Department of Mechanical and Aerospace Engineering

Investigating Off-Grid Energy Solutions for the Salmon Farming Industry

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Signed: *Helleik L. Syse*   Date: 31.08.2016

Abstract

Approximately half of all Norwegian fish farms use diesel generators to produce the electricity needed. The use of diesel generators could be greatly reduced by incorporating renewable energy generation. This thesis investigates potential renewable energy solutions for the fish farming industry.

The salmon farming industry was chosen as the object of study, because it is by far the largest part of Norwegian aquaculture. The history, current status and the future of salmon farming will be discussed. Potential renewable energy sources and storage options are outlined. Wind and solar power were found to be the best options available in today's market.

To evaluate potential renewable energy systems, the software tool HOMER energy was used. Electrical demand profiles for a typical Norwegian salmon farm was not available and had to be created from incomplete measured data and interviews. Three different systems were evaluated: A pure diesel generator system, a hybrid energy system and a 100% renewable energy system.

The evaluation showed that a hybrid energy system provided electricity at the lowest cost of these three systems over a 20-year period. To meet an average of 341.92 kWh per day, the system incorporated following components: 14 kW of installed wind turbine capacity, 35 kW of PV, 146 kWh's of Li-Ion batteries and two diesel generators (130 kW and 10 kW). With this system configuration, 34% of the electricity came from renewable energy sources. This system was found to have a 16% lower net present cost than a pure diesel generator system, and the CO_2 emissions were reduced by 47%.

It is concluded that a hybrid energy system is a feasible solution for offshore salmon farms. However, because there is a lack of cost data on small scale offshore renewable systems the result is uncertain. Damage to the system from weather and corrosion will have to be evaluated carefully when designing such a system, potentially driving up the costs further. A sensitivity analysis revealed that the cost of PV panels and wind turbines can go up by approximately 50% before the hybrid system gets a higher cost than the pure diesel system.

Acknowledgements

When I started researching for this thesis three months ago, I had little knowledge of the aquaculture industry. Over three hectic summer months I was able to learn enough about the industry to complete this thesis. However, this would not have been easy without the help of a number of people.

Firstly, I would like to express my utmost gratitude to my supervisors, Dr Paul Tuohy and Dr Siri M. Kalvig. As I travelled to Norway to write and research my thesis, Paul was available over email and video calls to discuss and give important feedback. When I arrived in Norway, Siri welcomed me with open arms, and quickly helped me establish the foundation for this thesis. Throughout the work she has helped me get in contact with key people, and given important feedback along the way. Paul and Siri's interest and knowledge in the field of renewable energy has been a great inspiration throughout the work.

Many thanks to Kjartan Melberg and Egil Andersen in the company Gwind, for bringing me along to meetings, and teaching me more about the business behind renewable energy systems. Kjetil Ørnes in Grieg Seafood also deserves a big thanks for providing information on salmon farming, and making a field trip possible.

I would also thank; Jean-Baptiste Curien for his insightful comments and feedback, and Prof. Arnfinn Nergaard for his help. Monicha Seternes, Trond Severinsen and David Campbell has also provided helpful comments on important questions.

My partner Elise has provided support and motivation throughout my 9-months of studying abroad and been invaluable during my work with this thesis. This would not have been the same without her. My parents deserve a big thanks for supporting me in all the choices I make, and encouraging me along the way. Lastly, a big thanks to all my friends for their support, and for not sending me too many holiday photos.

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Nomenclature

AC – Alternating current

CC – Capital cost

COE – Cost of electricity

DC – Direct current

EE – Excess electricity

EUR – Euros

GBP – Great Britain Pound

GHG – Greenhouse gas

GW – Gigawatt

HAWT – Horizontal axis wind turbine

kW – Kilowatt

kWh – Kilowatt-hours

L-A – Lead acid

Li-Ion – Lithium Ion

MW – Megawatt

N – Newton

NOK – Norwegian kroners

NPC – Net present cost

PV – Photovoltaic

RF – Renewable fraction

TSG – Tidal stream generator

USD – U.S. dollar

VAWT – Vertical axis wind turbine

WEC – Wave energy converter

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1 Introduction

From before the industrial revolution until today, the atmospheric CO_2 level has risen by 40% (Eggleton, 2013). An overwhelming fraction of scientists agree that humans are responsible for this increase, mainly by burning fossil fuels (Cook, et al., 2016). This increase in atmospheric CO_2 and other greenhouse gases has led to the global average temperature increasing by 0.85°C since 1850 (NASA, 2016). This might sound like a small increase, but it could have detrimental effects for all life on earth (IPCC, 2013).

We are already seeing the effects in the form of melting polar ice caps, rising sea levels, acidification of the oceans and more extreme weather patterns. If humans keep burning fossil fuel at the rate we do today, it has been estimated that the global average temperature will rise approximately 4°C before the end of the century. This will lead to irreversible changes to our climate (IPCC, 2014; Cook, et al., 2016). In 2015, 55 countries signed the Paris Agreement, setting a goal to try limit the global temperature rise to 1.5°C (Sutter & Berlinger, 2015). For this to happen, all countries must work together to cut their emissions down to zero by the second half of the 21st century (UN, 2015).

With an increasing human population, hungry for cheap energy, this is an almost impossible target to achieve. In order to do so, our fossil fuel driven economy must be transformed into a more sustainable, and it must happen fast. Changes have started to take place, people are getting aware, and the cost of renewable energy systems has decreased rapidly over the last decades.

This thesis will be looking at a very small part of this challenge in global terms; reducing fossil fuel use for the salmon farming industry in Norway. This alone will have a very small effect on a global scale, but it is the hope that projects like this will spread across all industries, in all countries. Together they will lay the foundation for a more sustainable future.

In national terms, the challenge of making salmon farms less dependent on fossil fuels could have larger implications. As the Norwegian electricity grid already has a large portion of hydropower, there is a lack of incentives from the government to expand with more renewable energy. Most industries in Norway use the readily available inexpensive hydropower, while many fish farms depend on fossil fuels because of their offshore location.

Norway is very dependent on the offshore oil and gas industry, but with a changing global energy landscape, the country should not keep all their eggs in one basket. The world leading knowledge of the oil and gas industry regarding sensitive offshore operations could be utilised for offshore renewables. Switching from fossil fuels to renewables for the fish farming industry could represent the start of an important offshore renewables industry in Norway.

1.1 Background

Fish farming, is a large and fast growing industry in Norway. Because of this, it is important to find sustainable farming methods that leads to lower environmental impacts than some of the methods used today. This will enable the industry to grow without damaging the environment. The aquaculture industry in Norway has received criticism from several sources for various environmental impacts. The ones that have received the most attention are sea lice, faecal waste, fish that escapes and the release of nutrients to the marine environment (Miljødirektoratet, 2012).

Another environmental issue that receives less focus is the use of fossil fuels to provide the energy needed for the feeding system and other components at the fish farms. Approximately 50% of the Norwegian fish farms use diesel generators to produce electricity (Bore, 2014). The rest is connected to the grid, which is approximately 95% clean hydropower in Norway (NVE, 2015).

