electrical energy by exploiting a red-ox reaction. Figure 3.1 shows a galvanic cell with an anode and cathode, each placed in a corresponding electrolyte solution separated by a membrane. An oxidization occurs at the anode, while there is a reduction at the cathode. In the process of oxidation and reduction, electrons flow from the anode to the cathode in the outer circuit due to the polarity differences caused by the chemical reactions. To maintain an electrical connection, a membrane keeps the electrolyte separated, while at the same time allowing anions to flow through. Without separating the anode and the cathode, the electrons will never flow in the outer circuit.[16]

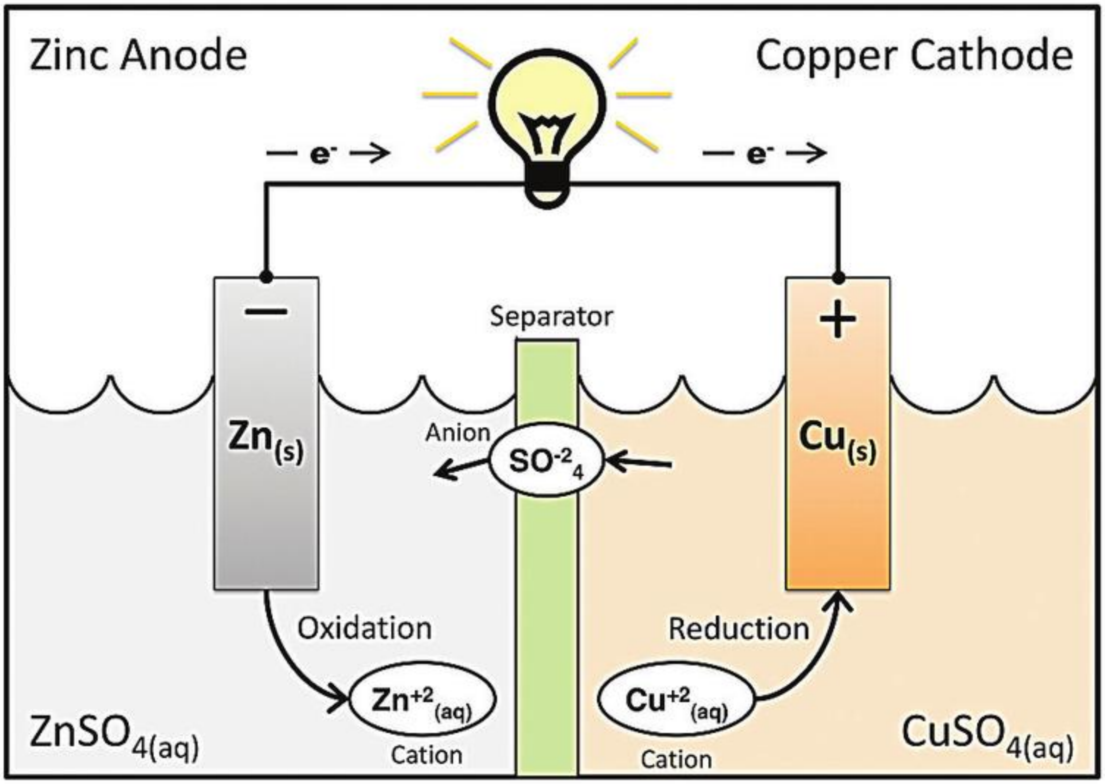

*Figure 3.1: Illustration of a galvanic cell[17].*

The amount of energy a battery can store is dependent on how much electrode material there is, in the case of Figure 3.1, zinc and cobber. As soon as the materials are consumed, the battery can no longer deliver electricity. To increase the capacity of a battery package, multiple batteries are connected in series or/and parallel. When connected in series, the voltages output is the equal to the sum of each cell. As for parallel, the voltage output is unchanged, however, the current is greater due to lower resistance. Batteries used in cars, laptops along with other electronic devices are connected in both parallel and series to achieve the right power output. Figure 3.2 is showing multiple cells connected in one module.[18]

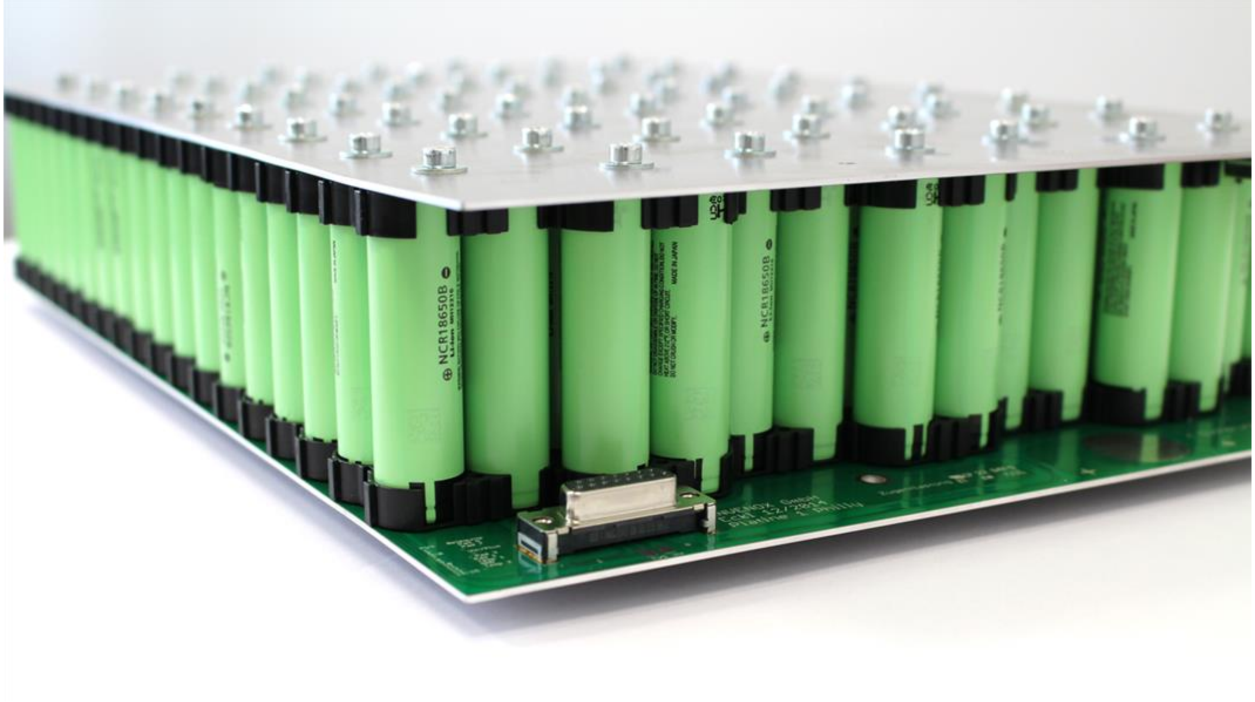

*Figure 3.2: An example of batteries connected in a battery module[19].*

There are many different types of batteries, with different chemical compounds. However, batteries are categorized into two different types; primary and secondary batteries. Primary batteries are essentially batteries sold in grocery stores, powering flash lights and other electrical devices. Despite varying in size, capacity and voltage level, all primary batteries have one thing in common; they cannot be recharged due to the irreversibility of the chemical reaction. For secondary batteries, the chemical reaction is reversible, enabling them to be recharged to their original state. The ability to recharge makes secondary batteries suitable for transportation, portable electronics, and hybrid systems.[16]

## 3.1 Secondary Batteries

Secondary batteries play an important role in every-day life. By powering phones, laptops, vehicles and other devices, today’s society would not be the same without them. There are several different types of secondary batteries, but the most common is lead acid, NiCd, NiMH and Li-ion batteries. Besides having the ability to be recharged, the different types have some unique characteristics.

The lead acid battery is the oldest rechargeable battery invented by Gaston Planté in 1859[20]. Due to its ability to supply high surge currents, the lead acid battery is often used in cars to provide currents high enough to start motor engines. The battery is made up of lead and sulfuric acid, making it the cheapest rechargeable battery as the materials are easily accessible. A long with being toxic, its short life span is of one the disadvantages of the lead acid battery[21]. In addition, compared to other rechargeable batteries, the energy density of the lead acid battery is low[16].

Nickel-cadmium were the first rechargeable battery to be used in small electronic devices and is still used in the airline industry. It is the only rechargeable battery that can be charged ultra-fast without taking damage due to stress. And in terms of cost per cycle, it is the cheapest of all the secondary batteries. However, like the NiMH battery, it suffers from the memory effect, reducing its capacity when charged before being fully discharged. The memory effect is caused by chemical byproducts, causing the chemical reaction to no longer be completely reversible. To prolong the life span of NiCd and NiMH batteries, a full discharge is needed regularly. Other disadvantages of the NiCd and NiMH batteries is the high self-discharge rate and the low efficiency of approximately 65% compared to 97-99% for Li-ion batteries[21]. Because of the toxicity of cadmium, the NiCd batteries are being replaced with NiMH and Li-ion batteries[21].

Despite the different types of Li-ion batteries depending on the material used as electrode, they share many of the same characteristics. Due to the high standard potential of above 3 V (three times that of a NiCd or NiMH battery), and being the lightest metal, lithium-ion batteries have the highest energy density of all secondary batteries[16]. Unlike the NiCd and NiMH batteries, lithium-ions batteries are not affected by the memory effect, allowing them to be recharged before being completely discharged without taking permanent damage. The depth of discharge for Li-ion batteries varies between 80-100%, which is significantly higher than what of a lead acid battery which is around 50%[20, 21]. In addition, the Li-ion battery is superior regarding life time expectancy of 5 – 10 years (depending on the amount of cycles) and maintenance (maintenance free). Unlike the NiCd and NiMH battery, which suffer from a self-discharge rate of 20-30%, the Li-ion battery losses less than 5% of the energy stored in a month[21]. However, one of the major drawbacks is the cost of approximately 209 $ per kWh, making the Li-ion battery the most expensive rechargeable battery[24]. As well as being expensive, lithium reacts heavily with air and water resulting in need of a closed container. Another disadvantage is the low tolerance for overcharging, which often leads the batteries limited to reach 95% of full storage capacity in battery systems for safety reasons[25].

# 4. Fuel Generator

Fuel generators are commonly used to power units located off the power grid. By combining a conventional combustion engine and a generator, the fuel generator is a reliable power source as it can produce power whenever needed. Due to the reliability, fuel generators are often used as emergency power sources at hospitals or other units where continuously power delivery is crucial. The size of a fuel generator ranges from a few watts to several megawatts.

## 4.1 Combustion engine

Combustion engines generates energy by a controlled explosion from a fuel with an oxidizer. The ignition of the fuel produces gases and intense heat. As the gases expands rapidly it forces a piston to move, converting the thermodynamic energy into mechanical energy. Figure 4.1 shows the principal structure of a combustion engine with the pistons mounted to a shaft. By adding more pistons, the force produced by the engine increases as well as it balances the force exerted on the shaft. Fuels commonly used in combustion engines are fossil fuels, however, the engines can be made to run on biofuels or even hydrogen. An advantage of the diesel engines is the ability to ignite the fuel without spark plugs. In a diesel engine, the air is first heated up by compressing the air before injecting the fuel. As the fuel is injected, the heat of the compressed air ignites the fuel, making the diesel engine more efficient. [26]

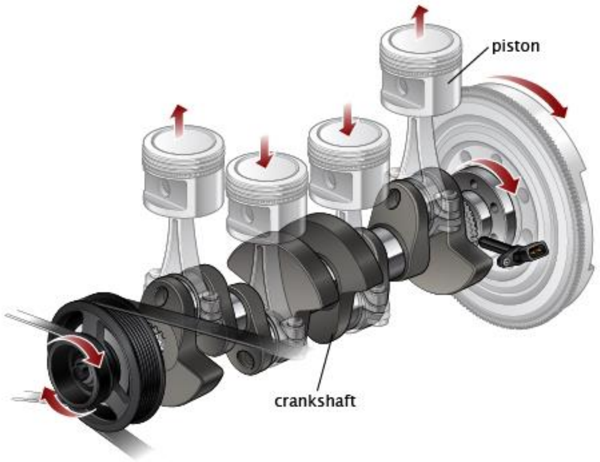

*Figure 4.1: An illustration of how the pistons creates the rotation of the shaft[27].*

As the combustion engines runs on fossil fuels, the engines emit $CO_2$ and other environmental gases. E.q 4.1 is a simplified reaction of diesel with enough air to provide a complete combustion.

$$C_{12}H_{23} + 17{,}75O_2 + 66{,}74N_2 \rightarrow 12CO_2 + 11{,}5H_2O + 66{,}74N_2 \qquad \textbf{(4.1)}$$

The equation shows the biproduct of the combustion of diesel. Fuels are in reality a mixture of different liquids with more complex chemical compound than what is shown in E.q 4.1. Hence, the emissions from a combustion engine does not only consists of $CO_2$, but also other environmental gases as; CO, $NO_x$, sulphur and other particulate matters[28]. The amount of environmental gases is dependent on the purity of the fuel. Refining the fuel removes other substances, increasing the purity of the fuel, making its chemical compound less complex and more like the one in E.q 4.1. However, as the refining process raises the price, fuels with high purity becomes too costly for everyday use. A common fuel for marine use is MdO (Marine diesel oil) and MgO (Marine gas oil), which is a heavier fuel than conventional diesel used by automobiles.

To determine the emissions, it is common to use emissions factors. An emissions factor is a value that relates the emissions of a specific gas to the quantity of the consumed fuel. The factors are usually expressed in g per kg fuel or kg per ton fuel and varies with type of fuel. However, for $CO_2$ emissions it is common to use a factor of 3.2 kg per kg fuel regardless of type of fuel as the $CO_2$ atom weighs 3.3 times more than the C atom and assuming a small portion of the C atoms forms CO [Håvard Karoliussen, 2018, personal communication, 3th of May].

## 4.2 Generator

A generator uses mechanical energy to produce electrical energy; the opposite is an electric motor. The generator is made up of two components, a stator and a rotor. The stator consists of cobber windings, while the rotor is made up of a magnetic material. According to Faraday’s law of induction, a voltage is induced in the cobber windings of the stator due to the change in magnetic flux as the rotor rotates[29]. The voltages induced varies with the number of windings, cross section, and the field strength of the magnet. As the change in magnetic flux varies during a rotation, the induced voltage fluctuates within a cycle as shown in Figure 4.2.

As the generator produces power, the total power is measured in apparent power (S), VA (*Volt Ampere*). The apparent power generated by the generator is a combination of active (P) and reactive power (Q). The reactive power is the portion of the produced power used to maintain magnetic and electric fields in the circuit and cannot be converted to work. The active power, or watt, is the power consumed by electrical components. The relation between the active power and apparent power is given by E.q 4.2 where cosφ is the power factor. [30]

$$P = S\cos\varphi \tag{4.2}$$

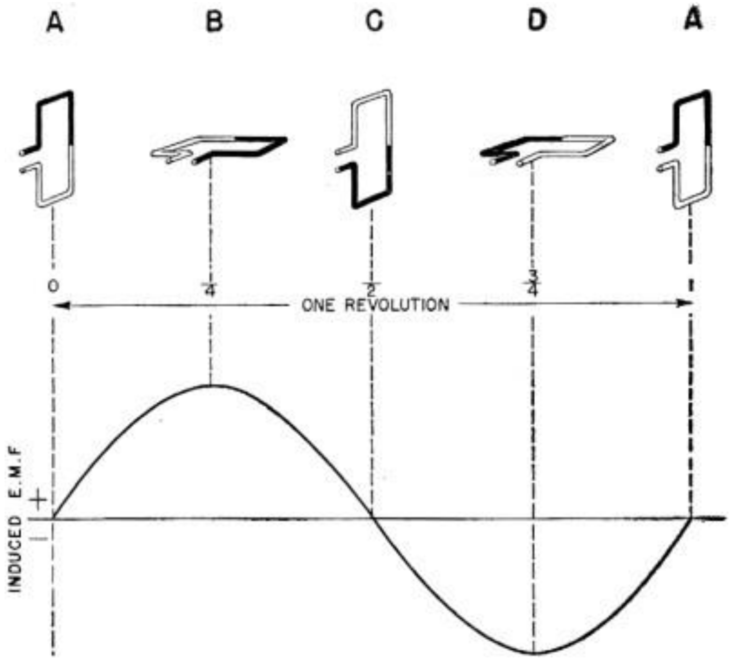

*Figure 4.2: Induced voltage due to flux cutting.[31]*

# 5. Analysis

This chapter contains analysis for wind and energy consumption data. The data gathered from the analysis will help determine the combination of the future system which will be presented in the next chapter.

When analyzing data, especially data form an unpredictable element like wind, one can only do assumptions of how the wind will behave in the future. However, by applying statistical mathematics to the data, it gives a picture of how the wind have behaved in the past, making a prediction of the future more accurate. The most common probability function in statistical mathematics is the normal distribution. The normal probability function fits distribution where the probability for an event to occur is symmetrical around a mean value. An example of this kind of distribution is the height of a population or a hundred tosses of a coin. The normal probability function is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad \mathbf{(5.1)}$$

Here, μ and σ is the expectation (mean value) and standard derivation. In general, results are presented in confidence interval, which are an interval which a random event occurs in in a certain percentage of the time. In most cases the 95% confidence interval is used, and is given by:

$$CI_{95} = \mu \pm 2 \cdot \sigma \qquad \mathbf{(5.2)}$$

Another well used probability function in wind analysis is the Weibull function. The Weibull function is known for modeling lifetime expectancy, but also fits well to model wind conditions[11, 32]. The probability density function of a Weibull distribution is given by:

$$f(x) = \frac{k}{b}\left(\frac{x}{b}\right)^{b-1} e^{-\left(\frac{x}{k}\right)^{b}} \qquad \mathbf{(5.3)}$$

Here, k is the shape parameter and b is the scale parameter. MATLAB® has built-in function for both normal and Weibull distribution, making it easy to fit a distribution to any given data set.

## 5.1 Wind data analysis

The wind data provided by NVES was measured at Veiholmen (Smøla) which is located about 15 km from Nekton Havbruk's plant at Gjelsøya, making it ideal for wind analysis for this specific plant. The data contains measurements from 1994 to 2014. However, the data used in this analysis are from the period between January 2005 and December 2014 due to hour-by-hour measures. To ensure validity, repeated measures in sequence and wind velocities at zero meters per second is excluded as these measures are considered to be failure of the measure devices.

Figure 5.1 shows the plot for wind velocities in 2011 hour by hour with a lot of fluctuations throughout the year. This is expected as the climate of the Norwegian coastline is characterized with stronger winds during the winter months [33]. A similar plot for the years 2005 to 2014 is found in Figure A.1 – A.10 in appendix A.

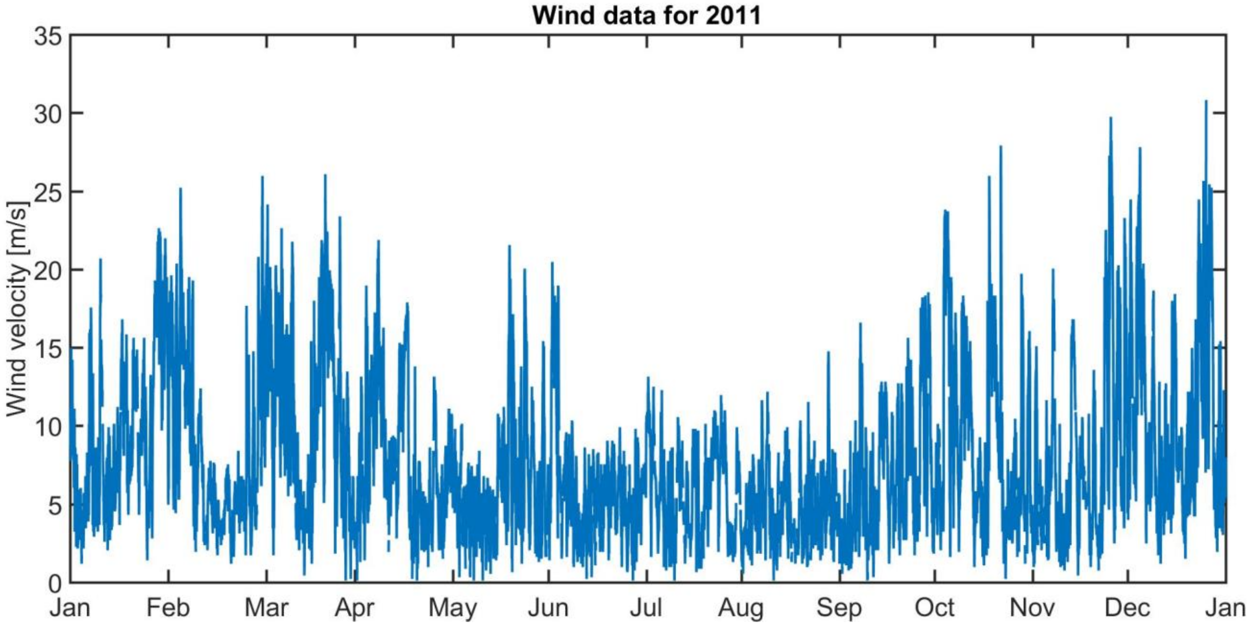

*Figure 5.1: Wind data for 2011.*

As part of the process of determining if the wind conditions are sufficient for wind power, the average wind velocity over a year is evaluated. An area with average wind velocity of 7.5 meters per second or above is considered to have good wind conditions for wind power [34]. By anticipating the average wind velocity is normal distributed, Table 5.1 lists the average wind velocities along with the 95% confidence interval for each month. Figure 5.2 is the normal distribution of average wind velocities for every year from 2005 to 2014. A mean value of 7.48 meters per second indicates that the area around Veiholmen is well suited for wind power, and the average wind velocity can be expected to be within 6.68 – 8.28 meters per second.

*Table 5.1: Average wind velocities for each month.*

| **Month** | **Average Wind Velocity [m/s]** | **95% confidence interval for average wind velocity [m/s]** |
|---|---|---|
| January | 8.71 | 8.60 – 8.81 |
| February | 8.30 | 8.20 – 8.41 |
| March | 8.57 | 8.47 – 8.68 |
| April | 6.98 | 6.90 – 7.08 |
| May | 6.40 | 6.32 – 6.47 |
| June | 6.37 | 6.30 – 6.45 |
| July | 6.02 | 5.96 – 6.10 |
| August | 5.93 | 5.86 – 6.00 |
| September | 7.76 | 7.66 – 7.87 |
| October | 7.85 | 7.76 – 7.94 |
| November | 8.21 | 8.11 – 8.31 |
| December | 9.19 | 9.08 – 9.29 |

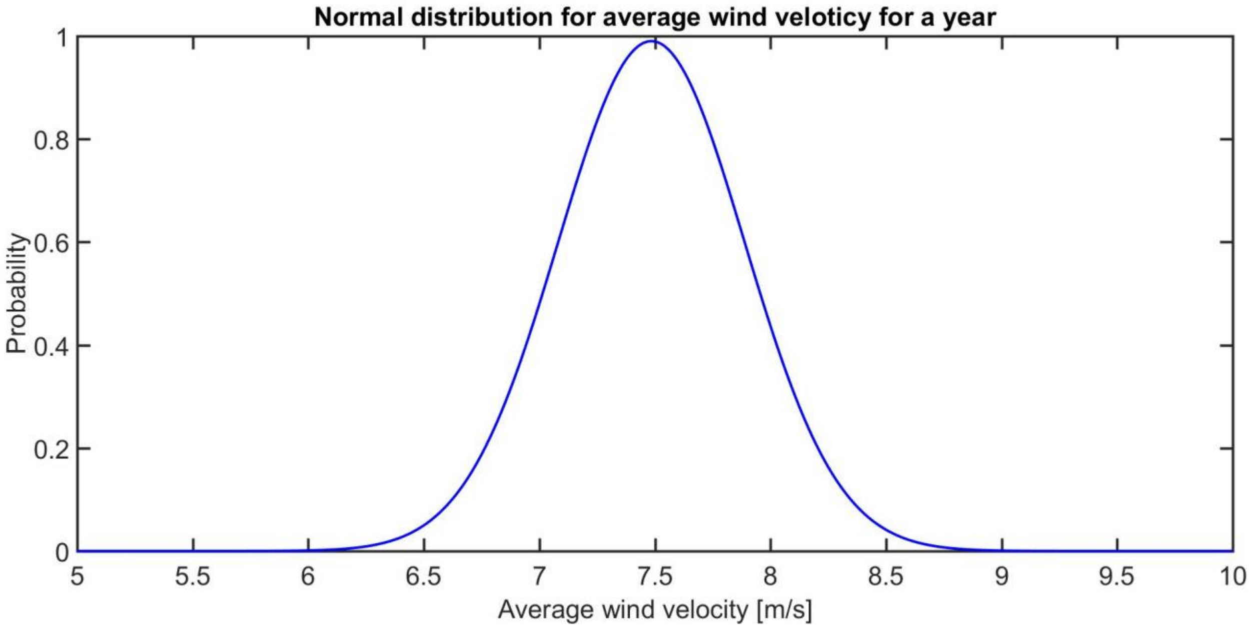

*Figure 5.2: The normal distribution for average wind velocity for 2005-2014.*

To get a better picture of the wind fluctuation over a year, it is assumed that the wind velocities are distributed to fit a Weibull distribution. By using MATLAB®'s built-in function 'fitdist', the wind velocities for each month in the period from 2005 to 2014 is distributed with the Weibull probability function. Figure 5.3 shows the Weibull distribution for the months with the highest and lowest wind velocities, in this case December and August. The plot clearly shows a higher fluctuation in wind velocities for December as the probability for wind velocities above 20 meters per second is much higher than for August. A plot with the Weibull distribution for every month can be found in Figure A.11 in appendix A.