Different solutions are proposed to deal with the problems outlined above. One proposal is to move the fish farms further offshore so the ocean currents will move the waste away instead of it concentrating in the fjords. This will however lead to an increased number of fish farms without a grid connection. Fish farms further offshore could have to rely either on diesel generators, or renewable off-grid energy solutions. It is possible that the rules and regulations to operate offshore will become stricter in the future, making renewable solutions a possible future scenario (Bellona, 2016).

Gwind is a small Norwegian company in Stavanger which specialises in off-grid energy solutions. This includes among others solar- and wind energy, batteries and backup diesel generators. The company has also developed and tested a 1 kW floating vertical axis wind turbine (VAWT). Gwind is currently looking at scaling up the wind turbine and specifically targeting the aquaculture industry in Norway (Melberg, 2016).

The company has previously done analysis on the optimal sizing of a VAWT as a power source for an offshore fish farm. The aim of this study is to look at the broader picture and investigate a range of possible off-grid energy configurations for offshore salmon farms. It was chosen to look specifically at salmon farming, as 94.5% of the aquaculture taking place in Norway is salmon farming (SSB, 2016).

This will be done by assessing the current status of salmon farming in Norway and investigate possible energy solutions. A range of different renewable energy technologies will be reviewed, with a special focus on wind and solar. Different storage options will also be evaluated. A computer modelling exercise will then be carried out to investigate potential feasible solutions, and optimised systems for the salmon farming industry. This will provide cost estimates, performance of different systems, and create a foundation for future research.

1.2 Objectives

- Get an overview of the aquaculture industry, with special focus on the rapid growing salmon farming industry in Norway
- Obtain demand data from an offshore salmon farm
- Understand what drives the demand, and investigate demand reduction measures
- Assess possible renewable energy sources and storage solutions
- Use a computer modelling tool to make a microgrid model for an offshore salmon farm

- Investigate different combinations of wind turbines, PV panels, batteries and diesel generators
- Recommend a renewable energy system, and do a sensitivity analysis to understand the cost uncertainties

1.3 Methodology

The steps taken to achieve the project objectives are:

1. Review the current status in the salmon farming industry with special focus on future trends, energy demands, and any existing renewable energy deployments.

2. Decide on a suitable modelling software and carry out a modelling exercise including the setting of demand profiles and the selection of relevant technical options for generation and storage.

3. Use this model to investigate potential feasible solutions and optimised systems for the salmon farming industry

4. Discuss the outcomes of the modelling against the objectives and overall aim.

5. Review the design process and identify where it could be improved in the future and provide a view on the future in this field

1.4 Thesis Structure and Information

Chapter 2 of this thesis explore the history of aquaculture and the status of salmon farming in Norway. The production chain, environmental problems and future solutions are described.

Chapter 3 evaluates potential energy resources, and the advantages and disadvantages for each of them. The costs and key parameters for each the different power resources are outlined.

Chapter 4 Provides background information for energy system modelling, and information about the key parameters used in the simulation. A demand profile will then be created for a reference salmon farm.

Chapter 5 displays the results obtained through computer modelling in HOMER.

Chapter 6 is a discussion where the uncertainties are evaluated, the feasibility of the solutions assessed, and recommendations and future work is outlined.

Chapter 7 provides a final conclusion for this project.

The costs in this thesis are given in £ (GBP) Since exchange rates change from day to day it was chosen to use a 3-year average for currency conversions. Some equipment prices were given in $ (USD), € (EUR) or (NOK), the same 3-year average method were used for these conversions. The exchange rates used are the following:

1£ = 11.62 NOK

1$ = 8.07 NOK = 0.69£

1€ = 9.02 NOK = 0.78£

-All photos, figures and tables without a reference is developed by the author.

Figure 1 Photo taken at the field trip to Teistholmen salmon farm. Sea cages were the salmons are kept in the background. From left-to-right: Helleik, Kjartan, Siri, Arnfinn, Egil and Jean-Baptiste

2 The Aquaculture Industry

Figure 2 Teistholmen Salmon farm outside Stavanger. Sea cages where the salmons are kept to the left, and the feed barge to the right.

2.1 History and Definition

The earliest traces of agriculture were in the Fertile Crescent and Chogha Golan in the geographical area which is now Iran, around 11,500 years ago (Balter, 2007). Humans ability to cultivate plants and animals were the key to the rise of sedentary civilisation. Throughout history agriculture developed gradually, becoming progressively more advanced and diverse (Balter, 2007).

The diversification of agriculture could be the reason for humans first experimentation with aquaculture. The definition of aquaculture from the Food and Agriculture Organization (FAO) is: *"Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc."* (FAO, 1988).

In many ways aquaculture can be seen as an extension of agriculture into the sea, ponds and flood plains. There is evidence of aquaculture going back 8,000 years, when the Gunditjmara people in Australia farmed eels in an artificial ponding system (Salleh, 2003). Aquaculture was also taking place in China around 4500 years ago, when carp fish were trapped in ponds after river floods subsided. The trapped fish were fed with faeces from nymphs and silkworm until they had grown to the desired size (FAO, 2009).

Throughout the last 2000 years' aquaculture has been present in numerous areas. The Romans had fish ponds (McCann, 1979), the Hawaiians built saltwater ponds more than 1,000 years ago, (Costa-Pierce, 1987) and it spread throughout Europe during the middle ages, to provide people far from the coast and big rivers with fresh fish (Kurlansky, 2002).

The big breakthrough in technology came when artificial fish hatching was commercialised in Newfoundland in 1889 (Pittsburgh Dispatch, 1890). This opened up for the industrialised aquaculture we see today.

As mentioned earlier, there is evidence that humans experimented with aquaculture already 8,000 years ago. Even though aquaculture has been present to a small extent for thousands of year, the main source of marine food has not been aquaculture, but wild fisheries throughout history (Balter, 2007). This started to change in the 1970s with a stagnating harvest from wild fisheries, and an increasing concern for depletion of the ocean resources.

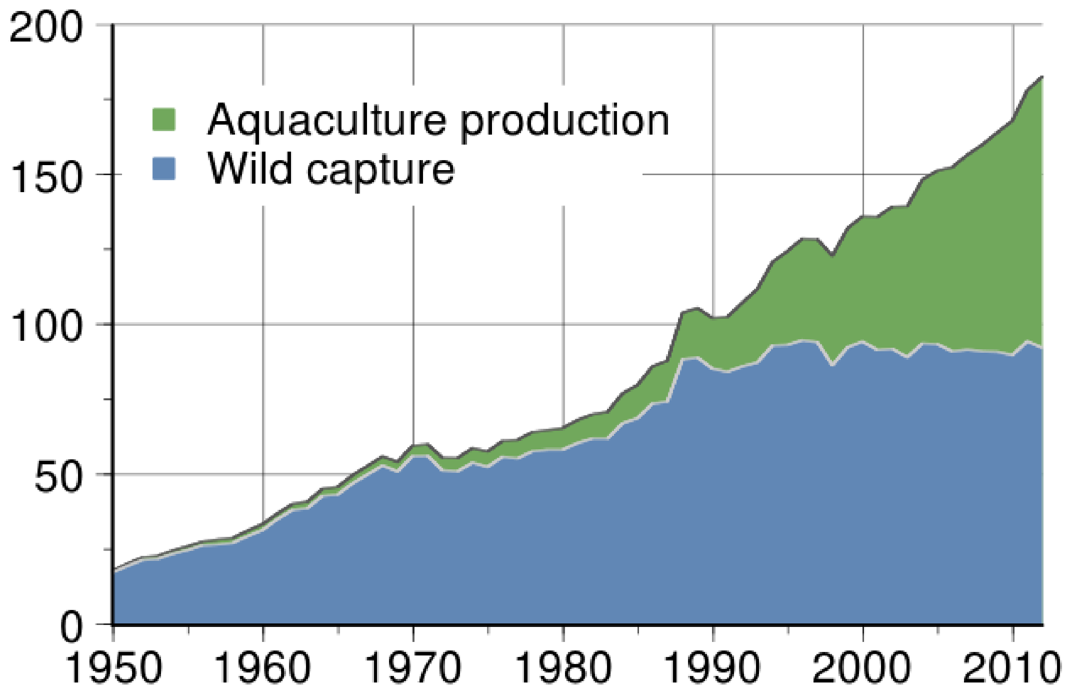

Figure 3 Global production and harvest of marine organisms in million tonnes. A rapid growth for aquaculture has taken place over the last 40 years. Today, nearly half of all marine organisms for human consumption come from aquaculture (FAO, 2011).

As Figure 3 shows, the first stagnation in wild capture happened in the 1970s, and thereafter a gradual increase in aquaculture production took place. The growth rate for the industry has been around 8 percent per annum over the last 30 years, arriving at the point we are at today, where approximately 50 percent of the consumed marine organisms come from aquaculture (Marine Harvest, 2015; FAO, 2011).

Future predictions are uncertain, and even though some parts of aquaculture, like the salmon industry has seen a small decrease in growth in the last decade, it is generally believed that the industry will keep growing in the future (Marine Harvest, 2015; World Ocean Review, 2013; Lenzi, 2013).

There are however many obstacles to be overcome, and with more knowledge of aquacultures' impact to the environment, many challenges must be solved for a responsible growth to take place in the future.

2.2 Aquaculture in Norway

The most common type of aquaculture in Norway is Atlantic salmon farming, which has taken place in Norway since 1969 (Hallenstvedt, 2015). Farming of salmon and trout is accountable for 99.7% of the aquaculture in Norway, with salmon farming having the biggest share of 94.5% (SSB, 2016). Because of this, salmon farming will be the focus of this thesis.

Some key conditions are required for efficient salmon farming; the water temperature should ideally be in the range 8-14°C, with moderate current conditions (Marine Harvest, 2015). Because of this, there is a limited number of locations around the world suitable for salmon farming; North America, Chile, Scandinavia, United Kingdom (Scotland), Russia and New Zealand. Other places could be suitable as well, but these are the locations where salmon farming occurs today (Willoughby, 1999).

Norway is in an especially fortunate location, with temperatures inside the ideal range most of the years, and a long coastline with many fjords, providing sheltered areas with stable current conditions. Available infrastructure along the coast is likely a key reason for the rapid development of salmon farming in Norway.

Norway produced a total of 1.1 million tons of Atlantic salmon each year, nearly half of the total global production of 2.3 million tons (FAO, 2016; Marine Harvest, 2015). The industry has had a rapid growth, seeing a ten-fold increase from 1987-2007. In the recent years the growth has been somewhat slower for a number of reasons, mainly; decreasing demand (political issues with China), environmental concerns, and less concessions given out by the government (Marine Harvest, 2015).

In 2015 the Norwegian aquaculture industry employed more than 24 000 people and contributed to 50 billion NOK (£4.30 billion) to Norway's Gross Domestic Product (GDP), making it one of Norway's most important export industries after the oil and gas industry (Norwegian Seafood Council, 2016).

The total numbers of sites where Salmonids are farmed is 994 per 31. December 2014. (Norwegian Directorate of Fisheries, 2015). Salmonids is the collective term for Atlantic salmon, Rainbow trout and Brown trout (Marine Harvest, 2015). The farming takes place all along Norway's coastline, with some inland locations where hatcheries and brown trout farming sites are located. The map in Figure 4 shows the locations in Norway where Salmonids are farmed.

Figure 4 Salmonid farming locations in Norway are shown by the red dots. As there is a total of 994 locations, the map does not have high enough resolution to show all the locations (Created from the map service at the Norwegian directorate of fisheries).

2.3 Current Status

The rapid growth of the salmon farming industry in Norway has led to a giant leap in technology for salmon farms. In the early 1970s a small number of fish were kept in homemade nets and fed by hand (Fiskeridirektoratet et al, 2010). Today salmon farming takes place on an industrial scale, where the fishes are kept in much larger nets with the largest commercial models having a circumference of 157 m and a depth of 30 m. In some of these nets up towards 500,000 adult salmons are kept at once, making manual feeding impossible (Mattilsynet, Fiskeridirektoratet, 2012).

This has led to the development of advanced and tailored technology such as automatic feeding systems, underwater cameras for monitoring, sensors and lighting systems. Norwegian companies are in the front of the technological development of fish farms, and it is these types of modern, state of the art salmon farms that will be the focus in the next chapters.

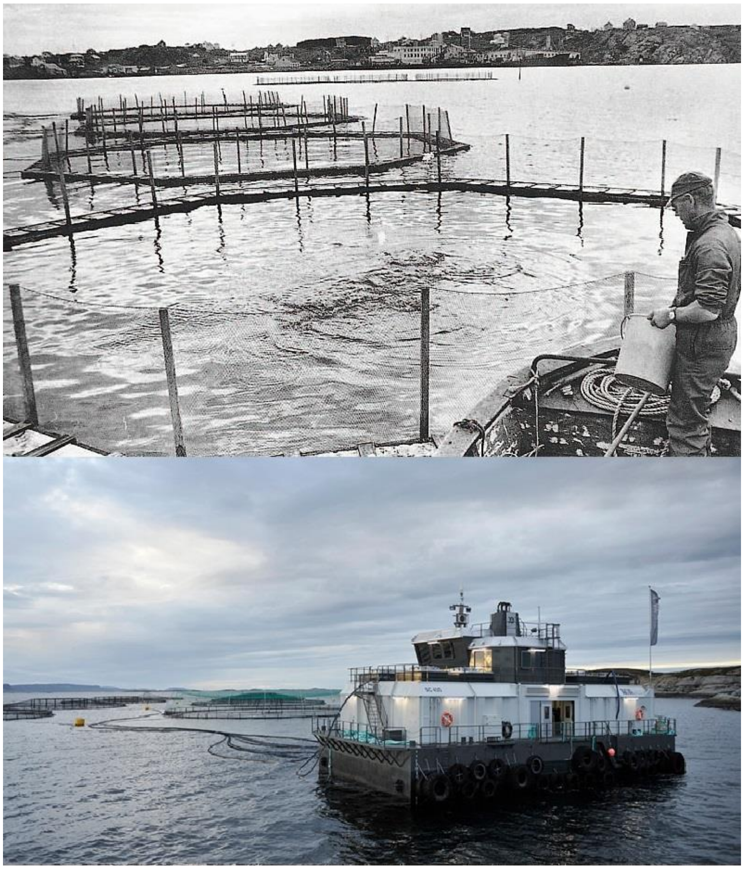

Figure 5 Top: Manual feeding on a salmon farm in 1972. (Adresseavisen, 1972-1973). Bottom: Modern salmon farm with an automated feeding barge (Akva Group, 2015).