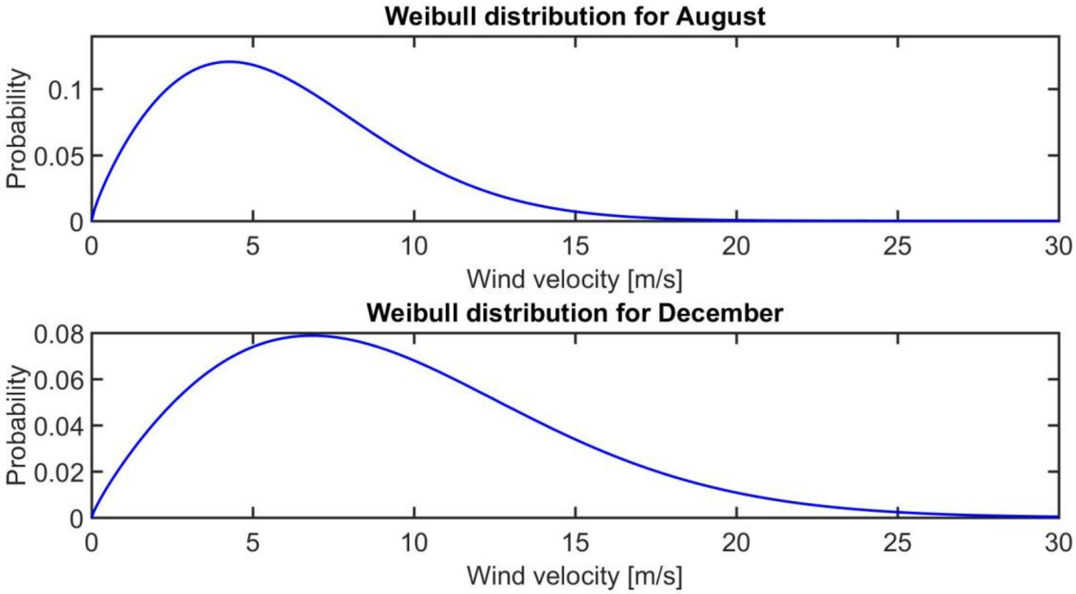

*Figure 5.3: Weibull distribution for wind velocities in August and December.*

By generating random number based upon the different distribution, the wind velocities can be simulated to replicate the wind conditions throughout a year. Figure 5.4 is a plot of the simulation based upon the different distributions, showing lower fluctuation and average wind velocity during the summer. The simulation does not consider the correlation of the wind velocity one hour and the velocity of the consecutive hours. However, it supports the assumption of higher average wind velocities and variation during the winter and lower in the summer.

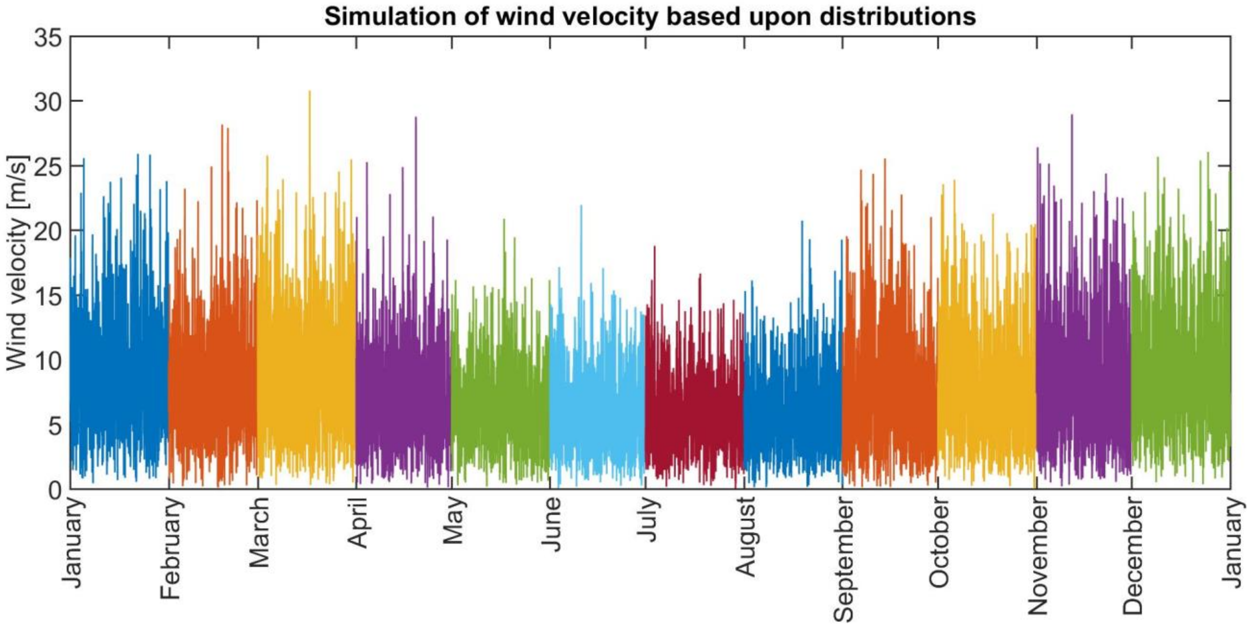

*Figure 5.4: Simulation based upon the different Weibull distributions.*

An interesting factor is the number of hours with wind velocities below or above a wind turbines production area. As mentioned in 2.2.1, a wind turbine starts to produce power at cut-in speed and stops at cut-out speed. Wind velocities below cut-in speed and above cut-out speed will yield no produced power from the wind turbine. Figure 5.5 illustrates numbers of hours without sufficient wind velocities to produce power based upon normal cut-in and cut-out speed of 3 m/s and 25 m/s[34]. It shows the correlation between one hour and the next as one dot represents number of hours without sufficient wind velocities in sequence. Figure A.12-A.14 In appendix A shows the plots of every year from 2005 to 2014. The expected number of hours in a year without production is between 783 and 1225 hours based upon the normal distribution of hours below 3 m/s or above 25 m/s in the period between 2005 and 2014 shown in Figure 5.6.

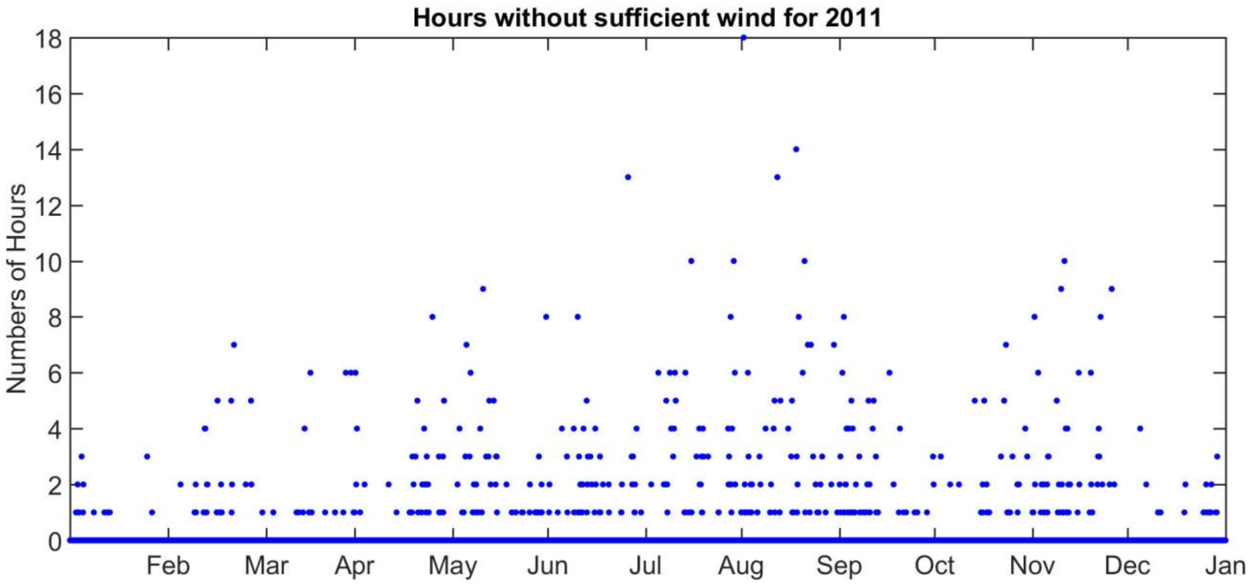

*Figure 5.5: Number of consecutive hours without sufficient wind velocities for 2011.*

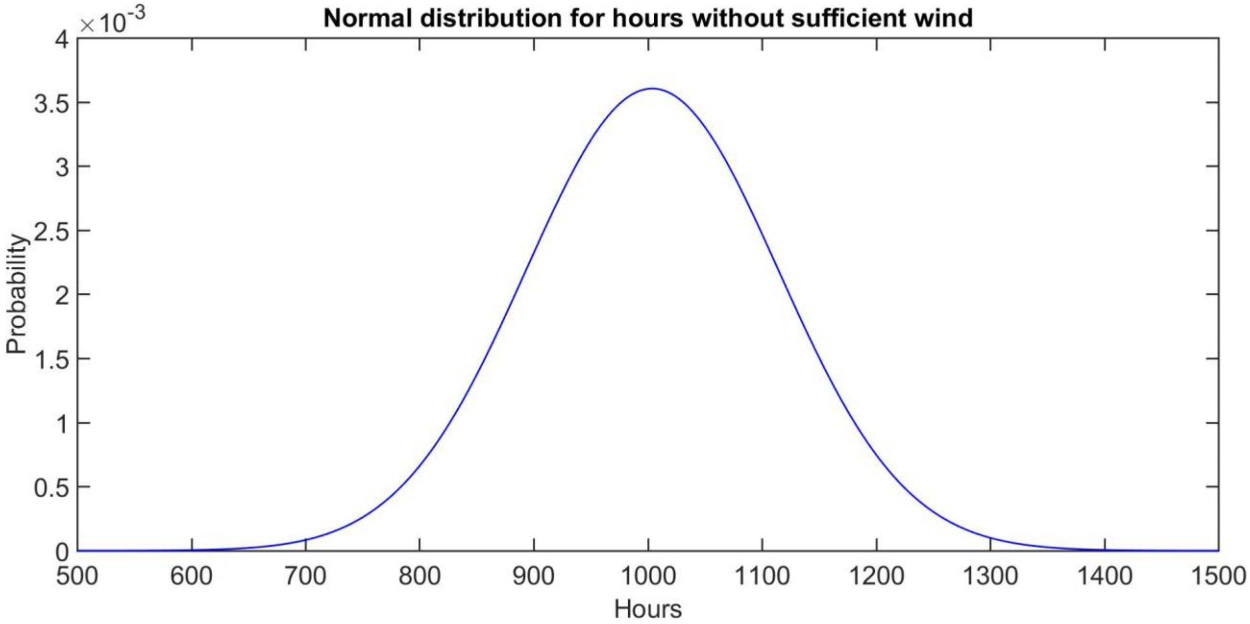

*Figure 5.6: The normal distribution for hours without production in a year.*

Because of the correlation between the wind velocity for one hour and the following hours, it is interesting to get a picture of the probability of periods without sufficient wind lasting longer than an hour. Figure 5.7 shows the cumulative probability of consecutive hours without sufficient wind velocities. In 95% of the time, the periods without sufficient wind last no longer than 5.9 hours.

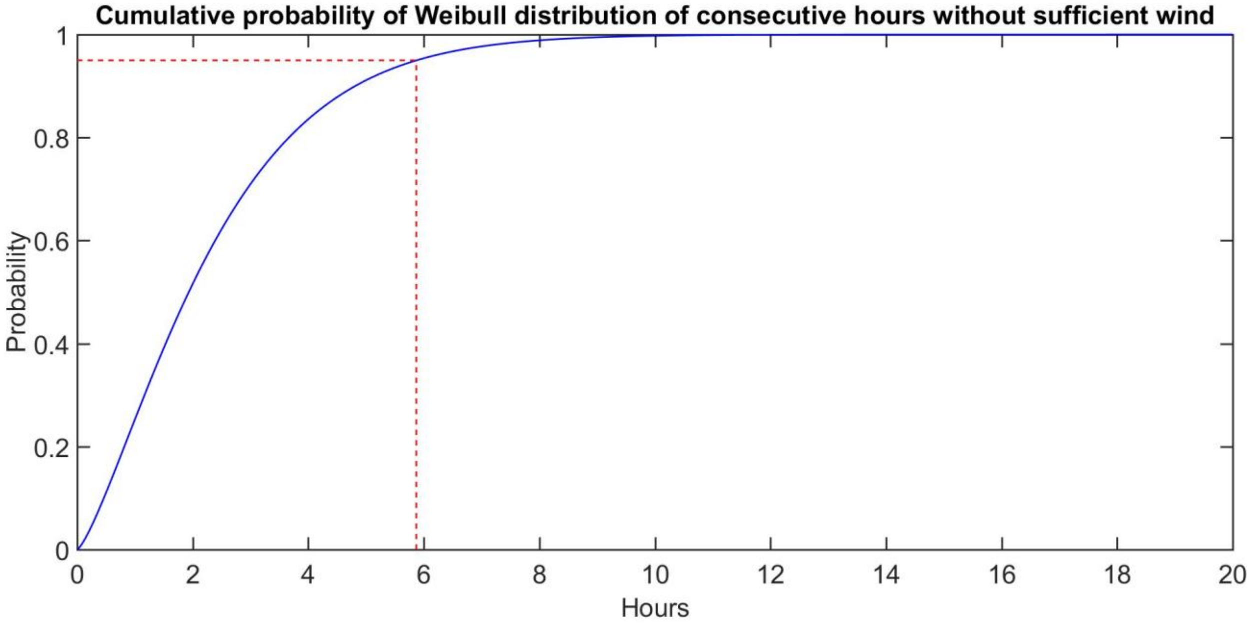

*Figure 5.7: The cumulative probability of Weibull distribution of consecutive hours without sufficient wind with 95% marked.*

## 5.2 Energy Consumption and Emission Analysis

The energy consumption data is gathered at Nekton Havbruk's plant at Gjelsøya by using a Fluke 435-II. The data consists of minute-by-minute measurements in the period from 11th to 26th of April. Figure 5.8 shows the energy consumption at the plant during this period, while Figure 5.9 illustrates the energy consumption during a 24-hour period. The figures clearly show periods where the fish is fed at different hours during the day. The periods tend to change as the fish grows. Because of the combination of small and bigger fish which is currently at the plant, the profile shown in Figure 5.8 is assumed to be representative for an average energy consumption during a year [Thomas Bjørdal, 2018, Phone call, 2nd of May].

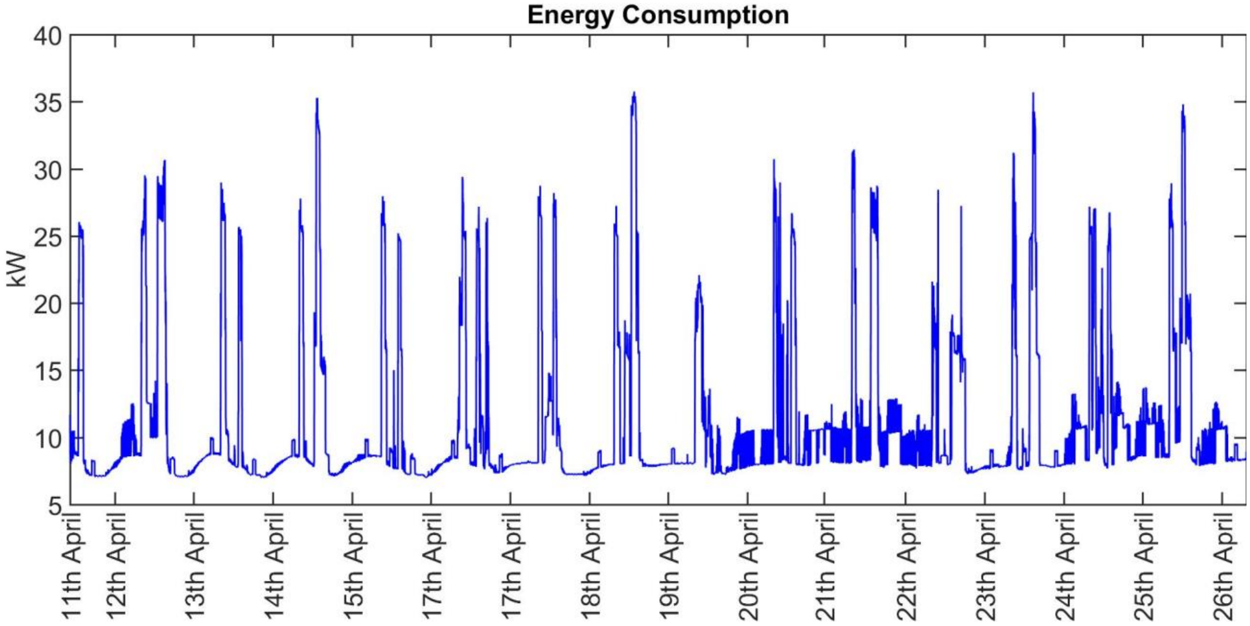

*Figure 5.8: Energy consumption profile for 11th to 26th of April.*

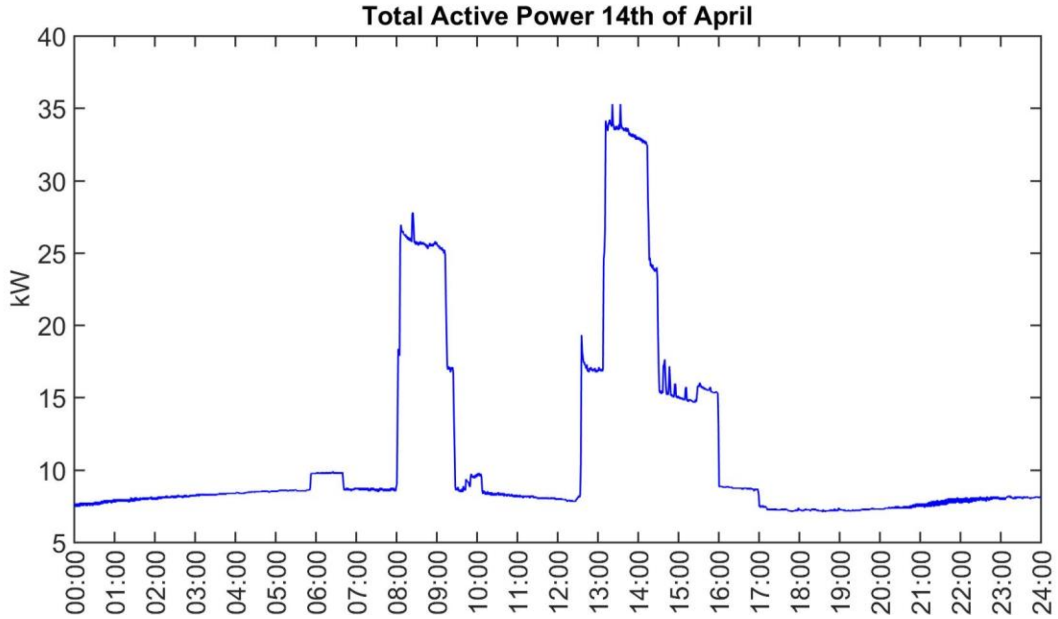

*Figure 5.9: Energy consumption for 14th of April 2018.*

Based upon the energy consumption profile in Figure 5.8 being representative for a year, the total energy consumption for the plant is 96.1 MWh a year. Assuming the fuel consumption fits the curves made with MATLAB®'s curve fitting tool in Figure 5.10 and Figure 5.11 based upon the values from [35, 36], the average fuel consumption per hour is 4.29 liter. A similar curve for the J250K generator, which is needed for higher energy demand, is found in Figure A.15 in appendix A. Furthermore, the total fuel consumption for a year is approximately 37 600 liters, making the total cost of 300 800 NOK with an average fuel price of 8 NOK per liter [Thomas Bjørdal, 2018, E-mail, 6th of May]. Assuming a lifetime of 20 years, this gives a LCOE (*Levelized cost of energy*) of 3.84 NOK per kWh. The LCOE gives a great indication of the costs throughout the lifetime per kWh produced, and is given by:

$$LCOE = \frac{Investment\ cost\ and\ lifetime\ O\&M\ costs}{Total\ energy\ production} \qquad \mathbf{(5.4)}$$

Because of the small size of the plant at Gjelsøya, it is interesting to see the total energy demand and emissions at larger plants. Table 5.2 shows the total energy consumption and LCOE for plants 1-4 times larger than the one at Gjelsøya.

*Table 5.2: Energy demand (E.D) and LCOE for 1-4 times the size of the plant at Gjelsøya.*

| | **1·E.D** | **2·E.D** | **3·E.D** | **4·E.D** |
|---|---|---|---|---|
| **MWh** | 96.1 | 192.2 | 288.3 | 384.4 |
| **LCOE [NOK per kWh]** | 3.84 | 3.28 | 3.05 | 2.91 |

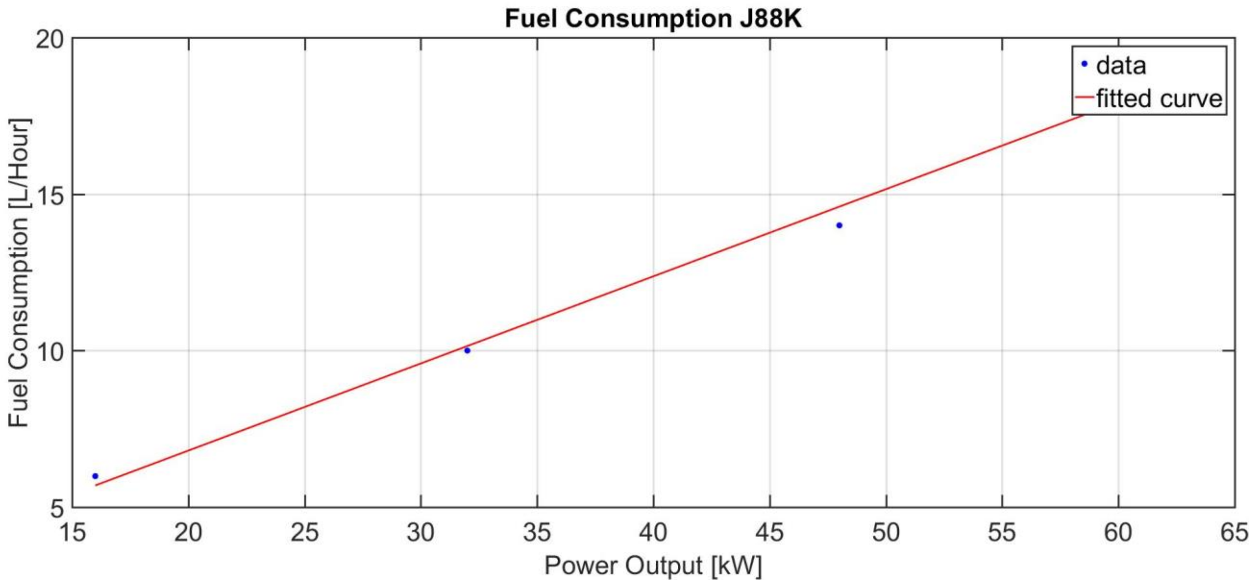

*Figure 5.10: Fuel consumption per hour for the J88K generator as a function of the capacity.*

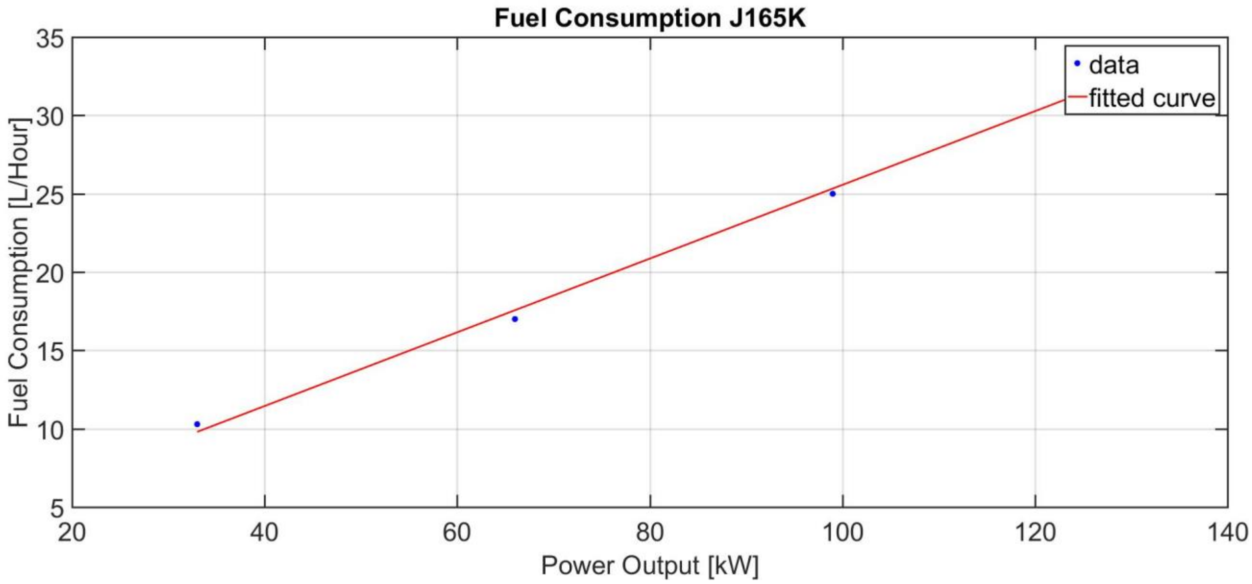

*Figure 5.11: Fuel consumption per hour for the J165K generator as a function of the capacity.*

In order to calculate the emissions based upon the fuel consumption, emissions factors for a tier 1 engine running on marine diesel is used[28, 37]. Table 5.3 list the different values for $CO_2$, $SO_x$, CO, $NO_x$ and PM. The total emissions in kg for a year, listed in Table 5.4, is calculated using MATLAB®.

*Table 5.3: Emissions factors for $CO_2$, $SO_x$, CO, $NO_x$ and PM[28].*

| | **$CO_2$** | **$SO_x$ [kg/ton fuel]** | **CO [kg/ton fuel]** | **$NO_x$ [kg/ton fuel]** | **PM [kg/ton fuel]** |
|---|---|---|---|---|---|
| **Emissions factors** | Total fuel in kg consumption times 3.2 | 20 | 7.4 | 78.5 | 2.9 |

*Table 5.4: Emissions based upon total fuel consumption.*

| **Emissions** | **$CO_2$ [kg]** | **$SO_x$ [kg]** | **CO [kg]** | **$NO_x$ [kg]** | **PM [kg]** |
|---|---|---|---|---|---|
| **1·E.D** | 103 500 | 647 | 239 | 2 540 | 94 |
| **2·E.D** | 176 900 | 1 106 | 409 | 4 340 | 160 |
| **3·E.D** | 246 700 | 1 542 | 570 | 6 052 | 224 |
| **4·E.D** | 314 000 | 1 962 | 726 | 7 700 | 284 |

# 6. Wind – Diesel Hybrid System with Battery Storage

To be able to achieve UN's goal of keeping the global temperature from increasing with 2 degrees Celsius, it is crucial to implement renewable energy technologies and look for new solutions for power generation[38]. The disadvantages of renewable energy resources like wind-, water- and solar-power are the unreliability due to weather conditions. For commercial energy production and distribution, this unreliability is a non-existing problem because of the scale of the power grids and number of power generators. However, for stand-alone systems located off the power grid, this unreliability becomes a major problem. Power generation for a stand-alone system based purely upon renewable energy technology is not a viable option due to periods without production. By combining renewable energy technology with conventional power generation from fossil fuel, a remote system can deliver power continuously with a high renewable penetration[39]. This type of system is known as a **hybrid system**. Today, there are several different hybrid systems applied all over the world with different combination of renewable energy sources; wind-diesel, wind-PV-diesel, wind-hydrogen-diesel or PV-hydrogen. Figure 6.1 is an example of a PV-wind hybrid system. Adding a battery storage allows the system to store renewable power in periods when the power production is higher than the consumption, thus further increasing the renewable penetration of the system.

*Figure 6.1: A PV-wind hybrid system[40].*

## 6.1 System Proposal

Based upon the analysis in the previous chapter along with other considerations, four different combinations of components will be proposed. As mentioned, a hybrid system can be a combination of several renewable energy sources. However, because of the excellent wind conditions at the plant's location, a wind turbine will be main power source with a diesel generator as a back-up. To increase the systems renewable penetration a battery package is implemented. Figure 6.2 is an illustration of the proposed system with the turbine placed on land, and the battery package along with the diesel generator on the barge. The feeding system is still the same as described in section 1.5.1.

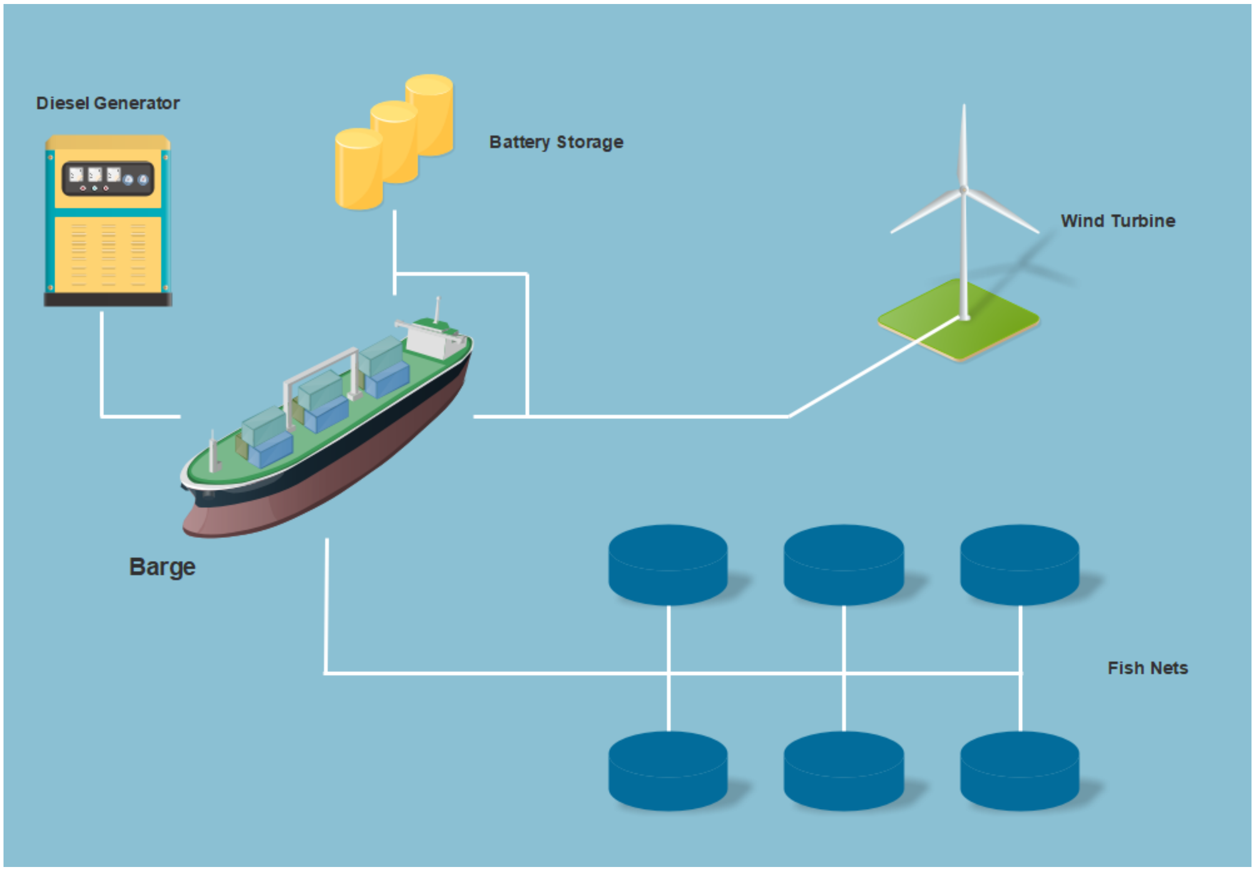

*Figure 6.2: Illustration of the proposed system.*

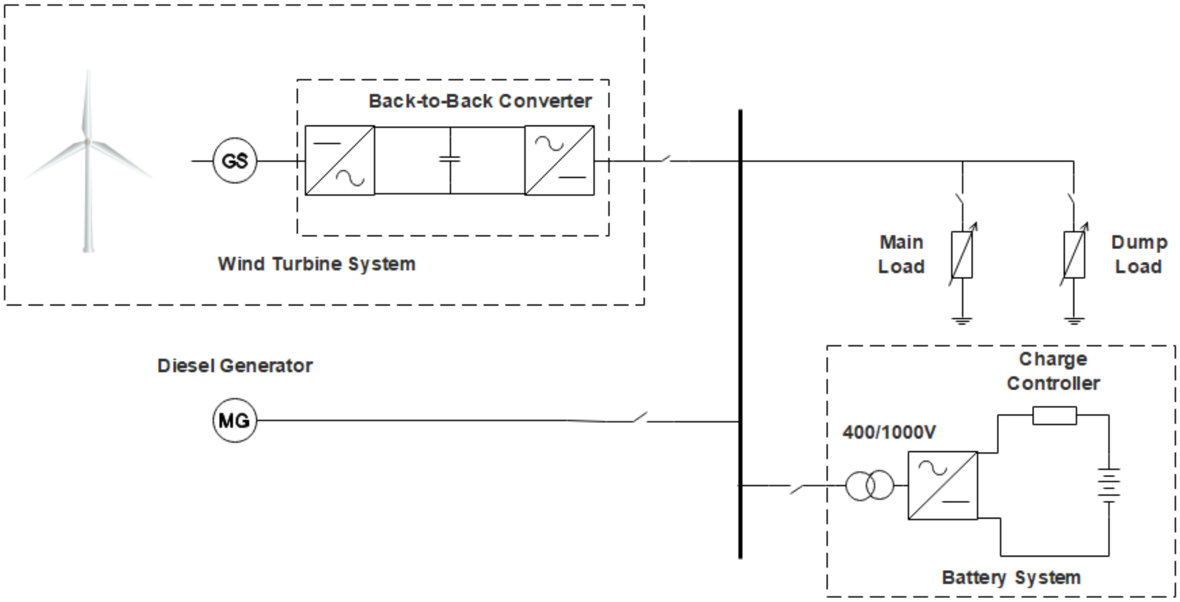

*Figure 6.3: Schematic drawing of the proposed system.*

Figure 6.3 is a schematic drawing of all the necessary electronic components to maintain a stable and functioning system. Because of altering wind velocities, the wind generator will induce harmonic frequencies which may cause damage to the system. To deal with this problem a back-to-back converter is implemented. The back-to-back converter is a rectifier and an inverter in series with a DC link in-between smoothening the voltages by filtering out harmonic frequencies. Most of the commercial wind turbines are delivered with a back-to-back converter implemented[41].

To make the system comparable with the battery storage, the voltage must be converted from AC to DC and vice versa by an inverter. The efficiency of a high quality inverter is quite high and varies between 90-95%[42]. Without an inverter, the batteries would continuously fluctuate between being charged and discharge due to the altering polarity of an AC-voltage. As the majority of battery system operates at 1000 V, the voltage has to be converted with a transformer.

To prevent the batteries from being overcharged or completely discharged, a charge controller is needed. The charge controller works as a switch by cutting the battery circuit in situation which may cause damage to the batteries. Besides from protecting the batteries from any damage, the charge controller prolongs the batteries lifetime[43]. Due to the losses mentioned in section 3.1, the efficiency of the inverters and the transformer, the total efficiency of a battery system, known as the round-trip efficiency, is usually between 80-83%[44, 45]. All the necessary components in the battery system are implemented by the battery manufactory.

Due to the grid's scale, it's vulnerable to differences in produced and consumed power. In situation of the wind turbine producing more power than what is consumed by the load, power will start to oscillate within the system causing harmonic voltages which may damage components. By installing a dump load in addition to the main load, the superfluous power will be absorbed, preventing it from oscillating within the system. The dump load is typically a heater or a different power equipment[46]. However, the utilization of the dump load will be discussed later based on the results from the simulations.

The four different proposed systems are listed in Table 6.1. Simulation in MATLAB® for each proposed system will determine which system has the highest renewable penetration and are the most cost efficient. Detailed information for each system can be found in Table B.1 – B.4 appendix B.

*Table 6.1: System proposal.*

| **System 1** | | **System 2** | |
|---|---|---|---|
| Wind Turbine | WES250 | Wind Turbine | WES100 |
| Battery Package | PBES Energy 100 | Battery Package | PBES Energy 100 |
| Generator | SDMO J165K | Generator | SDMO J165K |
| **System 3** | | **System 4** | |
| Wind Turbine | WES100 | Wind Turbine | WES100 |
| Battery Package | PBES Power 65 | Battery Package | - |
| Generator | SDMO J165K | Generator | SDMO J165K |

### 6.1.1 Investment Costs

Acquiring and installing the systems comes at a price and are different for each of them. Along with the purchase price for each component, the costs of the installation affect the investment cost as well. For example, the turbine must be shipped, mounted, and connected to the plant's grid with a sea cable. However, it is assumed that the installation and delivery costs are the same for each system as the installation remains unchanged (except system 4 which is without a battery package implemented). Table 6.2 shows the total cost for shipping and installation cost based on the economic analysis done by [47], along with [48],[49], and conversation with Thomas Bjørdal. The cost calculations for each system are an estimate, as the actual price may be higher or lower.

*Table 6.2: Total shipping and installation costs.*

| | | **Costs [NOK]** |
|---|---|---|
| | Shipping and installation of the wind turbine | 1 000 000 |
| + | Delivery and installation of the battery package (including inverter, transformer, and charge controller) | 250 000 |
| + | Cables | 240 000 |
| = | Total shipping and installation costs | 1 490 000 |

Furthermore, the total investment costs of each system are listed in Table 6.3 to Table 6.6, with the shipping and installation costs for system 4 being adjusted due to the lack of a battery package. Today's price of a battery package is 209 $/kWh[22, 24]. Due to already being installed at the plant, the investment cost of the generator is excluded. The prices are calculated based upon the exchange rate provided by [50] on the 7th of May at 13.20.

*Table 6.3: Total investment cost for system 1.*

| | **System 1** | **Cost [NOK]** |
|---|---|---|
| | Shipping and installation cost | 1 490 000 |
| + | WES250 Wind turbine (250 kW) | 4 900 000 |
| + | PBES Energy 100 (100 kWh) | 167 200 |
| = | Total investment cost | 6 557 200 |

*Table 6.4: Total investment cost for system 2.*

| | **System 2** | **Cost [NOK]** |
|---|---|---|
| | Shipping and installation cost | 1 490 000 |
| + | WES100 Wind turbine (100 kW) | 2 300 000 |
| + | PBES Energy 100 (100 kWh) | 167 200 |
| = | Total investment cost | 3 957 200 |

*Table 6.5: Total investment cost for system 3.*

| | **System 3** | **Cost [NOK]** |
|---|---|---|
| | Shipping and installation cost | 1 490 000 |
| + | WES100 Wind turbine (100 kW) | 2 300 000 |
| + | PBES Power 65 (65 kWh) | 107 640 |
| = | Total investment cost | 3 897 640 |

*Table 6.6: Total investment cost for system 4.*

| | **System 4** | **Cost [NOK]** |
|---|---|---|
| | Shipping and installation cost | 1 240 000 |
| + | WES100 Wind turbine (100 kW) | 2 300 000 |
| = | Total investment cost | 3 540 000 |

The total investment costs can be reduced by financial support from various instances. Enova, established by the Norwegian government, is an instance whose main task is to reduce Norway’s greenhouse emissions by providing financial support for renewable solutions for both private individuals and companies. For pioneer projects, the financial support provided can cover up to 40 percent of the total investment cost, making an otherwise impossible project possible [Thomas Bjørdal, 2018, E-mail, 7th of May]. Table 6.7 lists the total investment costs assuming a financial support of 30 percent is provided.[51]

*Table 6.7: Total investment cost assuming a financial support of 30% is provided.*

| **System** | **Cost [NOK]** |
|---|---|
| System 1 | 4 590 040 |
| System 2 | 2 770 040 |
| System 3 | 2 728 348 |
| System 4 | 2 478 000 |

# 7. Simulations

In this chapter the performance of the proposed systems will be simulated in MATLAB® based upon the average energy consumption found in 5.2 and the wind data from 2005 to 2014. The simulation will yield; renewable penetration, cuts in emissions in percentage, power delivered by the wind turbine, generator and batteries, as well as power absorbed by the dump load. The present value of the investment for 10 and 20 years with and without financial support, with the O&M (*operating and maintenance*) costs and the reduction in fuel cost included will also be determined. In the end, the payback time, which is the time of which the yearly savings has covered the total investment cost, and LCOE will be calculated. The performance of the system will also be simulated with two, three and four times the annual energy consumption to replicate larger plants. The code used to run the simulations can be found in Appendix C. Power produced by the wind turbine is found using the turbine's power curve[52, 53].

For simplification, some assumptions are made:

- Lifetime of wind turbine is 20 years.
- The battery system's round-trip efficiency of 80%.
- The battery cannot be fully charged (95% of maximum capacity).
- The battery cannot be fully discharged (20% of maximum capacity).
- The battery's self-discharge rate is neglected.
- The battery's lifetime is set to 10 years.
- The energy consumption data is converted from minute-by-minute measure to hour-by-hour by using average value for an hour.
- Discount rate is 5.5%.
- Fuel price and operating cost is constant throughout the simulations.

The emissions are determined the same way as in section 5.2, thus, the fuel consumption is assumed to fit the fuel consumption curves found with MATLAB®'s curve fitting tool. Due to the reduction in fuel consumption is determined in kg/year, the reduction in percent for each emission is the same and found by:

$$Cut\ in\ Emission = 1 - \frac{Emissions_{new\ system}}{Emissions_{old\ sytem}} \qquad (\mathbf{7.1})$$

The renewable penetration is the share of the total energy consumption covered by renewable sources, in this chase the wind turbine and the battery package. The renewable penetration is determined by:

$$Renewable\ penetration = 1 - \frac{MWh_{DieselGenerator}}{MWh_{Total\ Energy\ Consumption}} \qquad (\mathbf{7.2})$$

The present value is an indication of how profitable an investment is. By considering the risk involved, interest, and the expected marginal return, the present value shows the actual value of the investment in the future. The present value is given by:

$$Present\ Value = -I + \sum_{n=1}^{\infty} \frac{CF}{(1+r)^n} \qquad (\mathbf{7.3})$$

Here, I is the total investment cost, CF is the cash flow each year, r is the discount rate, and n is the number of periods (years). The discount rate considers the expected marginal return, risk involved, and the interest. The risk involved tries to consider the changes in interest and costs.

## 7.1 System 1 – 250 kW Turbine With 100 kWh Battery Package

Table 7.1 shows the results of the simulation for each year with total power produced, percentage of the energy demand covered by the wind turbine, diesel generator and battery, as well as absorbed power by the dump load in MWh. The 95% confidence interval for the 10-year period is also presented in the table. The renewable penetration and emission reduction is listed in Table 7.2. Figure 7.1 and Figure 7.2 illustrates the normal distribution for the energy demand covered by the turbine, generator, and the battery, renewable penetration, and emission cuts. Figure 7.1 also shows the normal distribution for the power delivered to the dump load.

*Table 7.1: The results from the simulation for each year for 250 kW turbine with 100 kWh battery package for system 1.*

| Year | Wind [MWh] | % of Energy Demand | Diesel Generator [MWh] | % of Energy Demand | Battery Power [MWh] | % of Energy Demand | Dump Load [MWh] |
|---|---|---|---|---|---|---|---|
| **2005** | 665.46 | 76.38 | 9.46 | 10.87 | 11.08 | 12.74 | 585.15 |
| **2006** | 619.52 | 72.33 | 14.80 | 16.02 | 10.76 | 11.65 | 539.16 |
| **2007** | 767.49 | 77.76 | 9.82 | 10.62 | 10.75 | 11.62 | 682.02 |
| **2008** | 631.76 | 74.05 | 12.43 | 13.47 | 11.52 | 12.48 | 548.91 |
| **2009** | 594.29 | 74.22 | 11.99 | 13.19 | 11.44 | 12.58 | 512.46 |
| **2010** | 555.37 | 72.29 | 12.74 | 13.84 | 12.76 | 13.86 | 472.75 |
| **2011** | 679.92 | 74.73 | 11.17 | 12.14 | 12.08 | 13.12 | 632.71 |
| **2012** | 718.44 | 78.58 | 8.93 | 9.72 | 10.74 | 11.69 | 632.71 |
| **2013** | 637.57 | 72.72 | 12.62 | 12.86 | 12.20 | 13.41 | 556.02 |
| **2014** | 517.91 | 73.81 | 10.28 | 13.12 | 10.24 | 13.07 | 447.18 |
| **95% CI** | 638.77 ± 148.00 | 74.69 ± 4.42 | 11.43 ± 3.65 | 12.68 ± 3.74 | 11.36 ± 1.59 | 12.62 ± 1.55 | 557.23 ± 141.73 |
| **95% CI for 2·E.D** | 638.77 ± 148.00 | 67.73 ± 4.98 | 43.09 ± 9.98 | 23.93 ± 5.03 | 14.99 ± 1.57 | 8.33 ± 0.78 | 497.97 ± 133.63 |
| **95% CI for 3·E.D** | 638.77 ± 148.00 | 62.78 ± 5.34 | 83.89 ± 16.40 | 31.07 ± 5.40 | 16.58 ± 1.56 | 6.14 ± 0.49 | 448.32 ± 125.88 |
| **95% CI for 4·E.D** | 638.77 ± 148.00 | 58.91 ± 5.63 | 130.51 ± 23.06 | 36.25 ± 5.62 | 17.41 ± 1.90 | 4.84 ± 0.38 | 404.69 ± 118.42 |

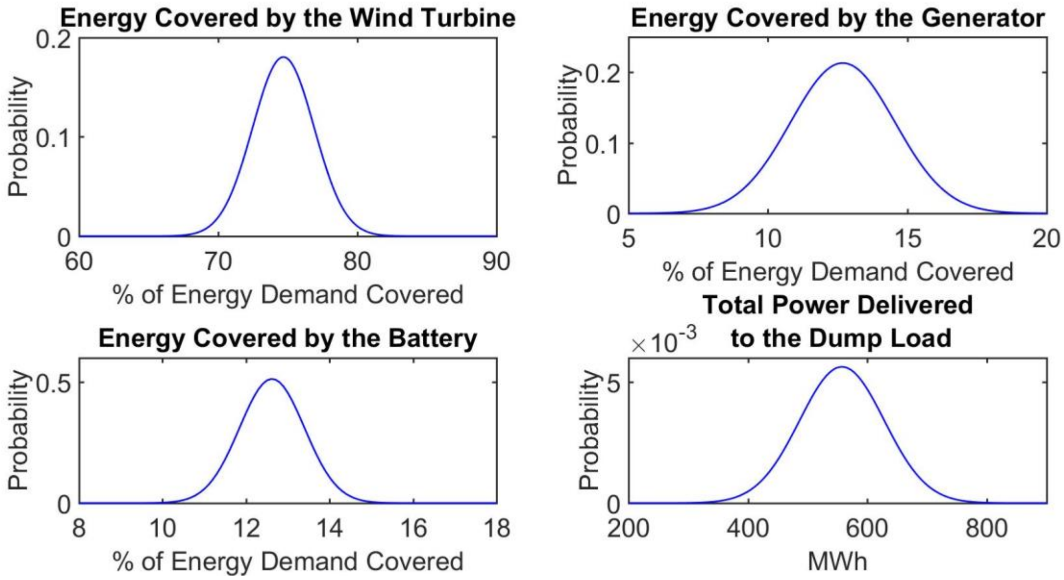

*Figure 7.1: The normal distribution for the total energy demand covered by the wind turbine, generator, and the battery as well as the normal distribution for the power delivered to the dump load for system 1.*