2.4 Production Chain

To understand the energy needs of the salmon farming industry, it is important to understand the production chain. This chapter will briefly explain the different stages of the salmon farming cycle.

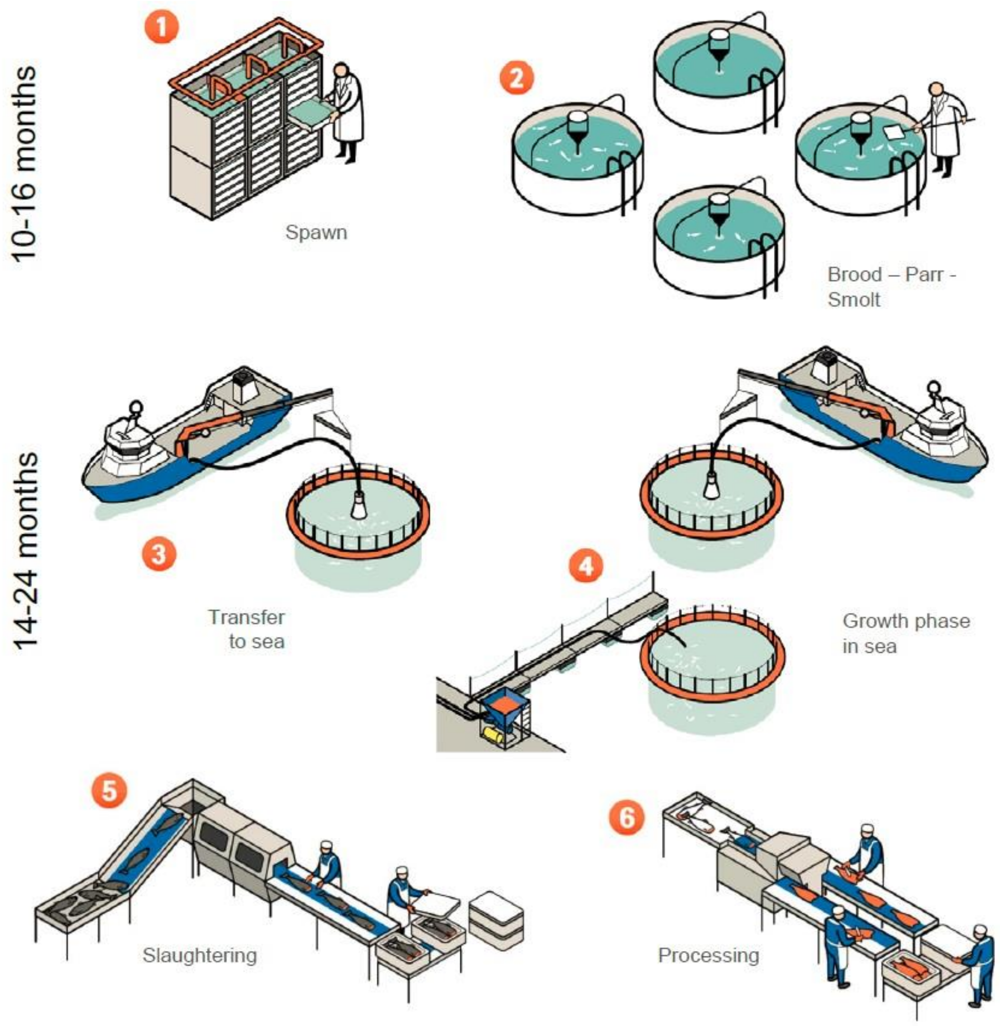

Figure 6 Atlantic salmon production cycle from spawning to slaughtering. This thesis will focus on the "growth phase in sea" (Marine Harvest, 2015)

Figure 6 shows the six main stages of Atlantic Salmon farming. In the first stage, salmon eggs are fertilized and after 25-30 days, the eggs start to show eyes. After this the fish spawn into Alevins, which feed on a yolk sack. For the second stage the fish is transferred to freshwater tanks where the salmons go through three growth phases; brood, parr and smolt. These two stages last for 10-16 months, depending on how large the salmons are grown.

After the salmons have been gradually adapted to life in seawater, in a process called smoltification, the salmons are transferred by a wellboat to the offshore salt water location, as shown in stage three. The industry standard in Norway is to transfer the salmons to large offshore sea cages when they reach a weight between 100-1000 grams. The fourth stage takes place in the sea cages, where the salmons are kept and fed in the cages for 14-24 months.

When the salmons have reached a weight of around 4.5-5.5 kg they are transported back to land to be slaughtered, which is the fifth stage. The sixth and last stage is the processing stage where the salmons are gutted and packed before they are sold. The total production cycle takes 24-40 months from fertilised eggs to harvested fish. The fairly large range is dependent on a number of factors like, amount of food given, water temperature, final weight and time spent at the different stages (Marine Harvest, 2015).

2.5 Energy Sources at the Different Stages

The first and second stage takes place on land, which means that a grid connection is available. The second stage is energy intensive because the water has to be continually changed using pumps. Water also needs to be heated/cooled to the ideal temperature, and artificial lighting is used to avoid the salmons maturing (Myrset, 2015). Development and research has taken place to make this stage more energy efficient; recirculating the water, installing LED lights and using energy efficient pumps (iLaks, 2016; Hægh & Kaldnes, 2014). As mentioned in chapter 1.1 the Norwegian grid is approximately 95% hydropower, making the land based stages less important to focus on. This is also the case for stage 5-6, which also takes place on land.

This means that the target stages for energy reduction and replacement of fossil fuels are stage 3 and 4. There are mainly two energy sources that are being used; grid connection for the fish farms close to shore, and diesel generators for the farms further offshore. In this thesis the energy demand in stage 4, the "Growth in sea stage" will be analysed, because numerous fish farms use diesel generators to provide electricity for this phase.

Different renewable energy sources will be analysed. To investigate the cost, stability and components involved a modelling exercise will be carried out. This could also be done for the other stages, but because stage 4 has the most pressing need for fossil fuel reduction, this was chosen as the focus area.

Electricity from the grid is inexpensive in Norway because of all the available hydropower. Over the last five years the average price for electricity from the grid for the industry in Norway has been 2.27 pence/kWh (25 øre/kWh) (SSB, 2015). Generating electricity from diesel generators can be almost 20 times more expensive, which will be shown in the computer modelling part.

2.6 The Larger Picture

As stated in the previous section it is the energy consumption from the offshore salmon farms that is the focus of this work. It is however important to take a step back and look at the overall energy consumption for salmon farming. This will also explain why the main focus for the industry has been to reduce the energy consumption from feed production, and thereby the costs associated with it. Figure 7 shows the cumulative energy use and Greenhouse Gas Emissions (GHG) for salmon farming overall.