*Table 7.2: The renewable penetration and emissions reduction for each year, and the 95% CI for the ten-year period for system 1.*

| **Year** | **Renewable penetration [%]** | **Emissions Reduction [%]** |
|---|---|---|
| **2005** | 89.13 | 88.56 |
| **2006** | 83.98 | 82.23 |
| **2007** | 89.38 | 88.05 |
| **2008** | 86.53 | 85.02 |
| **2009** | 86.81 | 85.01 |
| **2010** | 86.16 | 84.39 |
| **2011** | 87.86 | 86.55 |
| **2012** | 90.28 | 88.92 |
| **2013** | 86.14 | 84.51 |
| **2014** | 86.88 | 87.36 |
| **95% CI** | 87.32 ± 3.74 | 86.06 ± 4.34 |
| **95% CI for 2·E.D** | 76.07 ± 5.03 | 77.71 ± 5.37 |
| **95% CI for 3·E.D** | 68.93 ± 5.40 | 70.92 ± 5.67 |
| **95% CI for 4·E.D** | 63.75 ± 5.62 | 66.59 ± 5.89 |

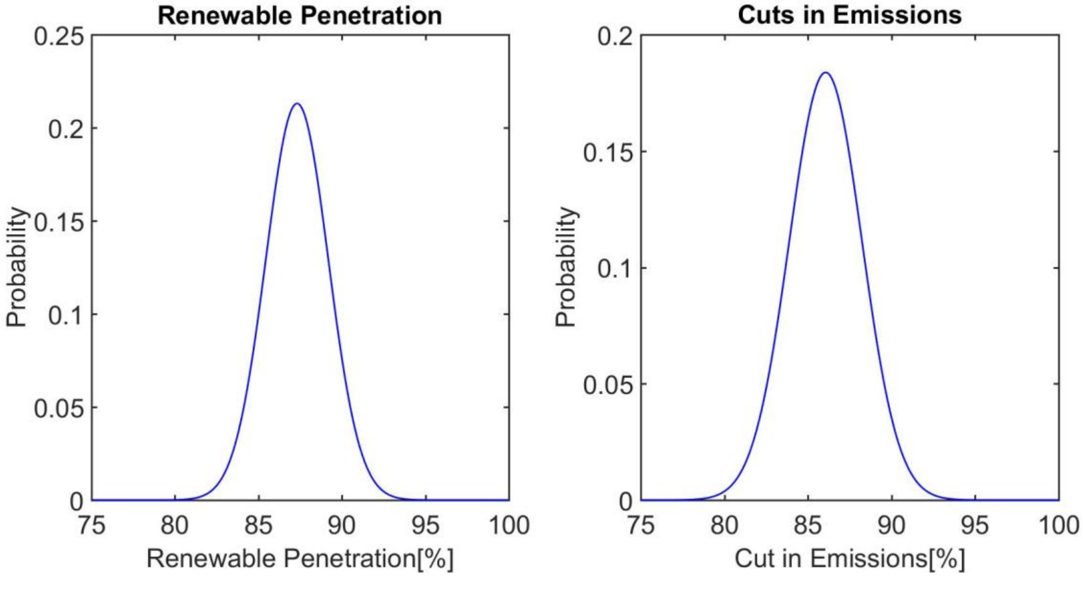

*Figure 7.2: The normal distribution for annual renewable penetration and cuts in emissions for system 1.*

Table 7.3 shows the present value for the investments for 10 and 20 years, with and without financial support along with the payback time and LCOE. Keep in mind that the payback time does not consider the discount rate.

*Table 7.3: Present value for the investment for 10 and 20 years, with and without financial support, payback time and LCOE for system 1.*

| **Energy Demand [E.D]** | **Present value for 10 years [NOK]** | **Present value for 10 years with 30% fin. Support [NOK]** | **Present value for 20 years [NOK]** | **Present value for 20 years with 30% fin. Support [NOK]** |
|---|---|---|---|---|
| **1·E.D** | -5 247 200 | -3 289 600 | -4 724 500 | -2 766 900 |
| **2·E.D** | -4 226 300 | -2 268 700 | -3 105 900 | -1 148 300 |
| **3·E.D** | -3 356 400 | -1 407 900 | - 1 741 100 | 216 500 |
| **4·E.D** | -2 118 500 | -661 000 | -556 900 | 1 400 600 |
| | **Payback time [Years]** | | **Payback time with 30% fin. Support [Years]** | |
| **1·E.D** | 38.5 | | 26.9 | |
| **2·E.D** | 21.4 | | 15 | |
| **3·E.D** | 15.6 | | 10.9 | |
| **4·E.D** | 12.6 | | 8.8 | |
| | **LCOE [NOK per kWh]** | | **LCOE with 30% fin. support [NOK per kWh]** | |
| **1·E.D** | 6.09 | | 4.84 | |
| **2·E.D** | 3.54 | | 2.92 | |
| **3·E.D** | 2.73 | | 2.32 | |
| **4·E.D** | 2.36 | | 2.05 | |

## 7.2 System 2 – 100 kW Turbine With 100 kWh Battery Package

Table 7.4 shows the results of the simulation for each year with total power produced, percentage of the energy demand covered by the wind turbine, diesel generator and battery, as well as absorbed power by the dump load in MWh. The 95% confidence interval for the 10-year period is also presented in the table. The renewable penetration and emission reduction is listed in Table 7.5. Figure 7.3 and Figure 7.4 illustrates the normal distribution for the energy demand covered by the turbine, generator, and the battery, renewable penetration, and emission cuts. also Figure 7.3 shows the normal distribution for the power delivered to the dump load.

*Table 7.4: The results from the simulation for each year for 100 kW turbine with 100 kWh battery package for system 2.*

| **Year** | **Wind [MWh]** | **% of Energy Demand** | **Diesel Generator [MWh]** | **% of Energy Demand** | **Battery Power [MWh]** | **% of Energy Demand** | **Dump Load [MWh]** |
|---|---|---|---|---|---|---|---|
| **2005** | 252.89 | 67.89 | 17.39 | 19.99 | 10.52 | 12.10 | 180.65 |
| **2006** | 235.09 | 64.16 | 23.12 | 25.03 | 9.97 | 10.80 | 163.25 |
| **2007** | 290.81 | 70.16 | 17.40 | 18.80 | 10.21 | 11.03 | 213.10 |
| **2008** | 241.35 | 65.40 | 21.98 | 23.81 | 9.95 | 10.77 | 168.43 |
| **2009** | 225.45 | 64.58 | 21.99 | 24.18 | 10.21 | 11.23 | 153.94 |
| **2010** | 206.41 | 63.26 | 22.86 | 24.83 | 10.96 | 11.90 | 134.35 |
| **2011** | 262.55 | 66.74 | 19.85 | 21.57 | 10.75 | 11.68 | 187.60 |
| **2012** | 271.52 | 69.95 | 16.98 | 18.48 | 10.62 | 11.56 | 193.94 |
| **2013** | 244.06 | 64.35 | 22.06 | 24.23 | 10.39 | 11.41 | 172.30 |
| **2014** | 196.94 | 64.77 | 19.04 | 24.30 | 8.55 | 10.92 | 135.40 |
| **95% CI** | 242.71 ± 57.40 | 66.13 ± 4.92.40 | 20.27 ± 4.85 | 22.52 ± 5.15 | 10.21 ± 1.33 | 11.34 ± 0.93 | 170 ± 50.03 |
| **95% CI 2·ED** | 242.71 ± 57.40 | 54.9 ± 6.69 | 69.45 ± 11.43 | 38.59 ± 5.76 | 11.73 ± 1.74 | 6.51 ± 0.51 | 129.08 ± 42.67 |
| **95% CI 3·ED** | 242.71 ± 57.40 | 47.91 ± 5.93 | 128.76 ± 18.73 | 47.69 ± 6.03 | 11.86 ± 1.83 | 4.39 ± 0.40 | 98.31 ± 35.75 |
| **95% CI 4·ED** | 242.71 ± 57.40 | 42.76 ± 6.00 | 193.91 ± 26.78 | 53.86 ± 6.23 | 12.14 ± 1.98 | 3.37 ± 0.38 | 73.36 ± 28.67 |

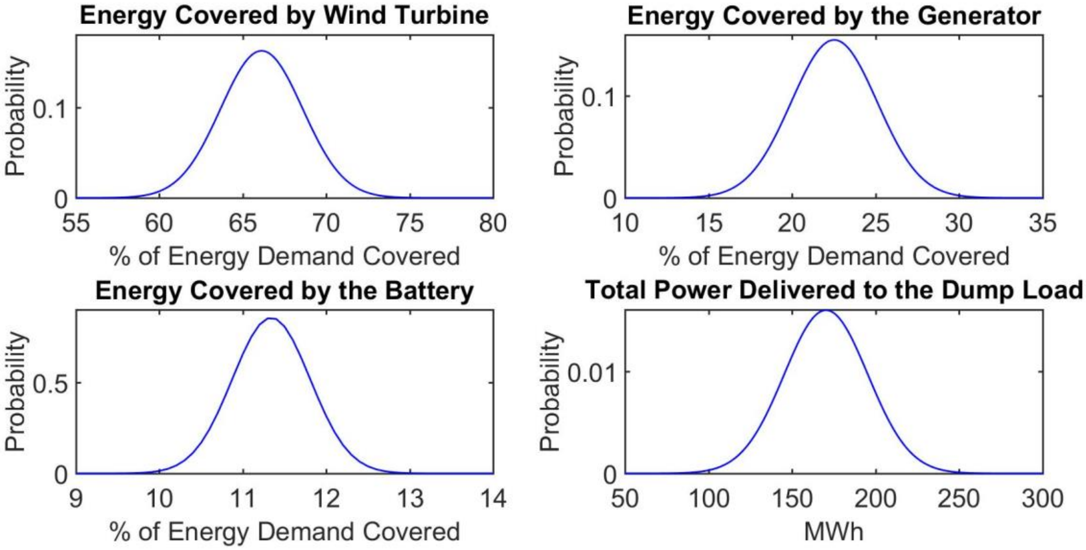

*Figure 7.3: The normal distribution for the total energy demand covered by the wind turbine, generator, and the battery as well as the normal distribution for the power delivered to the dump load for system 2.*

*Table 7.5: The renewable penetration and emissions reduction for each year, and the 95% CI for the ten-year period for system 2.*

| **Year** | **Renewable penetration [%]** | **Emissions Reduction [%]** |
|---|---|---|
| **2005** | 80.00 | 78.13 |
| **2006** | 74.97 | 71.40 |
| **2007** | 81.20 | 78.12 |
| **2008** | 76.19 | 72.38 |
| **2009** | 75.81 | 71.85 |
| **2010** | 75.17 | 71.01 |
| **2011** | 78.43 | 75.25 |
| **2012** | 81.52 | 78.47 |
| **2013** | 75.77 | 72.23 |
| **2014** | 75.70 | 76.17 |
| **95% CI** | 77.48 ± 5.15 | 74.50 ± 6.10 |
| **95% CI 2·ED** | 61.41 ± 5.76 | 64.18 ± 5.76 |
| **95% CI 3·ED** | 52.31 ± 6.03 | 54.64 ± 6.48 |
| **95% CI 4·ED** | 46.14 ± 6.23 | 50.35 ± 6.81 |

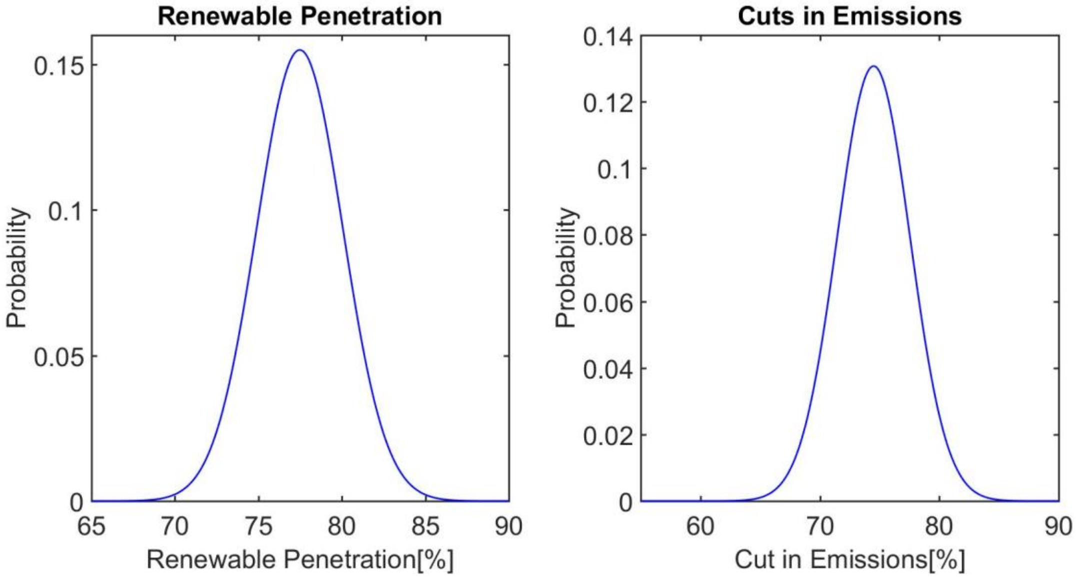

*Figure 7.4: The normal distribution for annual renewable penetration and cuts in emissions for system 2.*

Table 7.6 shows the present value for the investments for 10 and 20 years, with and without financial support along with the payback time and LCOE. Keep in mind that the payback time does not consider the discount rate.

*Table 7.6: Present value for the investment for 10 and 20 years, with and without financial support, payback time and LCOE for system 2.*

| **Energy Demand [E.D]** | **Present value for 10 years [NOK]** | **Present value for 10 years with 30% fin. Support [NOK]** | **Present value for 20 years [NOK]** | **Present value for 20 years with 30% fin. Support [NOK]** |
|---|---|---|---|---|
| **1·E.D** | -2 491 400 | -1 313 900 | -1 877 500 | -700 000 |
| **2·E.D** | -1 779 800 | -602 200 | -749 300 | 428 300 |
| **3·E.D** | -1 196 100 | -18 600 | 176 000 | 1 353 600 |
| **4·E.D** | -717 200 | 460 400 | 935 300 | 2 113 000 |
| | **Payback time [Years]** | | **Payback time with 30% fin. Support [Years]** | |
| **1·E.D** | 20.6 | | 14.4 | |
| **2·E.D** | 13.8 | | 9.7 | |
| **3·E.D** | 10.8 | | 7.6 | |
| **4·E.D** | 9.2 | | 6.5 | |
| | **LCOE [NOK per kWh]** | | **LCOE with 30% fin. support [NOK per kWh]** | |
| **1·E.D** | 4.16 | | 3.41 | |
| **2·E.D** | 2.84 | | 2.46 | |
| **3·E.D** | 2.43 | | 2.18 | |
| **4·E.D** | 2.24 | | 2.05 | |

### 7.3 System 3 – 100 kW Turbine With 65 kWh Battery Package

Table 7.7 shows the results of the simulation for each year with total power produced, percentage of the energy demand covered by the wind turbine, diesel generator and battery, as well as absorbed power by the dump load in MWh. The 95% confidence interval for the 10-year period is also presented in the table. The renewable penetration and emission reduction is listed in Table 7.8. Figure 7.4 and Figure 7.5 illustrates the normal distribution for the energy demand covered by the turbine, generator, and the battery, renewable penetration, and emission cuts. Figure 7.4 also shows the normal distribution for the power delivered to the dump load.

*Table 7.7: The results from the simulation for each year for 100 kW turbine with 65 kWh battery package for system 3.*

| **Year** | **Wind [MWh]** | **% of Energy Demand** | **Diesel Generator [MWh]** | **% of Energy Demand** | **Battery Power [MWh]** | **% of Energy Demand** | **Dump Load [MWh]** |
|---|---|---|---|---|---|---|---|
| **2005** | 252.89 | 67.89 | 19.65 | 22.59 | 8.27 | 9.51 | 183.49 |
| **2006** | 235.09 | 64.16 | 25.32 | 27.41 | 7.78 | 8.42 | 166.03 |
| **2007** | 290.81 | 70.16 | 19.59 | 21.17 | 8.02 | 8.66 | 215.85 |
| **2008** | 241.35 | 65.40 | 24.13 | 26.15 | 7.79 | 8.44 | 171.17 |
| **2009** | 225.45 | 64.58 | 24.08 | 26.48 | 8.12 | 8.93 | 156.56 |
| **2010** | 206.41 | 63.26 | 25.33 | 27.51 | 8.49 | 9.21 | 137.48 |
| **2011** | 262.55 | 66.74 | 22.04 | 23.94 | 8.56 | 9.30 | 190.37 |
| **2012** | 271.52 | 69.95 | 19.27 | 20.98 | 8.32 | 9.06 | 196.81 |
| **2013** | 244.06 | 64.35 | 24.33 | 26.73 | 8.11 | 8.91 | 175.28 |
| **2014** | 196.94 | 64.77 | 20.64 | 26.35 | 6.95 | 8.87 | 137.43 |
| **95% CI** | 242.71 ± 57.40 | 66.12 ± 4.92 | 22.44 ± 4.95 | 24.93 ± 5.08 | 8.04 ± 0.93 | 8.93 ± 0.71 | 173.05 ± 50.19 |
| **95% CI 2·E.D** | 242.71 ± 57.40 | 54.90 ± 5.92 | 72.14 ± 11.67 | 40.08 ± 5.75 | 9.04 ± 1.26 | 5.02 ± 0.38 | 132.46 ± 42.86 |
| **95% CI 3·E.D** | 242.71 ± 57.40 | 47.91 ± 5.93 | 131.49 ± 18.91 | 48.70 ± 6.00 | 9.13 ± 1.38 | 3.38 ± 0.30 | 101.75 ± 35.97 |
| **95% CI 4·E.D** | 242.71 ± 57.40 | 42.76 ± 6.00 | 196.63 ± 26.79 | 54.62 ± 6.18 | 9.43 ± 1.52 | 2.61 ± 0.28 | 76.78 ± 28.95 |

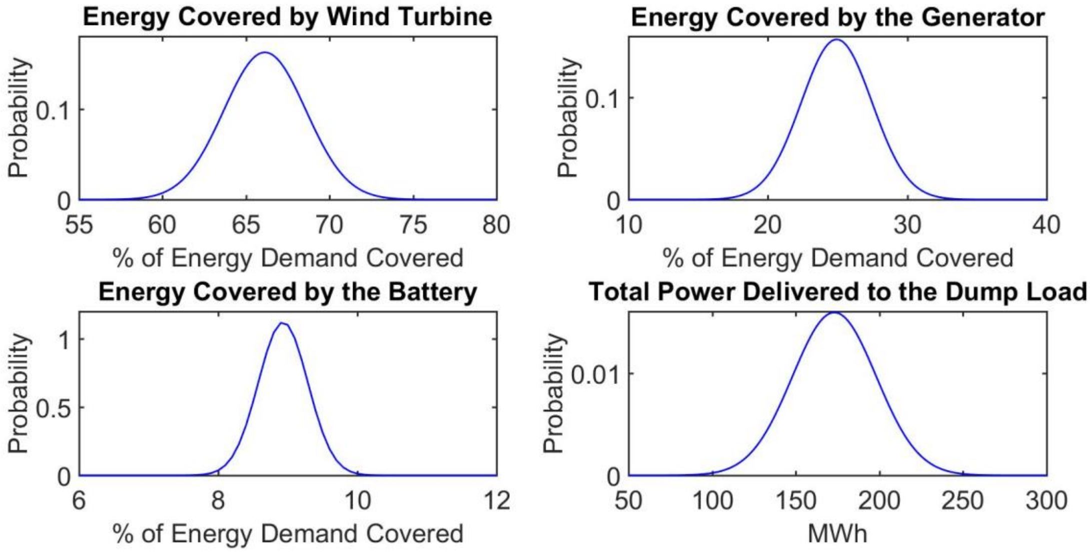

*Figure 7.5: The normal distribution for the total energy demand covered by the wind turbine, generator, and the battery as well as the normal distribution for the power delivered to the dump load for system 3.*

*Table 7.8: The renewable penetration and emissions reduction for each year, and the 95% CI for the ten-year period for system 3.*

| **Year** | **Renewable penetration [%]** | **Emissions Reduction [%]** |
|---|---|---|
| **2005** | 77.41 | 75.36 |
| **2006** | 72.59 | 68.67 |
| **2007** | 78.83 | 75.39 |
| **2008** | 73.85 | 69.78 |
| **2009** | 73.52 | 69.26 |
| **2010** | 72.49 | 67.90 |
| **2011** | 76.06 | 72.53 |
| **2012** | 79.02 | 75.52 |
| **2013** | 73.27 | 69.53 |
| **2014** | 73.65 | 74.05 |
| **95% CI** | 75.07 ± 5.08 | 71.80 ± 6.17 |
| **95% CI 2·E.D** | 59.92 ± 5.75 | 60.42 ± 6.32 |
| **95% CI 3·E.D** | 51.30 ± 6.00 | 54.22 ± 6.45 |
| **95% CI 4·E.D** | 45.38 ± 6.18 | 49.62 ± 6.80 |

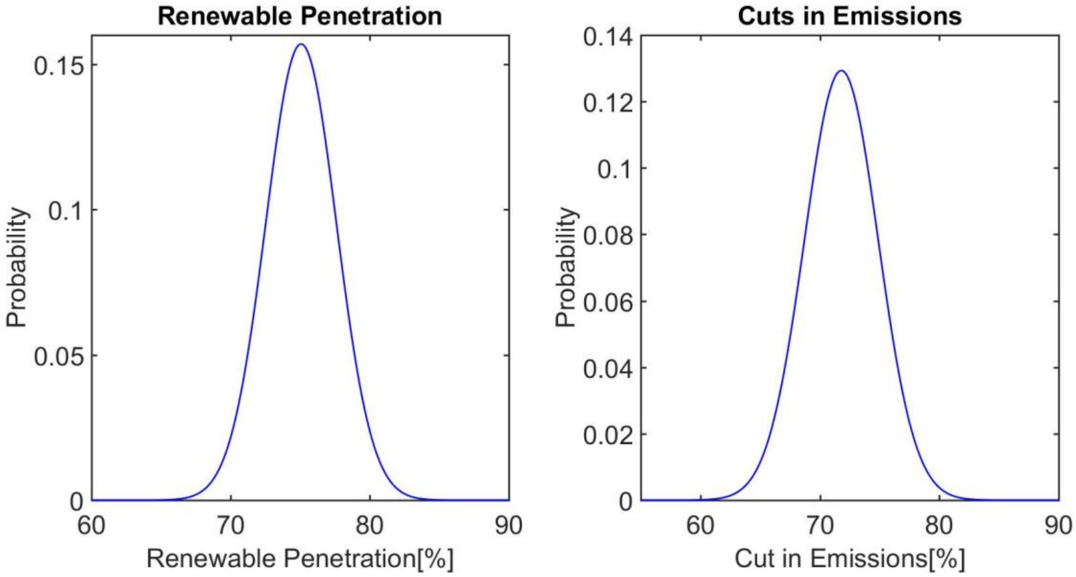

*Figure 7.6: The normal distribution for annual renewable penetration and cuts in emissions for system 3.*

Table 7.9 shows the present value for the investments for 10 and 20 years, with and without financial support along with the payback time and LCOE. Keep in mind that the payback time does not consider the discount rate.