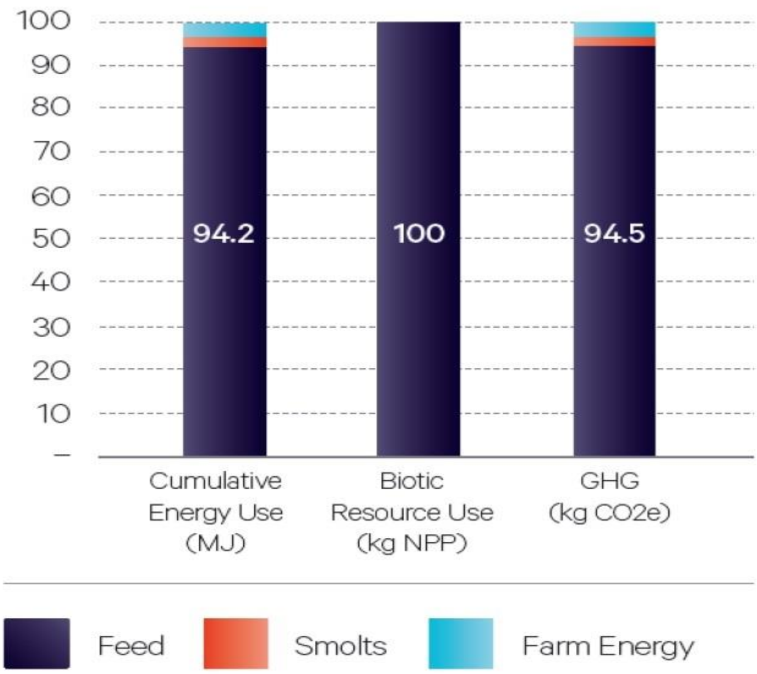

Figure 7 Cumulative energy use and GHG emissions for salmon farming, global average (Pelletier, et al., 2009)

The graph in Figure 7 shows that 94.2% of the cumulative energy usage is linked to feed production, and only around 4% of the cumulative energy to run the farm. Because of this, energy reduction associated with feed production has been seen as more important.

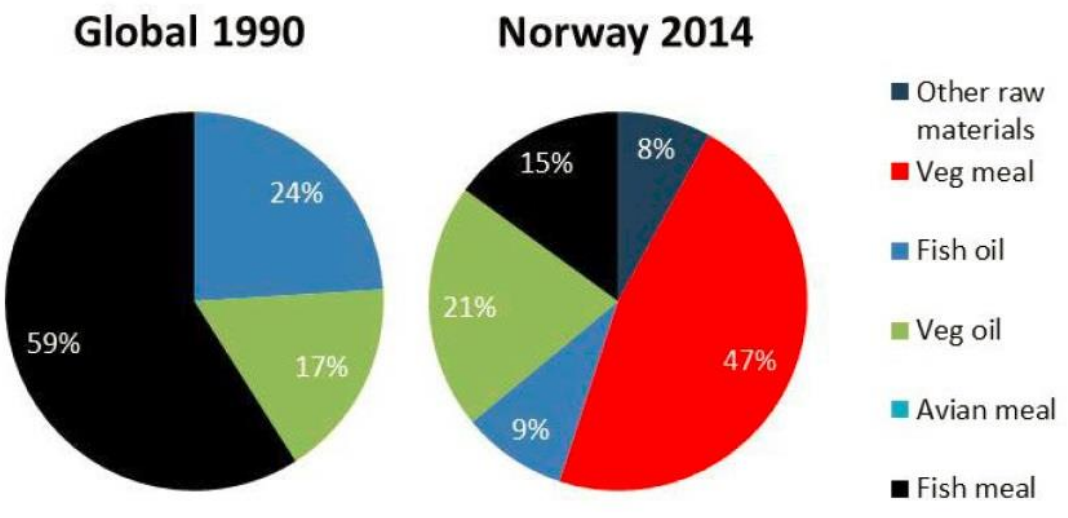

Figure 8 Historic development of Salmon feed ingredients (Marine Harvest, 2015)

Figure 8 shows the development of salmon feed ingredients. There has been a massive effort in the industry to reduce feed costs. This has been done through replacing most of the fish oil and fish meal with vegetable oils and vegetable meal. This leads to an overall lower energy consumption, as plant based feed requires less energy to be grown than vegetable meal. The exception for this is if the fish oil and fish meal comes from wild fisheries. The feed delivery systems on the salmon farms has also been optimised to reduce the feed waste in the delivery process. Thereby reducing the cumulative energy use associated with salmon feed (Severinsen, 2016; Marine Harvest, 2015).

It could be argued that the energy use from feed production has already been reduced to a lower limit, and reducing it further is hard to achieve. This is because the salmons need a certain amount of proteins and fats, and further reduction would seize the salmons' growth.

Raising livestock in general is energy intensive, and proteins from animals normally have a much higher CO_2 emission than plant based proteins. That being said, the CO_2 emission per kg edible salmon is much lower than most others livestock. With cattle being the most energy intensive, responsible for ten times more CO_2 than salmon per kg edible meat (Winter, et al., 2009).

Since the cost and thereby energy use of the feed production has been given a lot of attention, significant improvements have been made with regards to energy reductions. A logical next step is therefore to look at energy reduction for the farming process, as this has been given little attention so far.

2.7 Environmental Problems

As mentioned in the introduction, there are other issues than CO_2 emission from diesel generators that have received most of the attention both from the industry itself and from the media and government. The main environmental problems are outlined below. The background info for this chapter was compiled from the book “Norwegian aquaculture” by (Aarset, 2007) and several reports by the Norwegian institute of Marine Research; (Karlsen, et al., 2016; Samuelsen, et al., 2014; Svåsand, et al., 2015). It is important to understand the current environmental problems to predict the future development of salmon farming.

2.7.1 Escaped Salmon

It is illegal to release farmed salmons into the wild for a number of reasons. The main environmental problem with escaped salmon is that some of the escaped salmon will swim up rivers and mate with the naturally occurring wild salmon population. This could lead to less genetic diversity and the spread of diseases. Because of this, there is a lot of focus on keeping salmons from escaping from the farms. Since it is illegal to release farmed salmons, fines are normally given out to the responsible salmon farm. The salmon farmers also suffer economic losses if salmons escape, in lost revenues. Incidents where salmons escape still happens from time to time, typically because of damage to the sea cages - often in combination with bad weather.

2.7.2 Salmon Lice

When a large number of salmons are kept in a confined space like a net cage, a parasite called salmon lice can occur. Salmon lice also occur naturally, but the problem is more pronounced in salmon farms. The lice will stick to the skin of the salmon and live of the slime, blood and skin of the salmon. If a salmon attracts too many salmon lice it can die. To avoid the spread of salmon lice in the farms, strict limits for the maximum number of lice per salmon have been enacted.

To stay below these limits the salmon farmers use various methods to combat the lice. One of the drugs that is used to kill of salmon lice works by inhibiting the moulting process of the lice. It has been shown that this drug can damage shellfish, like lobster and crabs. There is also the fear of the salmon lice becoming resistant to the drugs that are being used, which has already happened to a certain extent. Another problem is that fishes that live close to the farms can be infected by the lice. Since only the salmons inside the sea cages are threated, the wild fish on the outside can accumulate so many lice that they die.

Research are currently being undertaken looking at other ways to remove salmon lice, like introducing the fish type "wrasse" to the farms. The plan is that these fish will eat the lice, and work as a biological way to combat the problem

2.7.3 Pollution of the Surrounding Areas

Approximately 5-10% of the feed that is given to the salmons are not eaten, and is therefore spread to the environment. There is also the problem with faecal waste or "sewage" from the salmons, which can lead to polluted subsea areas underneath the farms. The uneaten feed and faecal waste from the farms contributes to higher concentrations of nutrients in the nearby areas. The increased level of nutrients can lead to algal blooms and eutrophication in shielded fjords.

Different methods have led to less pollution from feeding and faecal waste. The feeding is better monitored, leading to less feed being released to the environment. Salmon farms located in areas with insufficient current conditions are being moved to better conditions as well. Even though there is less pollution per fish today than earlier, this is still a problem because the size and the number of farms have increased rapidly.

2.8 Future Solutions

The problems outlined above is a concern for the future growth of salmon farming. For the industry to grow in the future, it is important to find farming techniques that removes or reduce the environmental problems to a minimum.

There are a number of solutions that are proposed for improving the current environmental problems, and they involve moving the salmon farms out from the vulnerable fjords or containing the salmons in closed systems. Three different systems have received the most attention, and they are; land based fish farms, closed cage ocean fish farms and offshore fish farms. There is an ongoing discussion both in the scientific literature, and in the industry about which of these solutions would be the best. In the following three subchapters each of the three future solutions will be described briefly.

2.8.1 Land Based Fish Farms

Figure 9 A land based trout farm in Denmark. Not common in Norway, but widespread in other countries (Billund aquaculture, 2015).

In land based fish farms the fish is kept in giant water tanks on land, instead of keeping the fish in sea cages in the open water. The main advantages with a system like this are the following: (Compiled from; (Myrset, 2015; Teknologiradet, 2012))

- Less direct impact on the local environment, mainly problems with escaped fish, sea lice, faecal waste and reduced proliferation of diseases.
- More control over the water conditions because of filtration and flow regulation
- Collect organic material that can later be used as fertiliser
- A potential cost reduction because of less wastage and better feed utilization
- Renewable energy available from the electricity grid

Disadvantages:

- Probably higher cost than normal sea cage farming
- Higher overall energy use, because of water circulation pumps
- More visible due to large constructions on land

2.8.2 Closed Cage Ocean Fish Farms

Figure 10 Closed cage ocean farm in Norway. No openings, so this would operate like a closed system with pumps circulating the water (Marine Harvest, 2013).

A closed farm could be placed in similar locations as the standard net cages, but instead of the water flowing naturally through the net walls it is circulated by the use of pumps. The advantages of this design are: (Compiled from; (Aadland, 2014))

- The water is filtered before entering the tank. This reduces or eliminates the problems with sea lice and diseases
- Less feed is wasted
- The waste from the salmons can be collected and used for fertiliser or biogas production
- Lower risk of salmons escaping

Disadvantages:

- Higher cost than normal net cage farming
- Higher overall energy use, because of added pumps

- Still in the research stage

2.8.3 Offshore Fish Farms

Figure 11 A concept picture of an offshore fish farm. These would be large structures, similar to offshore oil platforms (SalMar, 2015).

A third option is to create larger more robust salmon farms that can be placed further offshore than today's farms. The construction of these farms are similar to offshore oil platforms. These farms would be much larger than the typical farm today, to be cost effective due to the higher construction costs. (Rønningen, 2014)

There are two other offshore fish farm alternatives to the robust offshore farm design shown in Figure 11. The first is submersible offshore farms. These would be similar to the standard farms today, but with the ability to be submerged in the case of bad weather to protect the structure. This enables them to be placed further offshore, because the limiting factor of wave height is less crucial. (Severinsen, 2016; Rønningen, 2014).

The other alternative is underwater salmon farms, which will stay submerged constantly. This will greatly reduce the impacts of waves and wind on the farm. One of the challenges of developing such farms is to create a stable air bubble inside the submerged sea cage. This is needed because the salmons need access to surface air to be able to regulate their swim bladders (Aarset, 2007).

The advantages of offshore fish farms are: (Compiled from; (Severinsen, 2016; Rønningen, 2014))

- Fewer problems with local pollution, as the ocean currents will disperse the waste
- Can be placed in areas that are biologically better suited than today's farms
- More available space for the industry to grow

Disadvantages:

- Does not eliminate the overall waste problem
- Could have higher costs
- No commercial offshore farms available today, however they are being developed and tested

2.9 Summary

Chapter 2 has explored the history of aquaculture all the way back to its beginning, 8000 years ago. The aquaculture industry in Norway has then been described, with special attention on salmon farming, which is the most important type of aquaculture in Norway. Going more in detail on salmon farming, the production chain for salmons has been outlined, with special focus on the energy sources at the different stages. It was decided to look at fossil fuel reduction in the "production in sea" phase, where diesel generators provide the electricity for half of all Norwegian fish farms as of today.

Salmon farming has received criticism for its impacts on the marine environment. The most important environmental problems are; escaped salmons, salmon lice and pollution of the surrounding areas. Three different future solutions to mitigate and resolve these problems were described. These are; Land based fish farms, closed cage ocean fish farms and offshore fish farms. It is uncertain which of these proposed concepts that will emerge as the best solution in the future. With stricter regulations in the future there is reason to believe that salmon farms in the future need to find different solutions than today. It could turn out that one of the designs presented here is the best solution. Alternatively, we could see a range of different solutions, depending on geography, size and climate for each specific location.

3 Energy Resources

The next step is to evaluate which energy resources that would be best suited for an offshore salmon farm, and could be harvested efficiently. The potential advantages and disadvantages for each of these resources will be described.

After reviewing the literature on different power sources, five potential resources were left; wind, solar, wave, tidal and diesel generators. The costs of connecting the salmon farm to the electricity grid with a sea cable will also be investigated.

As the salmon farms in focus are not connected to the grid, they would operate as an off grid system. Before diving into the potential energy resources, the architecture of an off-grid energy system will be explained.

3.1 Off-Grid Energy Systems

Off-grid energy systems are different than grid connected systems in a number of ways. The main difference is that they operate as a separate island, with no possibility to import power in the case of insufficient power generation. This goes the other way as well, if excess electricity is produced, this has to be stored using batteries or other storage solutions. The alternative is to dump the excess electricity as heat, but this would drive up the cost of electricity, as energy is wasted. The term excess electricity can be defined as: *"Surplus electrical energy that must be dumped because it cannot be used to serve a load or charge the batteries"* (HOMER Knowledgebase, 2011).

Renewable energy sources like wind and solar are intermittent, and because of this, the power production cannot be regulated to match the demand directly. This means that off-grid systems either needs some sort of storage, or/and a dispatchable back-up power resource. The most common way to design an off-grid system is to have what is commonly referred to as a hybrid energy system. This system incorporates one or more renewable resources in addition to a back-up generator and energy storage technology. The advantage of hybrid energy systems is that they are more reliable and normally have a lower electricity cost than systems relying on a single power resource (US Department of Energy, 2016).