*Table 7.9: Present value for the investment for 10 and 20 years, with and without financial support, payback time and LCOE for system 3.*

| **Energy Demand [E.D]** | **Present value for 10 years [NOK]** | **Present value for 10 years with 30% fin. Support [NOK]** | **Present value for 20 years [NOK]** | **Present value for 20 years with 30% fin. Support [NOK]** |
|---|---|---|---|---|
| **1·ED** | -2 494 200 | -1 334 200 | -1 888 200 | -721 200 |
| **2·ED** | -1 781 100 | -621 100 | -751 400 | 408 600 |
| **3·ED** | -1 192 200 | -32 100 | 182 400 | 1 342 400 |
| **4·ED** | -709 200 | 450 800 | 948 000 | 2 108 000 |
| | **Payback time [Years]** | | **Payback time with 30% fin. Support [Years]** | |
| **1·ED** | 21.2 | | 14.9 | |
| **2·ED** | 14.0 | | 9.8 | |
| **3·ED** | 10.9 | | 7.6 | |
| **4·ED** | 9.2 | | 6.5 | |
| | **LCOE [NOK per kWh]** | | **LCOE with 30% fin. support [NOK per kWh]** | |
| **1·E.D** | 4.19 | | 3.45 | |
| **2·E.D** | 2.85 | | 2.48 | |
| **3·E.D** | 2.43 | | 2.19 | |
| **4·E.D** | 2.24 | | 2.06 | |

### 7.4 System 4 – 100 kW Turbine Without a Battery Package

Table 7.10 shows the results of the simulation for each year with total power produced, percentage of the energy demand covered by the wind turbine, diesel generator, as well as absorbed power by the dump load in MWh. The 95% confidence interval for the 10-year period is also presented in the table. The renewable penetration and emission reduction is listed in Table 7.11. Figure 7.7 and Figure 7.8 illustrates the normal distribution for the energy demand covered by the turbine and the generator, renewable penetration, and emission cuts. Figure 7.7 also shows the normal distribution for the power delivered to the dump load.

*Table 7.10: The results from the simulation for each year for 100 kW turbine without a battery package for system 4.*

| **Year** | **Wind [MWh]** | **% of Energy Demand** | **Diesel Generator [MWh]** | **% of Energy Demand** | **Dump Load [MWh]** |
|---|---|---|---|---|---|
| **2005** | 252.89 | 67.90 | 27.92 | 31.10 | 193.84 |
| **2006** | 235.09 | 64.16 | 33.10 | 35.84 | 175.82 |
| **2007** | 290.81 | 70.17 | 27.61 | 29.83 | 225.90 |
| **2008** | 241.35 | 65.40 | 31.93 | 34.59 | 180.98 |
| **2009** | 225.45 | 64.59 | 32.20 | 35.41 | 166.75 |
| **2010** | 206.41 | 63.26 | 33.83 | 36.74 | 148.16 |
| **2011** | 262.55 | 66.75 | 30.60 | 33.25 | 201.19 |
| **2012** | 271.52 | 69.96 | 27.60 | 30.04 | 207.26 |
| **2013** | 244.06 | 64.35 | 32.45 | 35.65 | 185.49 |
| **2014** | 196.94 | 64.78 | 27.59 | 35.22 | 146.20 |
| **95% CI** | 242.72 ± 57.41 | 66.13 ± 4.92 | 30.48 ± 5.10 | 33.87 ± 4.92 | 183.16 ± 50.64 |
| **95% CI 2·E.D** | 242.72 ± 57.41 | 54.90 ± 5.70 | 81.18 ± 12.19 | 45.10 ± 5.70 | 143.81 ± 43.14 |
| **95% CI 3·E.D** | 242.72 ± 57.41 | 47.92 ± 5.94 | 140.63 ± 19.48 | 52.08 ± 5.94 | 113.20 ± 36.49 |
| **95% CI 4·E.D** | 242.72 ± 57.41 | 42.76 ± 6.00 | 206.07 ± 27.05 | 57.24 ± 6.00 | 88.59 ± 30.01 |

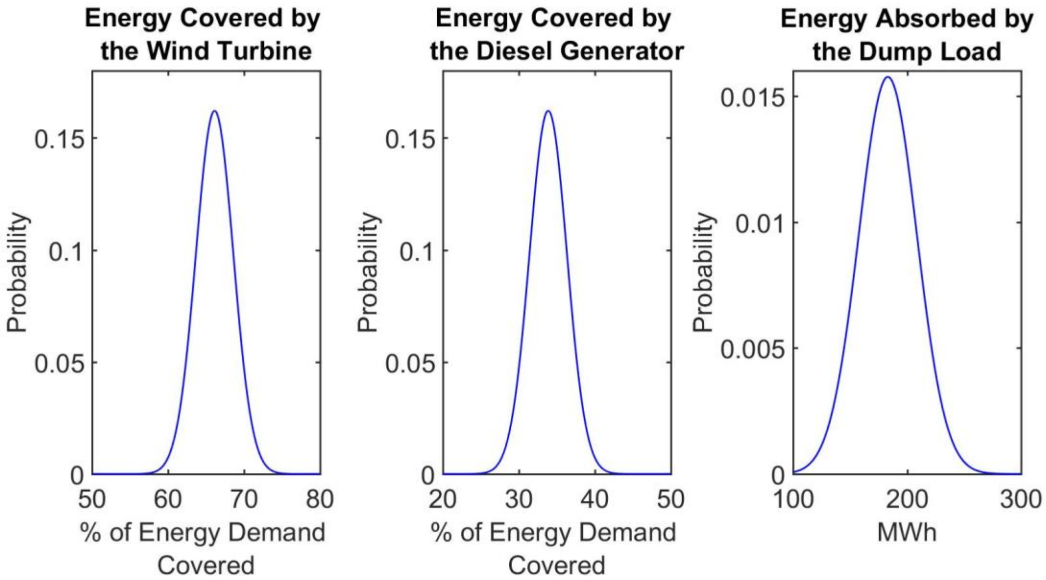

*Figure 7.7: The normal distribution for the total energy demand covered by the wind turbine, and the generator, as well as the normal distribution for the power delivered to the dump load for system 4.*

*Table 7.11: The renewable penetration and emissions reduction for each year, and the 95% CI for the ten-year period for system 4.*

| Year | Renewable penetration [%] | Emissions Reduction [%] |
|---|---|---|
| **2005** | 67.90 | 63.72 |
| **2006** | 64.16 | 57.54 |
| **2007** | 70.17 | 64.32 |
| **2008** | 65.41 | 58.50 |
| **2009** | 64.59 | 57.90 |
| **2010** | 63.26 | 60.00 |
| **2011** | 66.75 | 60.51 |
| **2012** | 69.96 | 63.63 |
| **2013** | 64.35 | 58.06 |
| **2014** | 64.78 | 64.20 |
| **95% CI** | 66.13 ± 4.92 | 60.43 ± 6.47 |
| **95% CI 2·E.D** | 54.90 ± 5.70 | 54.81 ± 6.58 |
| **95% CI 3·E.D** | 47.92 ± 5.94 | 50.64 ± 6.70 |
| **95% CI 4·E.D** | 42.76 ± 6.00 | 46.89 ± 6.88 |

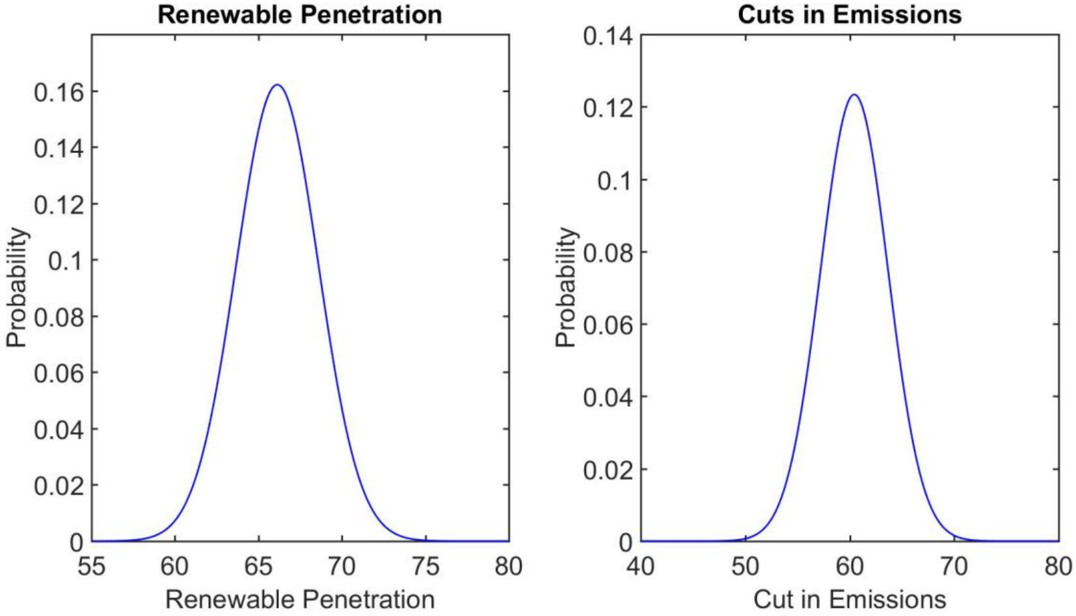

*Figure 7.8: The normal distribution for annual renewable penetration and cuts in emissions for system 4.*

Table 7.12 shows the present value for the investments for 10 and 20 years, with and without financial support along with the payback time and LCOE. Keep in mind that the payback time does not consider the discount rate.

*Table 7.12: Present value for the investment for 10 and 20 years, with and without financial support, payback time and LCOE for system 4.*

| **Energy Demand [E.D]** | **Present value for 10 years [NOK]** | **Present value for 10 years with 30% fin. Support [NOK]** | **Present value for 20 years [NOK]** | **Present value for 20 years with 30% fin. Support [NOK]** |
|---|---|---|---|---|
| **1·E.D** | -2 425 200 | -1 363 200 | -1 772 600 | -710 600 |
| **2·E.D** | -1 671 900 | -609 900 | -578 300 | 483 700 |
| **3·E.D** | -1 058 900 | 4 000 | 393 600 | 1 455 600 |
| **4·E.D** | -570 500 | 491 400 | 1 167 800 | 2 229 800 |
| | **Payback time [Years]** | | **Payback time with 30% fin. Support [Years]** | |
| **1·E.D** | 23.9 | | 16.8 | |
| **2·E.D** | 14.3 | | 10.0 | |
| **3·E.D** | 10.8 | | 7.5 | |
| **4·E.D** | 9.0 | | 6.3 | |
| | **LCOE [NOK per kWh]** | | **LCOE with 30% fin. support [NOK per kWh]** | |
| **1·E.D** | 4.21 | | 3.53 | |
| **2·E.D** | 2.83 | | 2.49 | |
| **3·E.D** | 2.40 | | 2.18 | |
| **4·E.D** | 2.22 | | 2.05 | |

# 8. Discussion

In this chapter the results will be evaluated. First, the wind analysis will be discussed and compared with other wind data to determine if the site is suited for wind power. Furthermore, the results from the energy consumption analysis as well as the approach will be assessed. With the wind and energy analysis in mind, the choice of hybrid system and components will be justified. At the end, the assumption for the simulation will be explained and discussed, and the results compared.

## 8.1 Wind Data Analysis

Due to the close proximity and low geographical interference between Veiholmen and the plant's location at Gjelsøya, the wind data provided by NVES are considered to fit the site's condition well. The data consists of measurements from 1994 to 2014. From 1994 to 2002 three to five measurements were taken per day, while the data from 2002 to 2014 consists of hour-by-hour measurements. The data from 1994 to 2002 turned out difficult to compare to the data from 2002 to 2014 because of the different amount of measures. Due to its lower resolution, it was made a decision to exclude the data from 1994 to 2002. Additionally, the data from 2002, 2003, and 2004 lacked measurements, and was therefore also excluded from the analysis to make the comparison more accurate. An analysis based upon all the data would be preferable. However, a ten-year period was considered to provide sufficient accuracy.

Furthermore, repeated measurements in sequence along with wind velocities at zero meters per second were excluded as these measurements were most likely failures of the measuring device. By removing these errors, the data became more accurate. The wind velocities were assumed to fit a Weibull distribution due to the wind velocities not being symmetrical around a mean value. Comparing Figure 5.1 and Figure 5.4 shows that the assumption was reasonable.

The analysis indicated an average wind velocity throughout a year of 6.68 – 8.28 meters per second. According to [34], the area around Veiholmen are well suited for wind power. Comparing the average wind velocity to [54, 55], which was granted concession, supports this claim. Furthermore, the analysis clearly indicated a pattern with higher wind velocities during the winter than for the summer, as shown in Figure 5.3 and Figure 5.4. This is supported by Figure 5.5, which shows a larger cluster of hours without sufficient velocities for wind power during the summer, assumed the cut-in and out speed are 3 and 25 meters per second. Some of the hours is due to wind velocities above the cut-out speed. However, the majority of these events is most likely caused by winter storms[56]. The number of hours without sufficient velocities for wind power ranged between 783 to 1225 during a year, with the periods lasting no longer than 5.9 hours. Resulting in the wind turbine to produce power in 86-91% of the time, which is above average of a modern wind turbine[57]. However, the plant must draw its power from a different power source during the down time of the wind turbine.

## 8.2 Energy Consumption and Emissions Analysis

The energy data gathered with a Fluke 435-II from the plant are considered to be accurate because of the high resolution of minute-by-minute readings and the quality of the equipment. However, as the data is only gathered for a brief period, it fails to give a complete picture of the energy consumption at the plant throughout the year. This leads to uncertainties in the yearly energy consumption, as well as the total fuel consumption per year. With data gathered for an entire year, the total energy consumption could be calculated with higher accuracy. However, in conversation with Thomas Bjørdal, the gathered data was assumed to fit an average consumption as the combination of the larger and smaller fish represented the average fish size for a year. Therefore, the annual energy consumption of 96.1 MWh is just an approximation. However, compared to the calculation made in [58], the approximation seems to be reasonable considering the different size of the plants.

Furthermore, the data clearly shows an increase in the consumed energy during feeding as shown in Figure 5.9. The feeding periods seems to be of equal length and occur at the same hour. In addition, based upon the capacity of the feed blowers, they seem to only run at 50-55% capacity which corresponds well with the values found in [59]. The energy consumption may differ from the data gathered throughout the year due to the combination of fish changes. This may affect the share of the energy demand covered by wind power due to the seasonal wind velocities.

The total fuel consumption was determined based on the assumption that the fuel consumption per hour versus capacity fitted the curves in Figure 5.10 and Figure 5.11. Comparing the curves in Figure 5.10 and Figure 5.11 with the curves for fuel consumption in [56, 57], they seem to follow the same pattern. Therefore, the fuel consumption is assumed to fit without significant inaccuracy. After conversation with Thomas Bjørdal the diesel price were set to 8 NOK per liter, which corresponds well with the prices used in [58, 62], making the total fuel cost of 300 800 NOK a year. Due to the high fuel consumption, a change in fuel price will have significant impact on the total cost.

The inaccuracy in the fuel consumption affects the determination of the emissions from the diesel generator. The emissions factors used to calculate the emissions of CO, $NO_x$, $SO_x$, and PM are from diesel engine using marine diesel at ships. This may result in inaccurate calculations as ships tend to move at a constant speed, thus holding the diesel engine at a constant capacity. However, as the diesel generator at the plant does not constantly fluctuate but produces constant power at different capacities as shown in Figure 5.9, it’s assumed that this inaccuracy is not of a high concern. Disregarding the inaccuracy in fuel consumption, the total emissions of 103 500 kg $CO_2$ is accurate based upon the weight ratio between carbon and carbon dioxide. In comparison, 103 500 kg $CO_2$ per year equals the $CO_2$ emissions of 23 vehicles a year[63]. Due to the well-known bird life in the area around Hitra and Smøla, measuring the actual emission would be preferable to determine the impact on the local wild life.

## 8.3 System Proposal

The proposed system described in chapter 6.1 was based upon the desire to reduce emissions and costs. An agreement from the start of the project, was to implement a wind turbine as one of the renewable power sources. Due to the excellent conditions indicated in the wind analysis and the well-developed technology, a wind turbine was chosen as the main power source. A HAWT was chosen above a VAWT due to the lower price per kWh. Wind power faces opposition regarding its visual pollution and effect on local bird life. However, as this is a remote location and the wind turbine will be placed on a small reef, the visual impact of the turbine is minimal. Additionally, the threat opposed for the bird life are in reference to [64] limited to birds nesting in close proximity to the turbine as well as no long term impact on the stock.

A battery package was implemented to further increase the systems renewable penetration, and thus reducing the emissions even more. From the different battery technologies, the Li-ion batteries were chosen above NiCd, NiMH, and lead acid batteries due to its appropriate characteristics. The lead acid battery was excluded due to its low energy density and expected lifetime compared to the other technologies. The disadvantage of the memory effect, left the NiCd and NiMH inferior compared to Li-ion as they need to be completely discharged before charged, which is inconvenient because of the sporadic wind power production. Furthermore, the generator is needed as a reliable on-off power source in cases when the power supplied by the turbine or the battery is insufficient. The 165 kVA diesel generator was chosen above the 88 kVA generator due to potential events when the energy demand is higher than 88 kVA.

Other technologies as PV, hydrogen, tidal, and wave power was considered. The advantage of PV-based energy is the synergy with wind power as the PV produces most power during the summer due to the high solar radiation. However, due to its low energy density of about 153 W per square meter, the required area for an installed capacity of for example 40 kW is approximately 260 square meters [65]. Furthermore, implementing PV would increase the complexity of the proposed system as well as the total cost, thus reduced the system’s profitability. Another uncertainty was the PV-panel’s ability to withstand the harsh conditions at the Norwegian coast.

Using hydrogen-based generators were considered as a solution to cut all emissions. The hydrogen would completely replace power generation based on fossil fuel, resulting in a renewable penetration of 100%. The removal of the diesel generator would eliminate the danger of a potential oil leakage, which would have a major impact on the plant’s fish stock and the local marine wild life. However, as there are no distributors in close proximity, this solution is not viable. Furthermore, wave and tidal power were excluded due to the technologies still being in its early stage.

The four different system proposals are based on the analysis from the wind and energy consumption data. With the simulation in mind, the idea was to design different systems to determine which combination gave the best results. System 1 was a combination of a 250 kW turbine with a 100 kWh battery package in the attempt to maximize the renewable penetration and emissions reduction without going out of a budget of 10 MNOK. System 2 and 3 were designed with a 100 kW turbine to asses if the size of the battery package had a major impact on the profitability, renewable penetration and emissions reduction. The last system was designed without a battery package to determine whether a wind-diesel system was a profitable solution without reducing the cuts in emissions significantly.

The investments costs of the systems are based on various sources. Some of the prices used in [47] is thought to be a bit high, especially the cost for foundation. However, the price for the necessary cables are used, as this is an actual offer from a cable manufacturer. Furthermore, the costs for the shipping and installation of the turbine are in reference to [49] and Thomas Bjørdal a reasonable approximation. The actual price of the turbine is retrieved from the price list for WES (*Wind Energy Solutions*)[66].

The biggest inaccuracy considering the investments costs are the expenses for the battery package. The inaccuracy is mostly due to the challenging task of finding reasonable costs of the individual components, shipping and installation of the battery package as the manufactures customize a unique package for every project. After some research, the expenses for the battery package was set to 209 $ per kWh in reference to [24] which is the price per kWh for Li-ion batteries used in electrical vehicles. It’s thought that the technology is similar to the one used in battery packages implemented in hybrid systems, thus presenting a reasonable expense based on the battery capacity. Based on the prices for a transformer, inverter, and installing from [47], [48], and [67] the delivery and installation costs of the battery package was estimated to approximately 350 000 NOK. However, as the battery package is delivered as a complete package, the total cost is assumed to be lower. Therefore, a total cost of 250 000 NOK is thought to be a better approximation. To obtain a better estimation of the total investment costs for each system an actual offer from a manufacture would be preferable.

Enova provides up to 40% financial support to pioneer projects. However, it was assumed that a financial support of 30% were more likely based on the financial support provided by Enova for aquaculture plants in the past[68].

## 8.4 Simulations with Results

The simulation is based on the idea of the wind turbine being the main power source in the system. Furthermore, the remaining power demand that cannot be covered by the turbine is either provided by the battery package or the diesel generator depending on the energy stored in the battery package. The code which the simulation is based on is assumed to be correct as the energy balance for every simulation adds up. To make the data comparable, the energy consumption data were converted from kW to kWh measures using the average kW in an hour. The charging/discharging process in the simulation is simplified as it does not consider the battery’s discharge/charge curve. Regardless of the lower resolution of the data and simplification of the battery’s charging/discharging process, the simulation is assumed to yield an accurate picture of the energy flow for the hybrid system.

The simulation is based upon several assumptions related to efficiencies, lifetime and prices. The power produced by the wind turbine according to its power curve is assumed to include any losses within the turbine system. The power from the turbine has to be transferred through the cable resulting in a small loss in power. However, these losses are assumed to be insignificant because of the low resistance of the cable. Due to the theory stated in section 3.1 and 6.1, the assumptions related to the battery system is thought to be reasonable. The losses associated with the battery’s self-discharge rate was neglected because of the continuous charge and discharge cycle and the assumption of these losses being insignificant. Besides, these losses are most likely included in the system’s round-trip efficiency.

For the present value, the discount rate was set to 5.5% based on the financial analysis done by E.R. Ystgård in [62] and the assumption that the risk involved is minimal along with an investment in a project like this is primarily to reduce $CO_2$ emissions rather than demanding high marginal return. The risk involved was assumed to be minimal due to the low cost of fuel, that are more likely to increase rather than decrease in the future as result of the decreasing activity in the Norwegian oil industry[69]. However, for simplicity, the fuel cost was set to a constant value of today’s price at 8 NOK per liter, which negatively impacts the present value, presenting a lower value than it will be in reality. Based upon Li-ion batteries being maintenance free, O&M costs related to the battery system was neglected. The O&M costs associated with the wind turbine was based on the price of 0.14 NOK per produced kWh[70]. The maintenance costs are distributed evenly through the period. Even though the O&M costs varies over time, this gives a good indication of the O&M expenses of a wind turbine. Due to the excepted lifetime of the battery package, the expenses of a repurchase of a new battery package after 10 years was included in the present value for 20 years to increase its accuracy.

The simulations gave different results for each system, both in performance and profitability. Based on the original energy consumption of 96.1 MWh, the results indicated high renewable penetration and cuts in emissions. However, none of the systems were profitable. The exaggerated capacity of the wind turbines led to negative present values as well as high payback times and LCOEs. The statement of an exaggerated capacity of the wind turbines can be justified with the amount of power absorbed by the dump load. For example, the dump load in system 1 absorbed 557.23 ± 141.73 MWh which is about 5.5 times the total energy demand at the plant. To make the proposed systems profitable for the plant at Gjelsøya it is crucial to utilize the power absorbed by the dump load. One solution is to use the superfluous power to produce necessary oxygen. With the numbers from [71], the amount of oxygen produced by utilizing the dump load from system 1 would be 1 600 tons. By being self-sufficient considering oxygen, the operational costs are reduced as well as the excess gas could be sold, increasing the plant’s income. Another solution of utilizing the dump load is to produce hydrogen through electrolyses and later use it as a power source. Such a system should be designed to completely remove the diesel generator, thus cutting all emissions. However, these solutions require purchase of necessary equipment affecting the total investment cost of the project. Utilization of the dump load needs further study.

The simulations also indicated that the systems became more profitable as the energy demand increased. This supports the statement that the systems’ capacity was exaggerated compared to the energy demand at Gjelsøya. The systems also utilized more of the power produced by the wind turbines as less power were absorbed by the dump load. However, as the energy demand increased to four times the demand at Gjelsøya, the renewable penetration and cuts in emission fell. For system 2 and 3 the cuts in emissions still were about 50% (50.35% ± 5.71% and 49.62 ± 6.80%) with a significant lower LCOE compared to the original system.

Overall, the results from the simulations indicates that a wind-diesel-battery or a wind-diesel hybrid system can be viable solution to cut approximately 50% of the emissions if designed with a renewable penetration of 50-60%, given that the plant is operating 15 years or longer. However, for a small-scale plant as the one at Gjelsøya, a hybrid system is unlikely to be profitable due to the high costs of installation and shipping compared to the reduction in fuel costs. Additionally, the simulation indicates that the battery has little impact on the systems performance and profitability. This is most likely due to the high cost per kWh, which resulted in a small battery package compared to the total energy demand.

To increase the industry’s interest in the solution, the costs and fuel prices must change. E.R. Ystgård did in [62] an analysis for the payback time and yearly saving based upon the fuel price, which indicated that the fuel price had a major impact on the profitability of the hybrid system. As the aquaculture industry is growing, it is crucial to reduce its emissions to protect the wild life at the Norwegian coastline and contribute to meet Norway’s total share of emissions in reference to the Paris agreement[72]. An important policy instrument is to cut the subsidies on the marine diesel used by the industry. Another factor is to reduce the costs of the technology, thus reducing the investment costs. In reference to [22] and [73], the technology are on the right track. To raise awareness and further validate this thesis’ results, a pilot project should be initiated.