An off-grid system for the salmon farming industry would have to be reliable, as salmons' worth up towards £10 million are kept in the sea cages at once (Ørnes, 2016). A prolonged power outtake because of faulty equipment could lead to huge economic losses. It therefore makes sense to include a back-up generator in such a system. Another aspect is that off-grid systems for offshore salmon farming would be exposed to saltwater, and generally harsher climate conditions than systems on land. This is likely to drive up the cost of the components, and the operation & maintenance cost (GWEC, 2016).

3.2 Wind Power

Figure 12 Wind turbines at Whitelee Windfarm outside Glasgow in Scotland. These wind turbines are much larger than what would be used at a salmon farm.

Wind energy can be harvested through the use of wind turbines by using the air flow to power a generator. All over the world there has been a steady increase in the total installed capacity of wind power, with an increase in global cumulative capacity of 70 times from 1996 to 2015 (GWEC, 2016). Onshore wind is already cheaper than gas and coal plants in some locations and the land use is relatively small, as it can be successfully integrated onto for example farmland (Neslen, 2014). Offshore wind has even more energy potential than onshore wind, but considerably higher installation and maintenance costs makes it a less viable solution as of today (Schwanitz & Wierling, 2016).

Both offshore and onshore wind could be potential power resources for offshore fish farms. Onshore wind would be the cheapest, but could only be used on locations close to small islands. Offshore wind power would require less geographical consideration.

A number of different offshore wind concepts can be deployed at a salmon farm. The cheapest solutions would probably be to install the wind turbines directly on the infrastructure already in place on a salmon farm e.g. the feed barge. With the current size of the barges, only relatively small wind turbines could be installed without increasing the size and thereby the cost of the barge. Another option is bottom fixed turbines in shallow waters, or floating wind turbines in deeper waters.

Since a floating feed barge is already needed for an offshore salmon farm, the most economically feasible solution would likely be to place the turbines on it. Having separate floating turbines would likely drive up the cost because extra foundation and anchoring lines are needed. Placing the turbines on the feed barge has the added benefit of easier access for maintenance and no need for underwater cables. The next chapter explores the concept of placing wind turbines on the feed barge.

3.2.1 Adding Wind Turbines to the Feed Barge

To investigate the potential for installing wind turbines on the already existing barges, the product specifications for a medium sized feed barge delivered by the company AKVA group was acquired. The weight of several wind turbines was also obtained (Table 2). The photo in Figure 13 shows the actual feed barge. Compared to the feed barge visited at Teistholmen salmon farm (Figure 25), this is a more modern design and it is constructed more like a boat.

Figure 13 Feed Barge for salmon farms (AC 450), wind turbines and PV panels can be placed directly onto it, or floating by the side (AKVAgroup, 2016)

The feed barge in Figure 13 has the following product specifications:

Capacity	
Feed capacity:	450 tons (8 silos)
Silage:	Up to 60 tons
Diesel tank:	Up to 30 tons
Freshwater tank:	Up to 6 cubic meters
Sewage:	Up to 5 cubic meters
Barge Spesifications	
Length (ex platforms):	22 m
Breadth:	12 m
Depth till main deck:	4.0 m
Minimum freeboard:	1.074 m

Table 1 Product specifications for the Feed Barge AC 450. High load capacity, meaning energy system components can be added (AKVAgroup, 2016)

The product specifications show that the feed barges are made to carry a lot of weight in feed, as much as 450 tons on this specific barge. There is also a diesel tank with a carrying capacity of up to 30 tons. If a renewable hybrid system where to be installed it is likely that the size of the diesel tank could be reduced without any complications. The feed capacity of 450 tons could be reduced as well to accommodate the extra weight of batteries and a wind turbine. It is however important to note that reducing the feed capacity will lead to more frequent feed deliveries by boat, thereby increasing the energy usage for transportation.

With the size and carrying capacity of a feed barge in mind, this can be compared to the weight of different wind turbine sizes (Table 2):

Turbine	Rated capacity (kW)	Total Weight (kg)	Max horizontal forces (N)	Tower height (m)
KW3Ex[1]	3	~500	NA	11
Visionair 5 (VAWT)[2]	3.2	756	NA	10
AirForce10[3]	10	2,100	10,900	15
WES80[4]	80	11,520	NA	31
WES250[5]	150	23,800	NA	39

Table 2 Parameters for a range of wind turbines. The weight is low compared to the capacity of the feed barge.

When comparing the weight of the wind turbines to the scale of the feed barge, it is clear that the weight of the smaller wind turbines is relatively insignificant. Taking the 10 kW wind turbine as an example, the weight of it is only equal to 0.4% of the feed capacity of this barge. There should be no problem with regards to weight of placing this turbine on the barge.

The company FuturEnergy was also able to provide the maximum horizontal forces that could occur from their 10 kW wind turbine. With a maximum of 10,900 Newton's (N), or 1,090 kg of horizontal force, this is seen as insignificant compared to the scale of the feed barge. For the other turbines the manufacturers could not provide data on the horizontal forces from the wind turbines. If it is decided to use the approach of installing a wind turbine on the feed barge, stability calculations would have to be carried out for each specific feed barge and chosen wind turbine size. It was decided to not go into detail on stability calculations, but make an assumption that wind turbines smaller than 100 kW can be placed directly on the feed barge.

[1] (Kingspan Environmental, 2016)
[2] (UGE, 2016)
[3] (FuturEnergy, 2016)
[4] (Wind Energy Solutions, 2016)
[5] (Wind Energy Solutions, 2016)

Another potential problem is the unproductive wake area and the turbulence that would occur if more than one wind turbine was added to the feed barge. The reason for this is that the size on the barge is limited, and the turbines would have to be grouped close together. It is possible to install only one turbine as well, but this would leave the system vulnerable in case the turbine had to be maintained. One solution that would reduce some of the problems is to install vertical axis wind turbines (VAWT) instead of the conventional horizontal axis wind turbines (HAWT). The potential advantages and disadvantages of VAWT will be outlined in the next section.

3.2.2 Vertical Axis Wind Turbines (VAWT)

Figure 14 A floating 1 kW vertical axis wind turbine (VAWT), tested by Gwind outside Stavanger. VAWTs have a lower centre of mass, which could be beneficial for floating wind turbines (Gwind, 2014).

Gwind has previously investigated and tested a 1 kW floating VAWT for offshore use (Figure 14). Research by Gwind shows that VAWTs could provide certain advantages (Melberg, 2016). The reasons for why VAWTs might turn out to be a better solution for salmon farms are outlined below. Potential disadvantages are also listed. The information in this section is compiled from the reports: *"Evaluation of different turbine concepts for wind power"* (Erikson, et al., 2006) and "*A retrospective of VAWT Technology"* (Sutherland, et al., 2012).

Advantages

- VAWT works better than HAWT in gusty and turbulent winds and can therefore be grouped closer together or closer to the ground.
- Lower centre of mass, as the gearbox is placed near the foundation. Could be beneficial if turbines are floating or placed on barge. It also eases the maintenance as the alternator is located at the base of the mast.
- VAWTs are omni-directional, meaning they do not need to turn up against the wind, less moving parts.
- Less noise production than HAWT.