# 9. Conclusion

The main objective of this bachelor project was to assess whether a wind-diesel hybrid system with a battery storage were a viable solution to cut emissions at aquaculture plants. With the results from the analysis and simulation done in this thesis, a conclusion is drawn.

With an average wind velocity of 6.68 – 8.28 meters per second, the wind analysis based on the wind data provided by NVES from Veiholmen indicated that the area is well suited for wind power. Regardless of the energy consumption data only contained readings from a brief period, it was assumed that it was representative as an average energy demand throughout the year due to the combination of smaller and larger fish currently at the plant. With an energy demand of 96.1 MWh a year, the total $CO_2$ emissions were 103.5 ton per year and higher for plants with two, three or four times greater energy demand than the plant at Gjelsøya.

Due to the excellent wind conditions, a wind turbine was chosen as the main power source for the hybrid system. A battery package was implanted to further increase the renewable penetration and cuts in emissions of the system. To make the system self-sufficient, a diesel generator was required as an on-off power source. Four different systems were proposed to determine the impact of the different components on renewable penetration, cuts in emissions and profitability.

The simulation yield a high renewable penetration and cuts in emissions, but negative profitability for each system based on the energy demand at the plant at Gjelsøya. However, as the energy demand increased, the profitability increased but the renewable penetration and cuts in emissions fell. The results indicated that the battery had a minor impact on the performance and profitability of the hybrid system.

Overall, the results from the simulations indicates that a wind-diesel-battery or a wind-diesel hybrid system can be viable solution to cut approximately 50% of the emissions if designed with a renewable penetration of 50-60%, given that the plant is operating 15 years or longer. However, for a small-scale plant as the one at Gjelsøya, a hybrid system is unlikely to be profitable due to the high costs of installation and shipping compared to the reduction in fuel costs. Because of the assumptions tied to the investment costs, the profitability should be viewed in a perspective, as this requires further research.

As the aquaculture industry is growing, it’s crucial to reduce its emissions to protect the wild life along the Norwegian coastline as well as contribute to meet Norway’s total share of emissions in reference to the Paris agreement. An important policy instrument to increase the industry’s interest in hybrid power solutions, is to cut the subsidies on the marine diesel.

To further investigate the possibilities of a wind-diesel hybrid-based power solution, a small/full-scale should be initiated.

# Future Work

As this thesis is based on several assumptions related to the total energy demand and costs, this thesis should be viewed as a preliminary study as it requires further work to conclude with better accuracy. However, as the code for the simulation is already written and attached, future work will be easy to perform as soon as the required data acquired. Further research should be conducted on:

- Energy consumption data gathered for a long period of time, preferably for as long as the fish's life cycle. The data should be gathered at a larger plant to get a more accurate picture of the energy demand for the majority of the plants in the aquaculture industry.
- Actual offers from manufactures should be acquired to get a better estimate of the expenses related to investment cost, present value, payback time and LCOE.
- Utilizing the dump load to reduce operational costs with oxygen or hydrogen production.
- Initiate a small/full-scale pilot project.

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# Appendix

# Appendix A

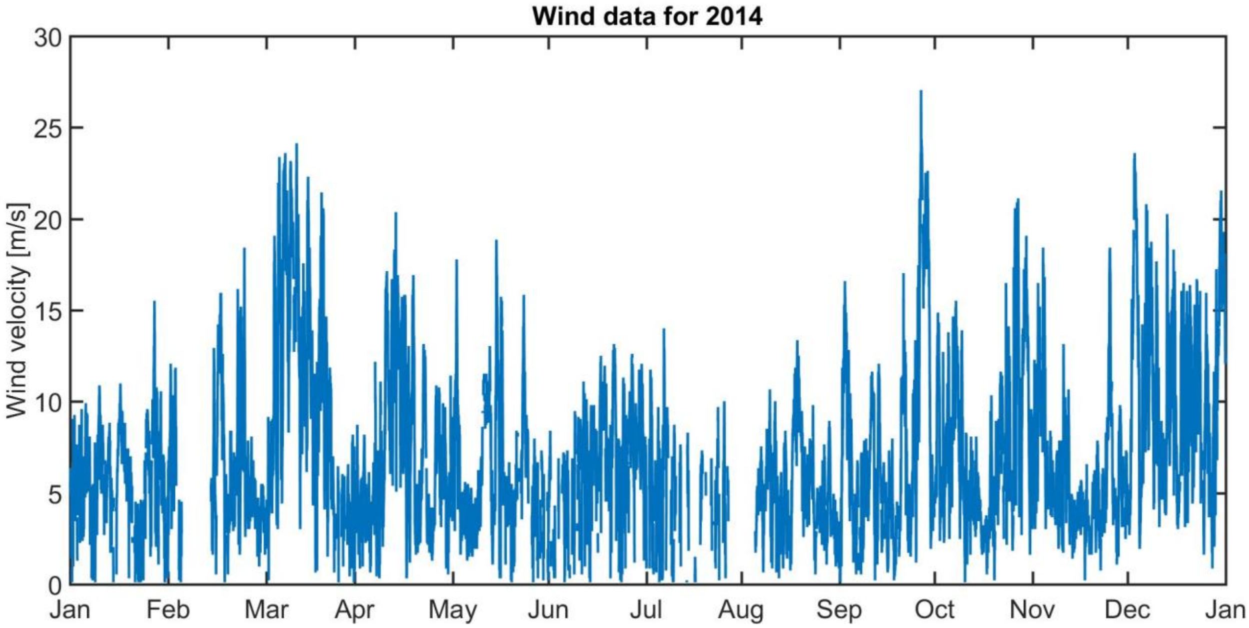


*Figure A.1: Wind data for 2014.*

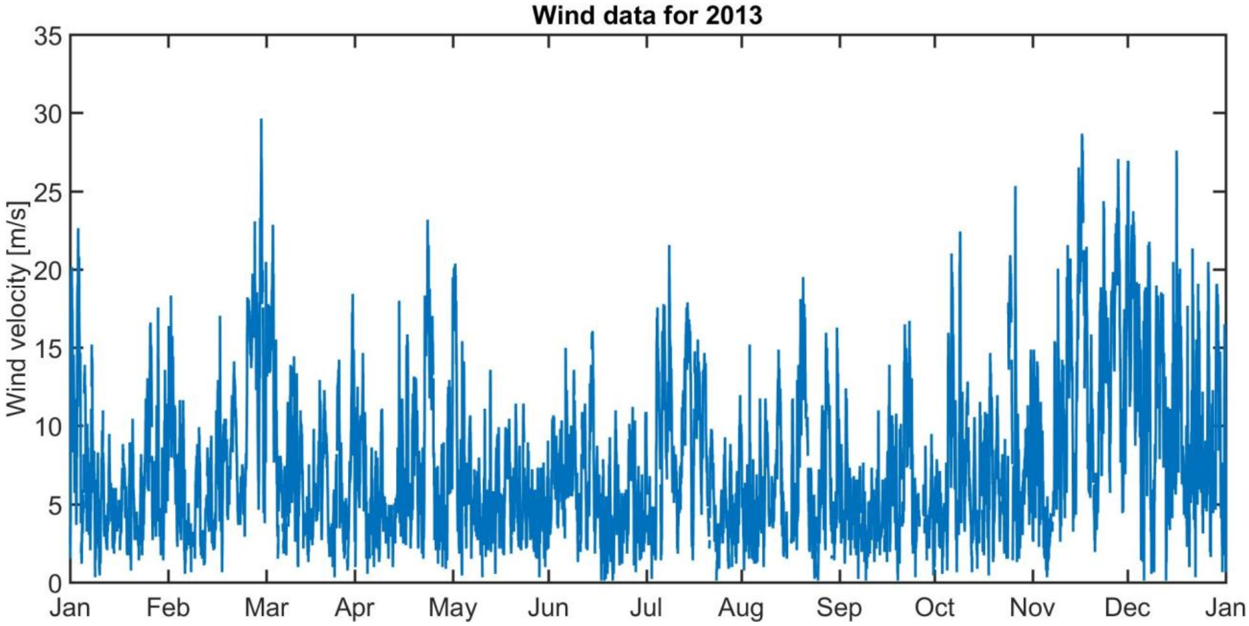


*Figure A.2: Wind data for 2013.*

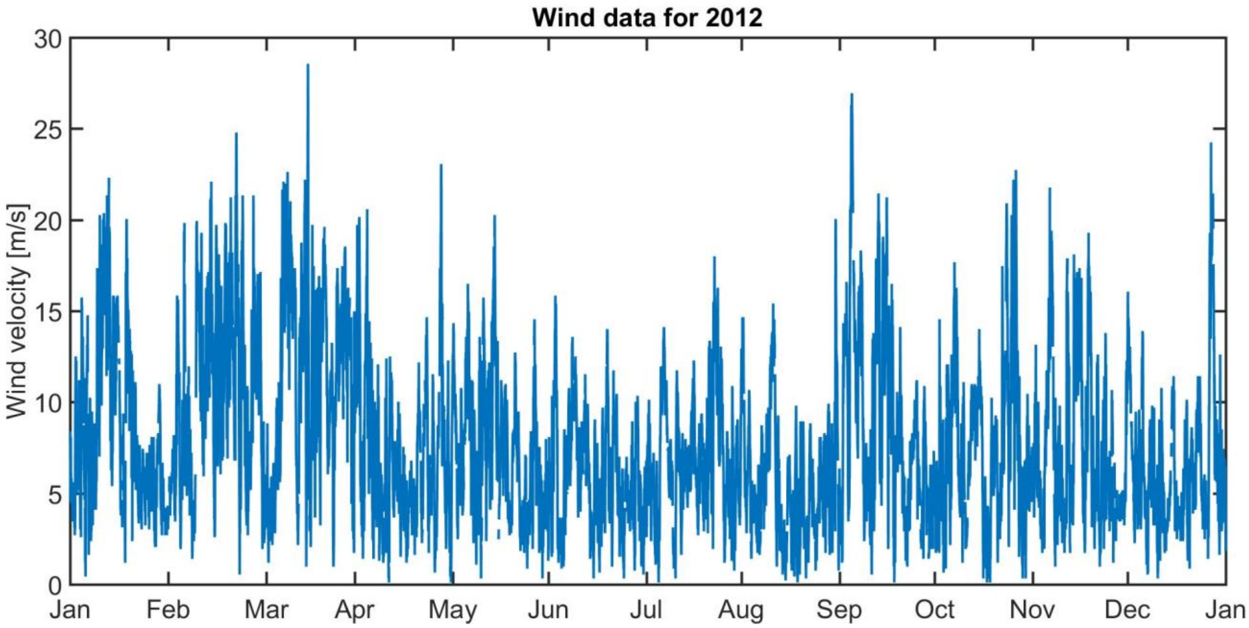


*Figure A.3: Wind data for 2012.*

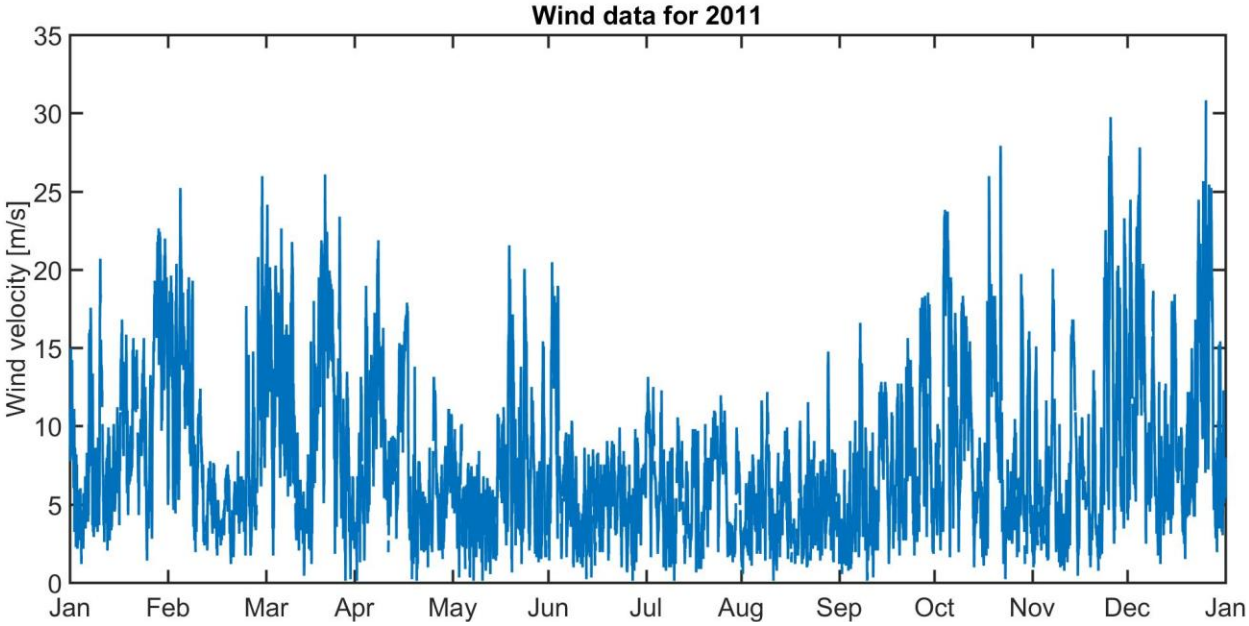


*Figure A.4: Wind data for 2011.*

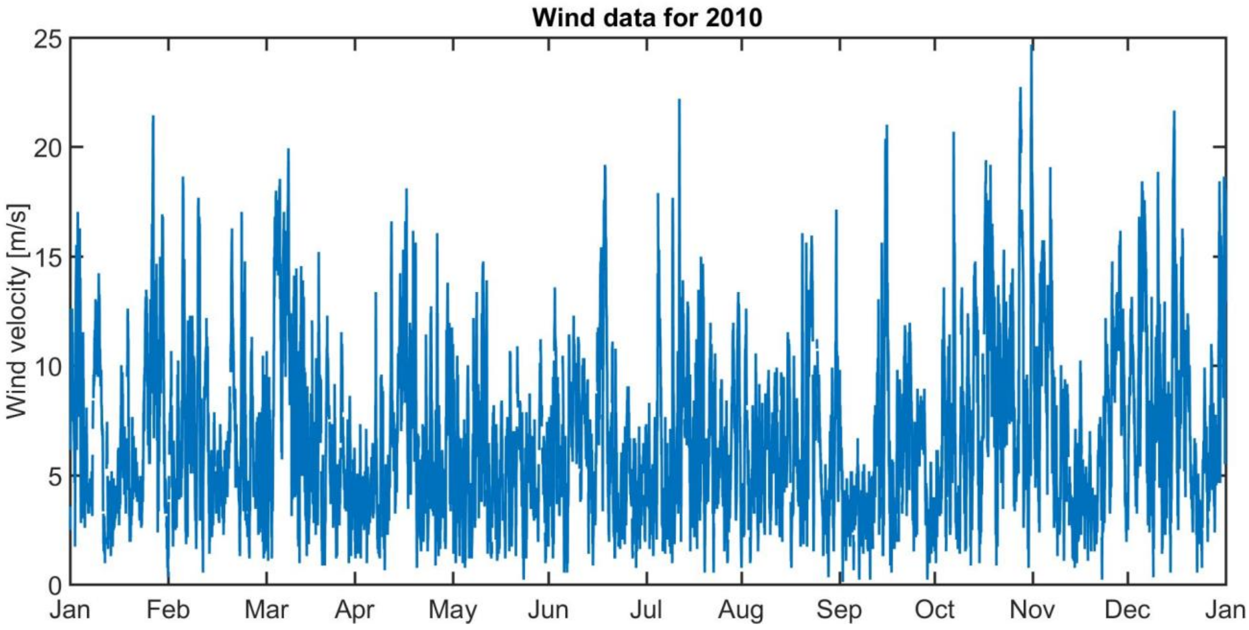


*Figure A.5: Wind data for 2010.*

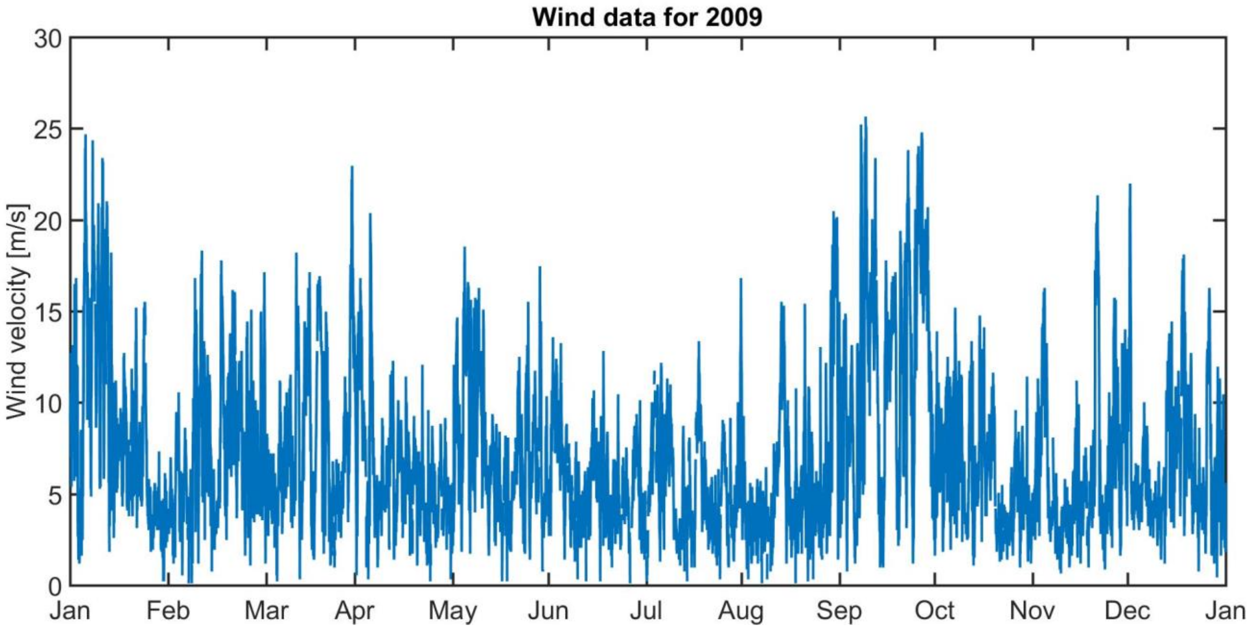


*Figure A.6: Wind data for 2009.*

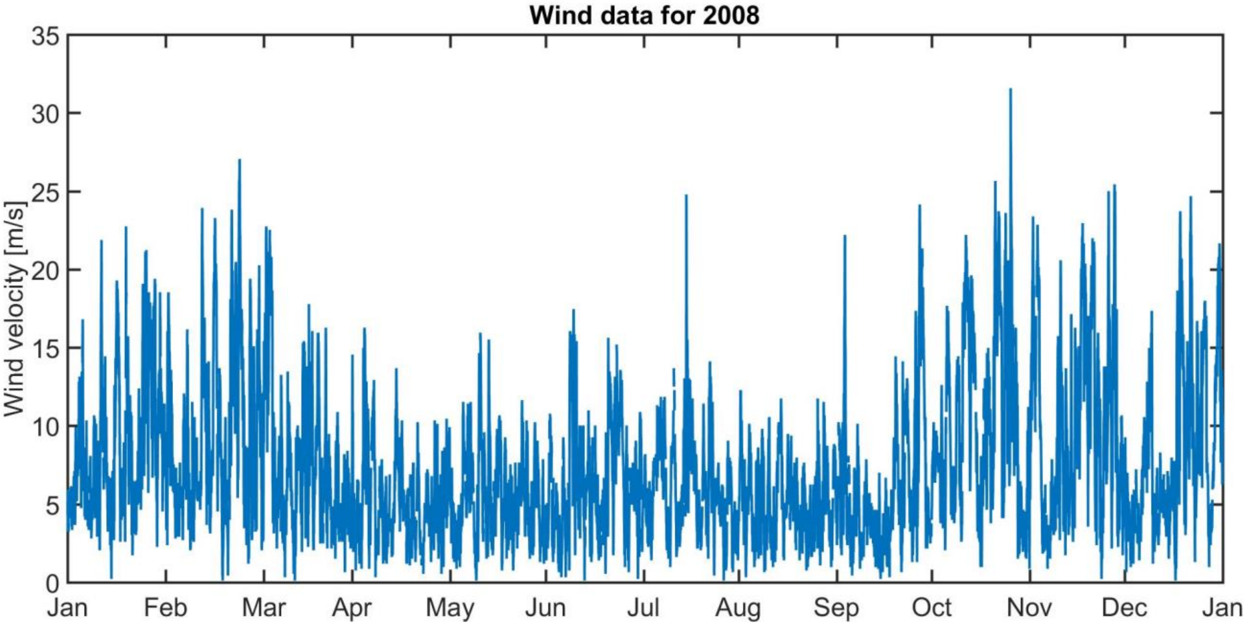


*Figure A.7: Wind data for 2008.*

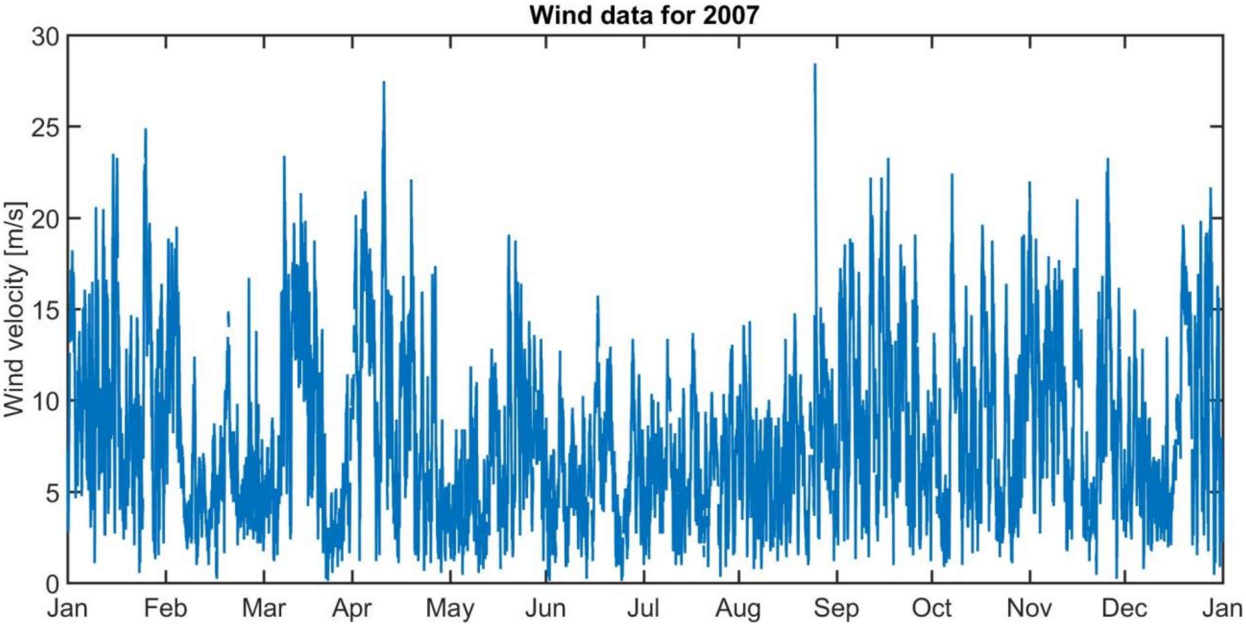


*Figure A.8: Wind data for 2007.*

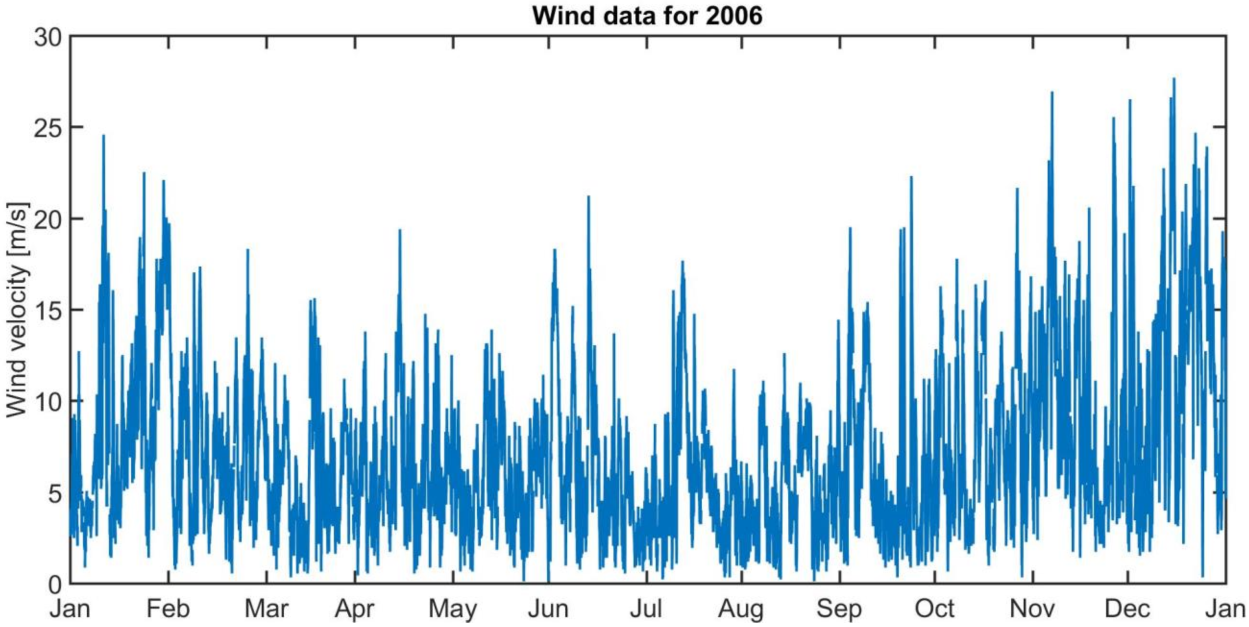


*Figure A.9: Wind data for 2006.*

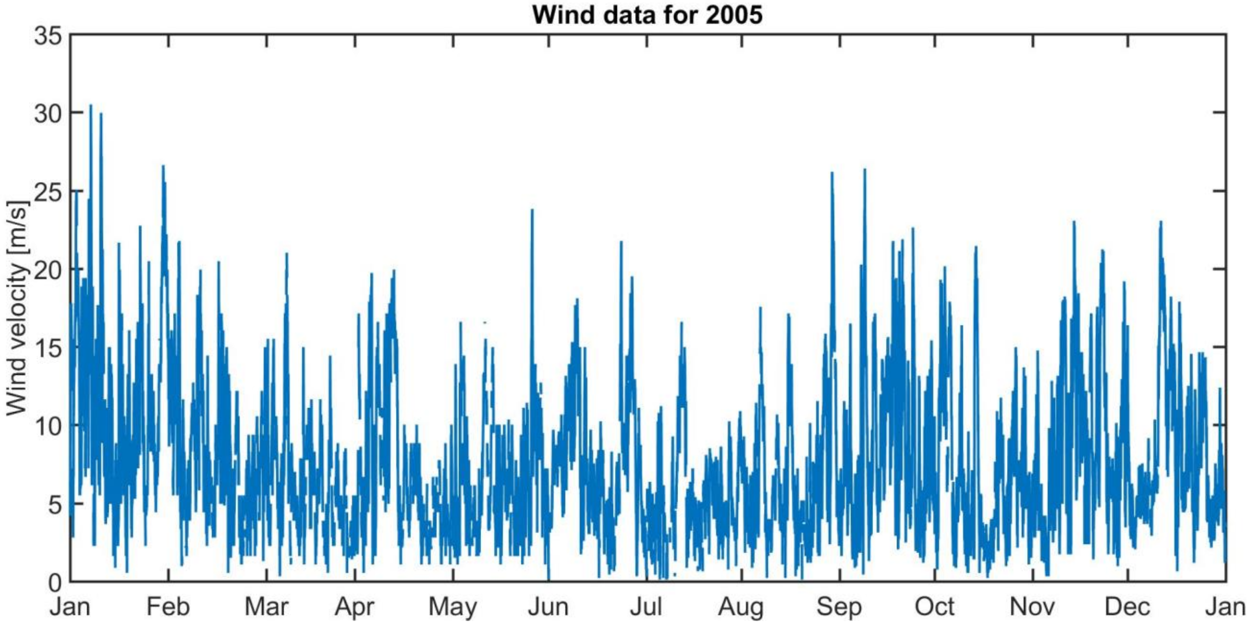


*Figure A.10: Wind data for 2005.*

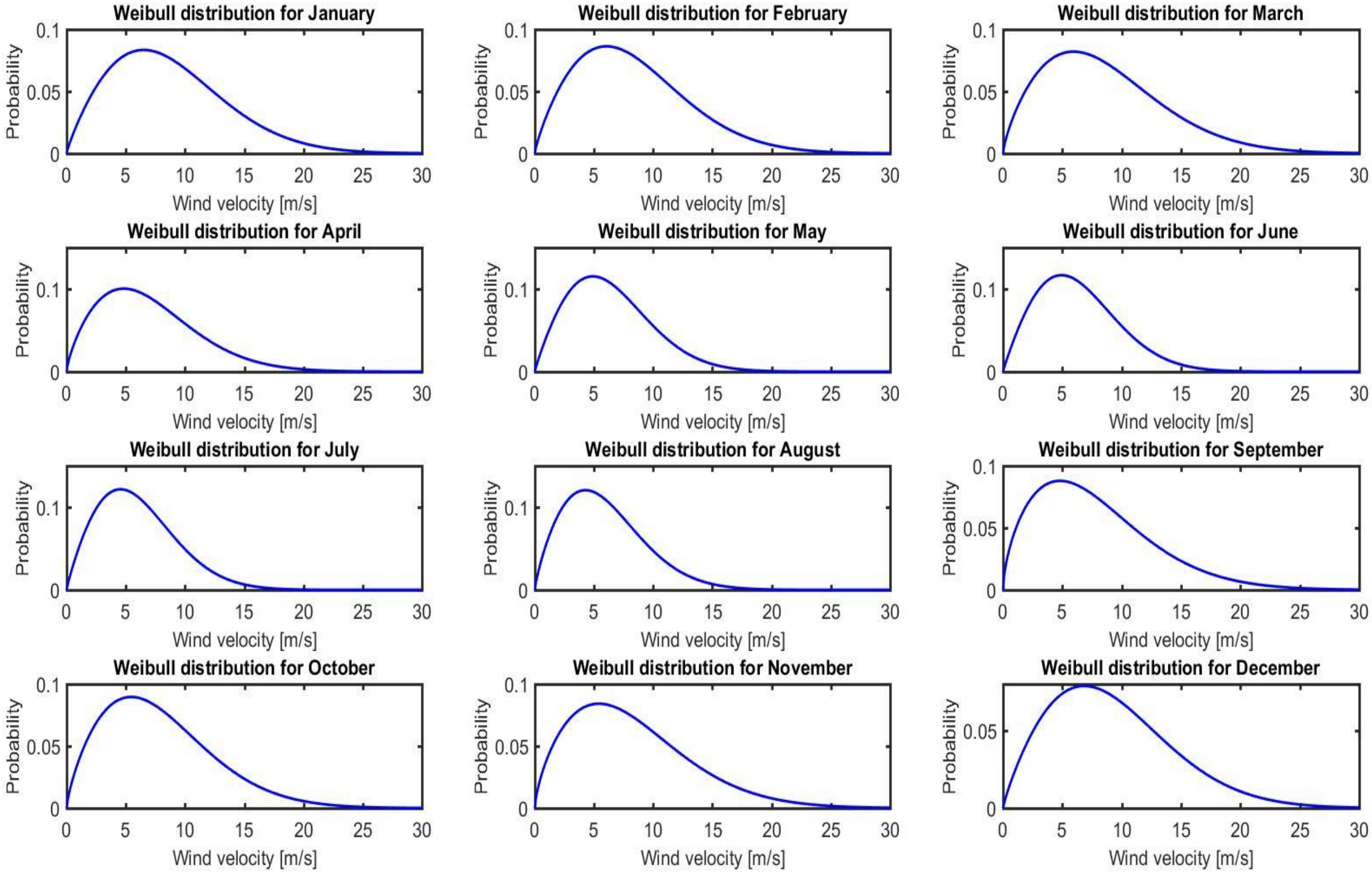


*Figure A.11: Weibull distribution for each month*

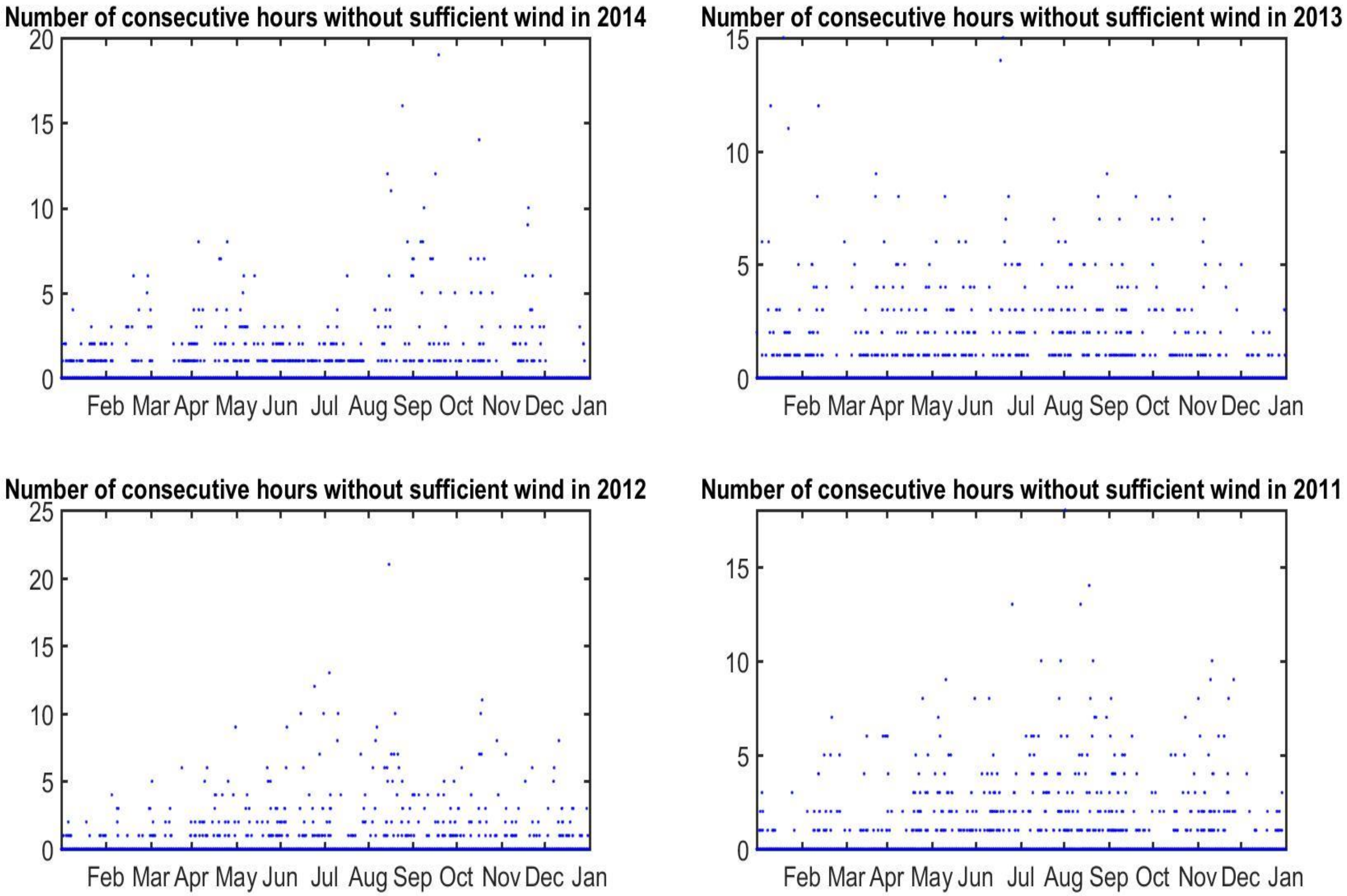


*Figure A 12: Number of consecutive hours without sufficient wind velocities for 2014 - 2011.*

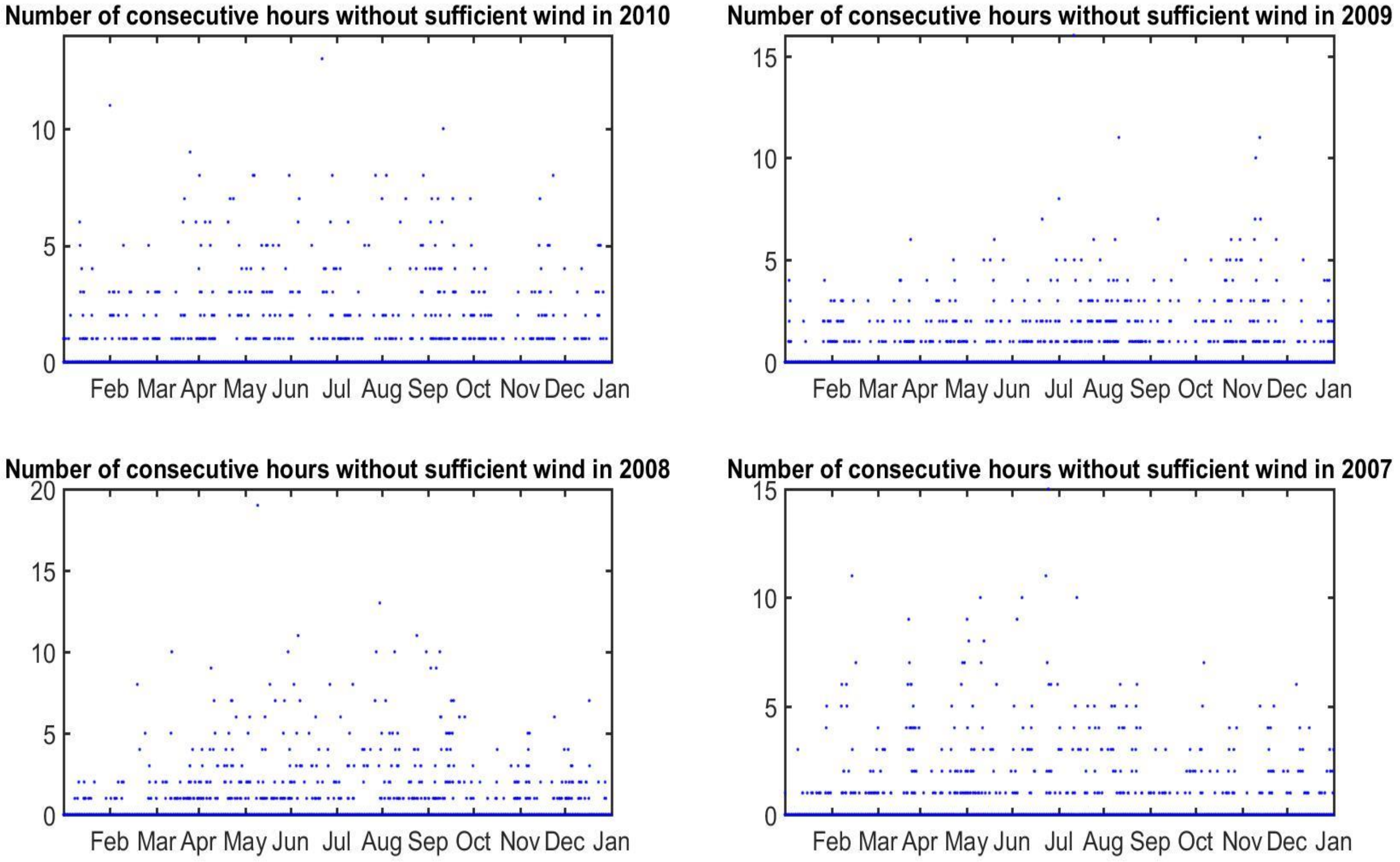
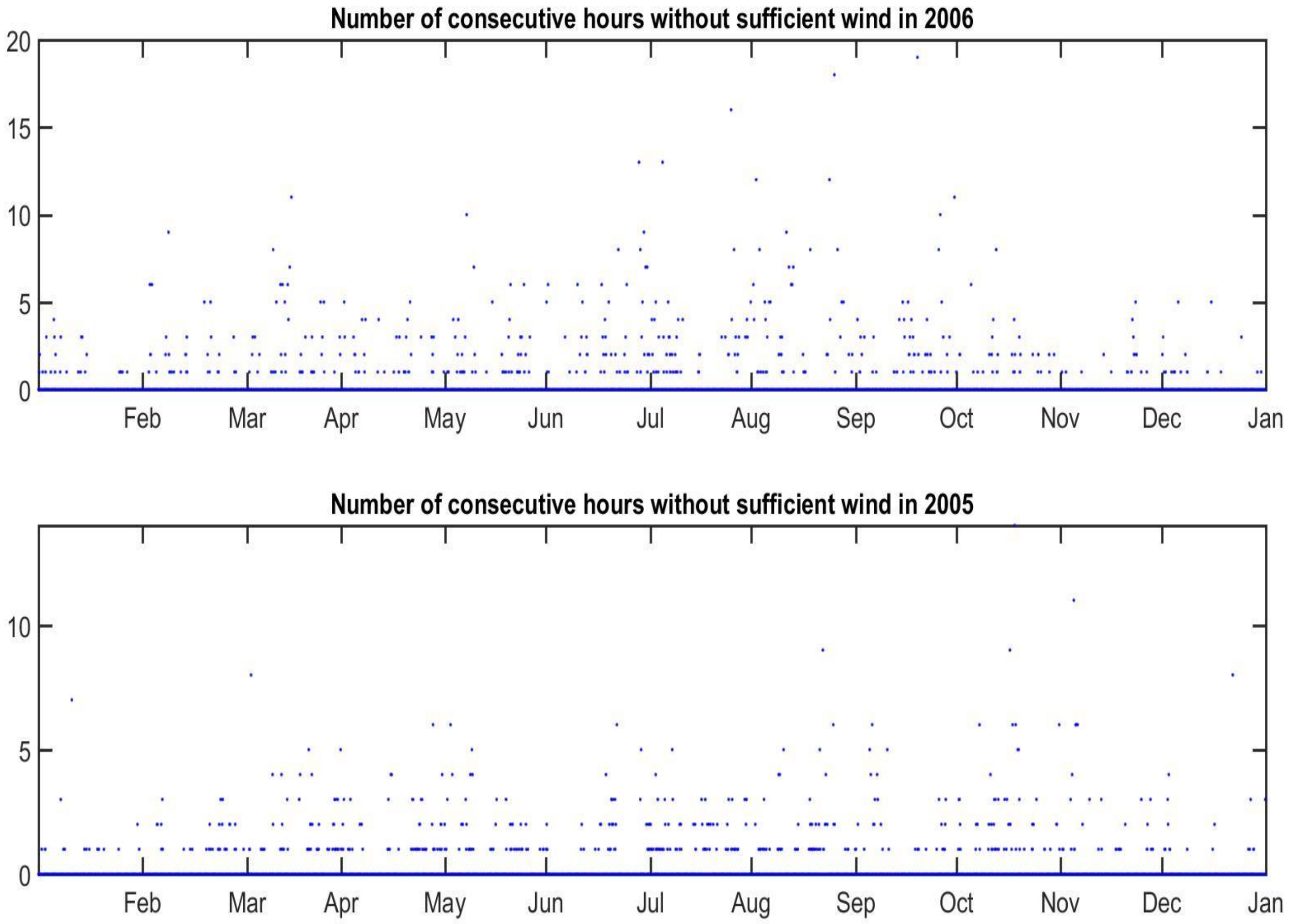


*Figure A 13: Number of consecutive hours without sufficient wind velocities for 2010 - 2007.*


Number of consecutive hours without sufficient wind in 2006

Number of consecutive hours without sufficient wind in 2005

*Figure A.14: Number of consecutive hours without sufficient wind velocities for 2006 and 2005.*

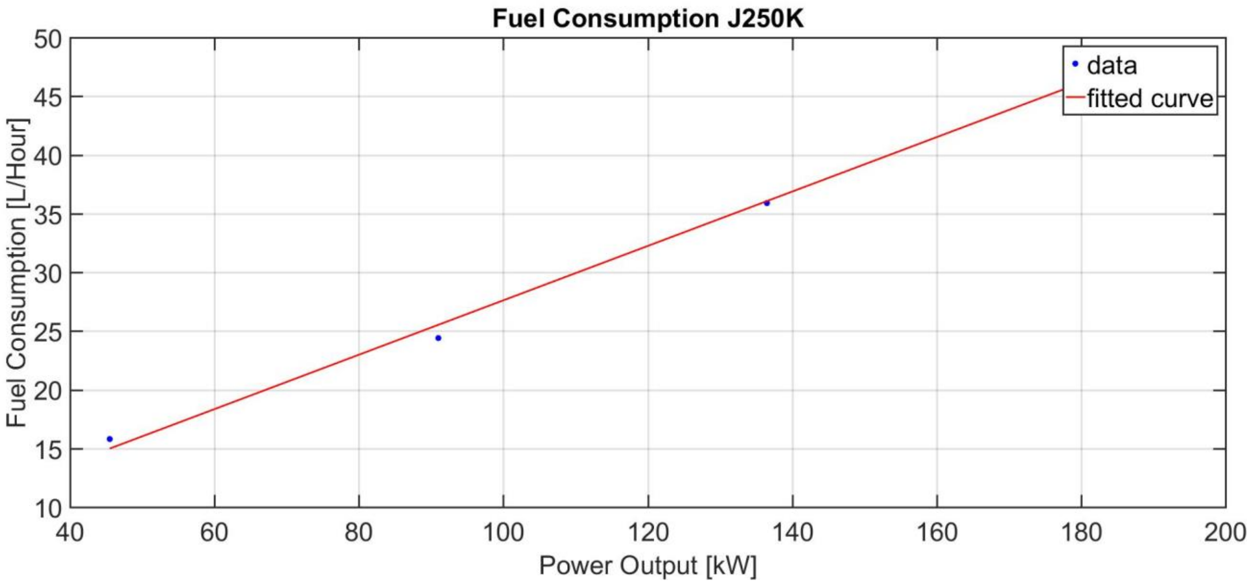


*Figure A.15: Fuel consumption per hour for the J250K generator as a function of the power output.*

# Appendix B

*Table B.1: Detailed system description for system 1.*

**System 1**

| **Wind Turbine** | **WES250** |
|---|---|
| Life expectancy | 20 years |
| Number of Blades | 2 |
| Rated Power | 250 kW |
| Rated Wind Speed | 13 m/s |
| Cut in Wind Speed | < 3 m/s |
| Cut out Wind Speed | 25 m/s |
| Grid Voltage | 400 V ± 10% |
| Grid Frequency | 50/60 Hz ± 3 Hz |
| Convter Type | Back-to-Back IGBT Converter |
| Generator Type | A-synchronous |
| Tower Height | 48 m |
| Yaw System | Active |
| **Battery System** | **PBES Energy 100** |
| Dimensions | W 896 mm, H 2550 mm, D 632 mm |
| Weight | 950 kg |
| Lifetime | 10 years |
| Energy | 100 kWh |
| Capacity | 112 Ah |
| Nominal Voltage | 888 VDC |
| Max Discharge Current | 336 A |
| Max Charge Current | 112 A |
| Efficiency (at 1C) | >97% |
| **Generator** | **SDMO J165K** |
| Frequency | 50 Hz |
| Voltage | 400/230 V |
| ESP | 132 kW |
| Dimensions | W 1114 mm, H 1470 mm, D 2370 mm |
| Dry Weight | 1578 kg |
| Speed(RPM) | 1500 |
| Power Factor | 0.8 |

*Table B.2: Detailed system description for system 2.*

**System 2**

| **Wind Turbine** | **WES100** |
|---|---|
| Life expectancy | 20 years |
| Number of Blades | 2 |
| Rated Power | 100 kW |
| Rated Wind Speed | 13 m/s |
| Cut in Wind Speed | < 3 m/s |
| Cut out Wind Speed | 25 m/s |
| Grid Voltage | 400 V ± 10% |
| Grid Frequency | 50/60 Hz ± 3 Hz |
| Convter Type | Back-to-Back IGBT Converter |
| Generator Type | A-synchronous |
| Tower Height | 48 m |
| Yaw System | Active |
| **Battery System** | **PBES Energy 100** |
| Dimensions | W 896 mm, H 2550 mm, D 632 mm |
| Weight | 950 kg |
| Lifetime | 10 years |
| Energy | 100 kWh |
| Capacity | 112 Ah |
| Nominal Voltage | 888 VDC |
| Max Discharge Current | 336 A |
| Max Charge Current | 112 A |
| Efficiency (at 1C) | >97% |
| **Generator** | **SDMO J165K** |
| Frequency | 50 Hz |
| Voltage | 400/230 V |
| ESP | 132 kW |
| Dimensions | W 1114 mm, H 1470 mm, D 2370 mm |
| Dry Weight | 1578 kg |
| Speed(RPM) | 1500 |
| Power Factor | 0.8 |

*Table B.3: Detailed system description for system 3.*

**System 3**

| **Wind Turbine** | **WES100** |
|---|---|
| Life expectancy | 20 years |
| Number of Blades | 2 |
| Rated Power | 100 kW |
| Rated Wind Speed | 13 m/s |
| Cut in Wind Speed | < 3 m/s |
| Cut out Wind Speed | 25 m/s |
| Grid Voltage | 400 V ± 10% |
| Grid Frequency | 50/60 Hz ± 3 Hz |
| Convter Type | Back-to-Back IGBT Converter |
| Generator Type | A-synchronous |
| Tower Height | 48 m |
| Yaw System | Active |
| **Battery System** | **PBES Power 65** |
| Dimensions | W 896 mm, H 2550 mm, D 632 mm |
| Weight | 950 kg |
| Lifetime | 10 years |
| Energy | 65 kWh |
| Capacity | 75 Ah |
| Nominal Voltage | 888 VDC |
| Max Discharge Current | 450 A |
| Max Charge Current | 225 A |
| Efficiency (at 1C) | >98% |
| **Generator** | **SDMO J165K** |
| Frequency | 50 Hz |
| Voltage | 400/230 V |
| ESP | 132 kW |
| Dimensions | W 1114 mm, H 1470 mm, D 2370 mm |
| Dry Weight | 1578 kg |
| Speed(RPM) | 1500 |
| Power Factor | 0.8 |

*Table B.4: Detailed system description for system 4.*

**System 4**

| **Wind Turbine** | **WES100** |
|---|---|
| Life expectancy | 20 years |
| Number of Blades | 2 |
| Rated Power | 100 kW |
| Rated Wind Speed | 13 m/s |
| Cut in Wind Speed | < 3 m/s |
| Cut out Wind Speed | 25 m/s |
| Grid Voltage | 400 V ± 10% |
| Grid Frequency | 50/60 Hz ± 3 Hz |
| Convter Type | Back-to-Back IGBT Converter |
| Generator Type | A-synchronous |
| Tower Height | 48 m |
| Yaw System | Active |
| **Generator** | **SDMO J165K** |
| Frequency | 50 Hz |
| Voltage | 400/230 V |
| ESP | 132 kW |
| Dimensions | W 1114 mm, H 1470 mm, D 2370 mm |
| Dry Weight | 1578 kg |
| Speed(RPM) | 1500 |
| Power Factor | 0.8 |

## Appendix C

```
%% Loads the required files
load('PowerForYear_Hour.mat')
load('Wind.mat')
load('ActivePowerTotalAvg.mat')
load('PowerForYear.mat')

%% Creating functions for the power curves for 80 kW, 100 kW, and 250 kW WES
turbines and fuel consumption.
WES80 = [0 0 0 0 2.9 6 11 17.7 27.3 39.2 51.4 63.8 74.2 79.9 82.2 82.9 83.3
83.3 83 83 83];
Wind80 = [0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20];
WES100 = [0 0 0 1 2.9 6 11 17.7 27.3 39.2 53.8 68.4 82.8 89.1 95.9 98.7 99.5
100 100 100 100 100 100 100 100];
Wind100 = [0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24];
WES250 = [0 0 0 1 4.4 14.9 29.3 56.3 77.2 115.8 145 179 222 250 250 250 250
250];
Wind250 = [0 1 2 3 4 5 6 7 8 9 10 11 12 12.5 13 14 15 16];

FuelConsumption_88 = [19.5 14 10 5.99];
FuelConsumption_X_88 = [64 48 32 16];
FuelConsumption_165 = [33.5 25 17 10.29];
FuelConsumption_X_165 = [132 99 66 33];
FuelConsumption_250 = [47.10 35.9 24.4 15.8];
FuelConsumption_X_250 = [182 136.5 91 45.5];


[xData, yData] = prepareCurveData( Wind80, WES80 );
ft = fittype( 'smoothingspline' );
[fitresult_80, gof3] = fit( xData, yData, ft );

[xData, yData] = prepareCurveData( Wind100, WES100 );
ft = fittype( 'smoothingspline' );
[fitresult_100, gof] = fit( xData, yData, ft );

[xData, yData] = prepareCurveData( Wind250, WES250 );
ft = fittype( 'smoothingspline' );
[fitresult_250, gof2] = fit( xData, yData, ft );

[fitFuelConsumption_88, gof_88] = fit( transpose(FuelConsumption_X_88),
transpose(FuelConsumption_88), 'poly1' );
[fitFuelConsumption_165, gof_165] = fit( transpose(FuelConsumption_X_165),
transpose(FuelConsumption_165), 'poly1' );
[fitFuelConsumption_250, gof_250] = fit( transpose(FuelConsumption_X_250),
transpose(FuelConsumption_250), 'poly1' );
%% Defining lists.
Renewable_Penetration(1:10) = 0;
Emissions_Cut(1:10) = 0;
Controll_List(1:10) = 0;
FuelPrice_Reduction(1:10) = 0;
WindProd_List(1:10) = 0;
DieselGenerator_List(1:10) = 0;
BatteryDeliver_List(1:10) = 0;
```

```
DumpLoad_List(1:10) = 0;
Maintenance_Cost_WindTurbine(1:10) = 0;
Wind_Percent_List(1:10) = 0;
DieselGen_Percent_List(1:10) = 0;
Battery_Percent_List(1:10) = 0;
Losses_List(1:10) = 0;
Table_List(9, 10) = 0;

u = input('Annual E.D? ');
%% Assuming the battery is delivered at 60% of its capacity.
Battery_Capacity = input('Battery Capacity[kWh]?: ');
Battery(1) = Battery_Capacity*0.6;

WindSpeed(1:8760) = 0;
Power(1:8760) = 0;
%% for loop for the years 2005 - 2014.
for i = 1 : 10;
    WindPowerProd(1:length(PowerForYear_Hour)) = 0;
    DieselGenerator(1:length(PowerForYear_Hour)) = 0;
    Battery(1:length(PowerForYear_Hour)) = 0;
    Battery_Deliver(1:length(PowerForYear_Hour)) = 0;
    DumpLoad(1:length(PowerForYear_Hour)) = 0;
    Battery_Charge(1:length(PowerForYear_Hour)) = 0;
    Wind_Percent(1:length(PowerForYear_Hour)) = 0;
    DieselGen_Percent(1:length(PowerForYear_Hour)) = 0;
    Battery_Percent(1:length(PowerForYear_Hour)) = 0;
    Power = u*PowerForYear_Hour;
    FuelFlow_Old(1:length(PowerForYear_Hour)) = 0;
    FuelFlow_New(1:length(PowerForYear_Hour)) = 0;
    Losses(1:length(PowerForYear_Hour)) = 0;
    %% Cycling through the years of wind readings
    if i == 2
        WindSpeed = WindFor2006(:,5);
    elseif i == 3
        WindSpeed = WindFor2007(:,5);
    elseif i == 4
        WindSpeed = WindFor2008(:,5);
    elseif i == 5
        WindSpeed = WindFor2009(:,5);
    elseif i == 6
        WindSpeed = WindFor2010(:,5);
    elseif i == 7
        WindSpeed = WindFor2011(:,5);
    elseif i == 8
        WindSpeed = WindFor2012(:,5);
    elseif i == 9
        WindSpeed = WindFor2013(:,5);
    elseif i == 10
        WindSpeed = WindFor2014(:,5);
    else
        WindSpeed = WindFor2005(:,5);
    end
   %% Excluding eventd without wind measurements
    I = isnan(WindSpeed);
    Power(I) = nan;
    for n = 2 : length(PowerForYear_Hour)
```

```
       %% Skipping events without wind reading while still keeping the same
energy stored in the battery.
       if isnan(WindSpeed(n))
           Battery(n) = Battery(n-1);
           continue
       elseif WindSpeed(n) < 3 || WindSpeed(n) > 25
           WindPowerProd(n) = 0;
       else
           WindPowerProd(n) = fitresult_100(WindSpeed(n)); % The wind power
produced from the turbine, fitresult_100 = 100 kW turbine, _250 = 250 kW
turbine.
       end

       if WindPowerProd(n) < 0
           WindPowerProd(n) = 0;
       end
       rest = Power(n) - WindPowerProd(n);
       if rest > 0
          Wind_Percent(n) = WindPowerProd(n);
       else
           Wind_Percent(n) = Power(n);
       end
       Battery_Check = Battery(n-1)/Battery_Capacity;
       %% if statement for energy flow
       if rest > 0 && Battery_Check > 0.20  % if statement to check if the
battery can provide power (DoD of 80%).
           Battery_Discharge = (Battery(n-1) - Battery_Capacity*0.20); % How
much power can the battery provide.
           if Battery_Discharge > rest/sqrt(0.8) % Because of the losses in
the battery package, the battery has to provide more power than what the load
demand.
               Battery_Deliver(n) = rest;
               Battery_Percent(n) = rest/Power(n);
               Battery(n) = Battery(n-1) - rest/sqrt(0.8); % How much power
thats stored in the battery after discharge. 80% = Round trip efficiency,
half the power is lost during discharge and half during charge.
               Losses(n) = rest/sqrt(0.8) - rest;
           else % In cases where the battery only can provide some of the
power, the diesel generator provides the rest.
               Battery_Deliver(n) = Battery_Discharge*sqrt(0.8);
               Battery_Percent(n) = Battery_Deliver(n)/Power(n);
               Battery(n) = Battery_Capacity*0.20;
               Losses(n) = Battery_Discharge*(1 - sqrt(0.8));
               DieselGenerator(n) = rest - Battery_Deliver(n);
               DieselGen_Percent(n) = DieselGenerator(n)/Power(n);
           end
       elseif rest > 0 && Battery_Check <= 0.20 % if the battery can't
provide the remaining energy demand.
           DieselGenerator(n) = rest;
           DieselGen_Percent(n) = DieselGenerator(n)/Power(n);
           Battery(n) = Battery(n-1);
       elseif rest < 0 && Battery_Check < 0.95 % if statement to check if the
battery is under 95% of stored capacity.
           Battery_C = Battery_Capacity*0.95 - Battery(n-1); % How much
energy the battery can store without exceed the 95% safety limit.
           C_rest = abs(rest);
           if Battery_C > C_rest*sqrt(0.8)
```

```
               Battery(n) = Battery(n-1) + C_rest*sqrt(0.8);
               Battery_Charge(n) = C_rest*sqrt(0.8);
               Losses(n) = C_rest*(1 - sqrt(0.8));
           else
               Battery(n) = Battery(n-1) + Battery_C;
               Battery_Charge(n) = Battery_C;
               DumpLoad(n) = C_rest - Battery_C/sqrt(0.8);
           end
       elseif rest < 0 && Battery_Check >= 0.95 % if the battery can't stored
the superfluous power its directed to the dump load.
           DumpLoad(n) = -rest;
           Battery(n) = Battery(n-1);
       else
           DumpLoad(n) = -rest;
           Battery(n) = Battery(n-1);
       end
    end
    Controll_List(i) = sum(WindPowerProd, 'omitnan') + sum(DieselGenerator,
'omitnan') + sum(Battery_Deliver, 'omitnan') - sum(Battery_Charge, 'omitnan')
- sum(DumpLoad, 'omitnan') - sum(Power, 'omitnan') - sum(Losses,
'omitnan')*0.5;
    Losses_List(i) = sum(Losses, 'omitnan');
    Wind_Percent_List(i) = (sum(Wind_Percent, 'omitnan')/sum(Power,
'omitnan'))*100;
    DieselGen_Percent_List(i) = (sum(DieselGenerator, 'omitnan')/sum(Power,
'omitnan'))*100;
    Battery_Percent_List(i) = (sum(Battery_Deliver, 'omitnan')/sum(Power,
'omitnan'))*100;
    %% Storing the total energy for component for each year.
    WindProd_List(i) = sum(WindPowerProd, 'omitnan')*10^-3;
    DieselGenerator_List(i) = sum(DieselGenerator, 'omitnan')*10^-3;
    BatteryDeliver_List(i) = sum(Battery_Deliver, 'omitnan')*10^-3;
    DumpLoad_List(i) = sum(DumpLoad, 'omitnan')*10^-3;
    %% Determing the fuel consumption, emissions, renewable penetration and
emissions reduction.
    for n = 1 : length(PowerForYear_Hour)
        if u*PowerForYear_Hour(n) > 132
           FuelFlow_Old(n) = fitFuelConsumption_250(u*PowerForYear_Hour(n));
        elseif u*PowerForYear_Hour(n) > 64
            FuelFlow_Old(n) = fitFuelConsumption_165(u*PowerForYear_Hour(n));
        else
            FuelFlow_Old(n) = fitFuelConsumption_88(u*PowerForYear_Hour(n));
        end

        if DieselGenerator(n) ~= 0 && ~isnan(DieselGenerator(n))
            FuelFlow_New(n) = fitFuelConsumption_165(DieselGenerator(n));
        end
    end
    Emissions_CO2_Old = sum(FuelFlow_Old)*10^-3*860*3.2;
    Emissions_CO2 = sum(FuelFlow_New)*10^-3*860*3.2;
    Fuel_Reduction = sum(FuelFlow_Old) - sum(FuelFlow_New, 'omitnan');
    CO2_Reduction = (1 - (Emissions_CO2/Emissions_CO2_Old))*100;

    RP = (1 - sum(DieselGenerator, 'omitnan')/sum(Power, 'omitnan'));
    Renewable_Penetration(i) = RP*100;
    Emissions_Cut(i) = CO2_Reduction;
```

```
    FuelPrice_Reduction(i) = Fuel_Reduction*8;
    %% Creating the table for printing
    Table_List(1,i) = sum(WindPowerProd, 'omitnan')*10^-3;
    Table_List(2,i) = Wind_Percent_List(i);
    Table_List(3,i) = sum(DieselGenerator, 'omitnan')*10^-3;
    Table_List(4,i) = DieselGen_Percent_List(i);
    Table_List(5,i) = sum(Battery_Deliver, 'omitnan')*10^-3;
    Table_List(6,i) = Battery_Percent_List(i);
    Table_List(7,i) = sum(DumpLoad, 'omitnan')*10^-3;
    Table_List(8,i) = RP*100;
    Table_List(9,i) = CO2_Reduction;

    Maintenance_Cost_WindTurbine(i) = sum(WindPowerProd, 'omitnan')*0.14;
end
%% Creating normal distribution for the different variables.
pRenewablePenetration = fitdist(transpose(Renewable_Penetration), 'Normal');
pEmissionsCut = fitdist(transpose(Emissions_Cut), 'Normal');
pFuelPrice_Reduction = fitdist(transpose(FuelPrice_Reduction), 'Normal');
pWindProd = fitdist(transpose(WindProd_List), 'Normal');
pDieselProd = fitdist(transpose(DieselGenerator_List), 'Normal');
pBatteryDeliver = fitdist(transpose(BatteryDeliver_List), 'Normal');
pDumpLoad = fitdist(transpose(DumpLoad_List), 'Normal');
pWind_Percent = fitdist(transpose(Wind_Percent_List), 'Normal');
pDiesel_Percent = fitdist(transpose(DieselGen_Percent_List), 'Normal');
pBattery_Percent = fitdist(transpose(Battery_Percent_List), 'Normal');

yRenewablePenetration = pdf(pRenewablePenetration, 60:0.1:100);
yEmissionsCut = pdf(pEmissionsCut, 50:0.1:100);
yFuelPrice_Reduction = pdf(pFuelPrice_Reduction, 500000:1000:700000);
yWindProd = pdf(pWindProd, 150:1:350);
yDieselProd = pdf(pDieselProd, 10:0.1:30);
yBatteryDeliver = pdf(pBatteryDeliver, 0:0.1:15);
yDumpLoad = pdf(pDumpLoad, 200:1:900);
yWind_Percent = pdf(pWind_Percent, 40:0.1:90);
yDiesel_Percent = pdf(pDiesel_Percent, 5:0.1:50);
yBattery_Percent = pdf(pBattery_Percent, 0:0.1:20);
%% Plots
figure(1)
subplot(1,2,1)
plot(60:0.1:100, yRenewablePenetration, 'b')
title('Renewable Penetration')
ylabel('Probability')
xlabel('Renewable Penetration[%]')
xlim([60 90])
subplot(1,2,2)
plot(50:0.1:100, yEmissionsCut, 'b')
title('Cuts in Emissions')
ylabel('Probability')
xlabel('Cut in Emissions[%]')
xlim([55 90])

figure(2)
subplot(2,2,1)
plot(40:0.1:90, yWind_Percent, 'b')
title('Energy Covered by Wind Turbine')
ylabel('Probability')
```

```
xlabel('% of Energy Demand Covered')
xlim([40 90])
subplot(2,2,2)
plot(5:0.1:50, yDiesel_Percent, 'b')
title('Energy Covered by the Generator')
ylabel('Probability')
xlabel('% of Energy Demand Covered')
xlim([5 50])
subplot(2,2,3)
plot(0:0.1:20, yBattery_Percent, 'b')
title('Energy Covered by the Battery')
ylabel('Probability')
xlabel('% of Energy Demand Covered')
xlim([0 20])
subplot(2,2,4)
plot(200:1:900, yDumpLoad, 'b')
title('Total Power Delivered to the Dump Load')
ylabel('Probability')
xlabel('MWh')
xlim([50 300])
%% Displaying the annual results and 95% CI
printmat(transpose(Table_List), 'Energy Distribution' , '2005 2006 2007 2008
2009 2010 2011 2012 2013 2014', 'Wind[MWh] %Coverbywind DieselGenerator[MWh]
%CoveredbyGen BatteryDeliver[MWh] %CoveredbyBattery DumpLoad[MWh]
RenewablePentration Emissions_Cut')
disp(['95% CI Renewable Penetration: ', num2str(pRenewablePenetration.mu) '
+- ' num2str(2*pRenewablePenetration.sigma)])
disp(['95% CI Emissions Reduction: ', num2str(pEmissionsCut.mu) ' +- '
num2str(2*pEmissionsCut.sigma)])
disp(['95% CI Fuel Cost Reduction: ', num2str(pFuelPrice_Reduction.mu) ' +- '
num2str(2*pFuelPrice_Reduction.sigma)])
disp(['95% CI WindProd: ', num2str(pWindProd.mu) ' +- '
num2str(2*pWindProd.sigma)])
disp(['95% CI DieselGenerator: ', num2str(pDieselProd.mu) ' +- '
num2str(2*pDieselProd.sigma)])
disp(['95% CI BatteryDeliver: ', num2str(pBatteryDeliver.mu) ' +- '
num2str(2*pBatteryDeliver.sigma)])
disp(['95% CI Dump Load: ', num2str(pDumpLoad.mu) ' +- '
num2str(2*pDumpLoad.sigma)])
disp(['95% CI Wind Percent: ', num2str(pWind_Percent.mu) ' +- '
num2str(2*pWind_Percent.sigma)])
disp(['95% CI Diesel Percent: ', num2str(pDiesel_Percent.mu) ' +- '
num2str(2*pDiesel_Percent.sigma)])
disp(['95% CI Battery_Percent: ', num2str(pBattery_Percent.mu) ' +- '
num2str(2*pBattery_Percent.sigma)])
t = 1:1:length(PowerForYear_Hour);
%% Plot
figure(3)
subplot(2,2,1)
plot(t, WindPowerProd)
title('Wind Power Produced For 2014')
ylabel('kW')
xlim([0 length(t)])
set(gca, 'XTick', [0 744 1416 2160 2880 3624 4344 5088 5832 6552 7296 8016
8760])
```

```
set(gca, 'XTickLabel',
{'January','February','March','April','May','June','July','August','September
','October','November','December'})
set(gca,'XTickLabelRotation',90)
subplot(2,2,2)
plot(t,DieselGenerator)
title('Diesel Generator Produced For 2014')
ylabel('kW')
xlim([0 length(t)])
set(gca, 'XTick', [0 744 1416 2160 2880 3624 4344 5088 5832 6552 7296 8016
8760])
set(gca, 'XTickLabel',
{'January','February','March','April','May','June','July','August','September
','October','November','December'})
set(gca,'XTickLabelRotation',90)
subplot(2,2,3)
plot(t, Battery_Deliver)
title('Power Delivered by Battery For 2014')
ylabel('kW')
xlim([0 length(t)])
set(gca, 'XTick', [0 744 1416 2160 2880 3624 4344 5088 5832 6552 7296 8016
8760])
set(gca, 'XTickLabel',
{'January','February','March','April','May','June','July','August','September
','October','November','December'})
set(gca,'XTickLabelRotation',90)
subplot(2,2,4)
plot(t, DumpLoad)
title('Power Delivered to Dump Load For 2014')
ylabel('kW')
xlim([0 length(t)])
set(gca, 'XTick', [0 744 1416 2160 2880 3624 4344 5088 5832 6552 7296 8016
8760])
set(gca, 'XTickLabel',
{'January','February','March','April','May','June','July','August','September
','October','November','December'})
set(gca,'XTickLabelRotation',90)
%% Calculating costs, present value and payback time.
Price_WindTurbine = input('Wind Turbine Price? ');
Price_Per_kWh_Battery = 209*8; % Price per kWh in dollars times the exchange
rate from $ to NOK.
Battery_Costs = Battery_Capacity*Price_Per_kWh_Battery + 218000; % The total
costs for the battery package.
Installation_Costs = 1240000; % Including cost for cables.
Maintenance_Costs = mean(Maintenance_Cost_WindTurbine, 'omitnan'); %
Maintenance cost for the wind turbine, 0.14 NOK per kWh.
Yearly_Savings = pFuelPrice_Reduction.mu - Maintenance_Costs;
TotalInvestmentCost = Price_WindTurbine + Installation_Costs + Battery_Costs;
% Present value with and without financial support.
PresentValue_10 = pvvar([-TotalInvestmentCost Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings], 0.055);
PresentValue_20 = pvvar([-TotalInvestmentCost Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings (pFuelPrice_Reduction.mu - Battery_Costs -
Maintenance_Costs) Yearly_Savings Yearly_Savings Yearly_Savings
```

```
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings], 0.055);
PresentValue_10_Sup = pvvar([-TotalInvestmentCost*0.70 Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings], 0.055);
PresentValue_20_Sup = pvvar([-TotalInvestmentCost*0.70 Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings (pFuelPrice_Reduction.mu -
Battery_Costs - Maintenance_Costs) Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings Yearly_Savings
Yearly_Savings Yearly_Savings Yearly_Savings], 0.055);
disp(['Present Value for 10 Years: ', num2str(PresentValue_10)])
disp(['Present Value for 20 Years: ', num2str(PresentValue_20)])
disp(['Present Value for 10 Years_Sup: ', num2str(PresentValue_10_Sup)])
disp(['Present Value for 20 Years_Sup: ', num2str(PresentValue_20_Sup)])

% Payback time calculations.
PayBack_Check = TotalInvestmentCost;
Years = 0;
while PayBack_Check > Yearly_Savings
   PayBack_Check = PayBack_Check - Yearly_Savings;
   Years = Years + 1;
end
Years = Years + PayBack_Check/Yearly_Savings;

PayBack_Check_Sup = TotalInvestmentCost*0.7;
Years_Sup = 0;
while PayBack_Check_Sup > Yearly_Savings
   PayBack_Check_Sup = PayBack_Check_Sup - Yearly_Savings;
   Years_Sup = Years_Sup + 1;
end
Years_Sup = Years_Sup + PayBack_Check_Sup/Yearly_Savings;
LCOE = (TotalInvestmentCost + (sum(FuelFlow_Old)*8-
pFuelPrice_Reduction.mu)*20 + Maintenance_Costs*20 +
Battery_Costs)/(sum(Power, 'omitnan')*20); %LCOE for 20 years without
financial support
LCOE_Sup = (TotalInvestmentCost*0.7 + (sum(FuelFlow_Old)*8-
pFuelPrice_Reduction.mu)*20 + Maintenance_Costs*20 +
Battery_Costs)/(sum(Power, 'omitnan')*20); %LCOE for 20 years with financual
support
disp(['Pay Back Time: ', num2str(Years)])
disp(['Pay Back Time With Sup: ', num2str(Years_Sup)])
disp(['LCOE: ', num2str(LCOE)])
disp(['LCOE Sup: ', num2str(LCOE_Sup)])
```