Disadvantages

- Fewer turbines available on the marked, which could result in higher costs and fewer tested solutions.
- The turbines available on the marked has a maximum rated capacity of 10kW, there is a lack of standardised larger turbines
- Less efficient than HAWTs for similar sized turbines – higher cost per kWh of produced electricity

As seen there are both advantages and disadvantages, but the fact that the VAWTs can be placed closer together and therefore utilize gusty more turbulent winds could be an important factor if designing a multi turbine system. Having a lower centre of mass could prevent the barge or other foundation from becoming unstable as well. It was therefore decided to incorporate VAWTs in the analysis in addition to HAWTs.

3.2.3 Cost of Wind Turbines

The initial approach was to evaluate possible wind turbines by obtaining the costs for a range of turbines, and test each of them in the computer modelling tool. However, it proved to be difficult to collect cost estimates for every single turbine size, as they normally come in fixed capacities, e.g. 1kW, 3kW, 10kW, 50kW, etc. There is also a lot of uncertainty around the total cost, because the wind turbine manufacturer cost does not always include all the necessary components, like control system, foundation, cabling, etc. Also the installation cost is not included in this figure.

Another problem with only testing certain wind turbine sizes is that a sub-optimal system might be designed. Say that the optimal wind turbine size to meet the salmon farm demand was 34 kW, however, simulations were only carried out looking at 10 kW and 50 kW wind turbine. If a 50 kW turbine had been chosen because of the imprecise analysis, more electricity than needed would be generated, and the overall cost would go up.

Because of this problem it was decided to investigate a continuous range of wind turbine sizes, with 1 kW size increments from 1-100 kW. Both HAWTs and VAWTs were investigated. The power produced from a wind turbine is dependent on the power curve. The power curve of a wind turbine is an approximation of the power output from a wind turbine under different wind speeds. Figure 15 shows the power curves used for modelling the two different turbine concepts. The VAWT power curve was created by normalising the curve of the 3.2 kW Visionair5 VAWT, so that the peak power output was equal to 1 kW. The power curve for the HAWT is the power curve for a "generic 1kW wind turbine", extracted from the software tool, HOMER energy.

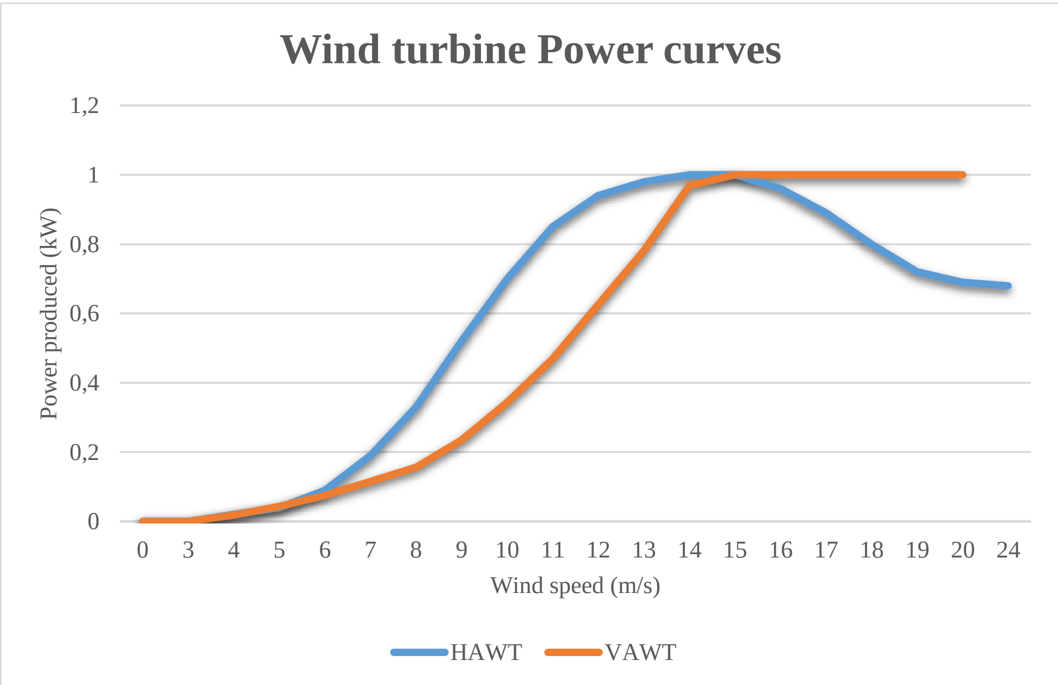

Figure 15 Normalised wind turbine power curves used in computer modelling. The HAWT performs better in low – medium winds, while the VAWT performs better in strong winds.

As can be seen from Figure 15, the two different wind turbine concepts have different power curves. The power curve for the HAWT (blue line) rises more quickly than the curve of the VAWT (orange line). This means that the HAWT is more efficient in low winds. In higher winds on the other hand the VAWT will have a higher efficiency, as there is no drop off in power production before the cut out speed of 20 m/s.

By looking at the two power curves, we can already estimate that the HAWT will have a higher annual power production than the VAWT. This is because it is more efficient in the wind speed range 6-15 m/s, which occurs much more frequently than wind speeds above 15 m/s in most locations. The annual wind speed follows a Weibull distribution.

To be able to model every 1 kW incremental, a flat rate per kW of installed capacity was established for both wind turbines designs. According to windustry.org the average total cost per kW for small scale turbines (less than 100 kW) is between 2,000£-6,000£ per kW of installed capacity (windustry, 2012). This was used as an initial estimate for the two turbine designs. It is not an optimal estimate to use a flat rate for the cost of a wind turbine. This is because wind turbines normally follow what is known as "the economics of scale". This is a general rule which makes the cost per kW lower the bigger the turbine is. However, this is seen as a better approach than only testing a handful of turbines.

The Operation & Maintenance (O&M) cost vary significantly for different wind power projects. A common estimate is that the O&M cost for onshore wind farms start at 1% of the projects capital cost and rise to 4% progressively throughout the projects 20-year lifetime (IRENA, 2012). This is not necessarily applicable to single turbine offshore installations, but it was used as an estimate. Offshore installations are more expensive than onshore installations to operate and maintain. To incorporate this, it was assumed a flat rate of 4% annually of the wind turbines capital cost throughout the projects lifetime.

The capital cost and O&M cost for each of the wind turbines used in the computer modelling are summarised in Table 3. The same cost was used for VAWTs and

HAWTs. A fixed hub height of 25 metres was set, and the same O&M cost. The lifetime was also assumed to be the same, making the power curves the only difference.

Turbine	Capital cost (£/kW)	O&M (%)	O&M cost (£/kW/year)	Lifetime (years)	Hub height (m)
HAWT	5000	4	200	20	25
VAWT	5000	4	200	20	25

Table 3 Wind turbine costs and parameters used in computer modelling. The same costs were used for HAWTs and VAWTs

Because there is a high grade of uncertainty to these cost estimates, a sensitivity analysis will be carried out to evaluate what impacts changing wind turbine costs have to the project.

3.3 Solar Power

Figure 16 Photovoltaic (PV) panels on the Isle of Eigg in Scotland. PV panels could be placed directly on the feed barge, or as floating modules.

Solar energy can be converted to electricity in two ways. Either directly by using Photovoltaic Panels (PV panels), or by concentrating the sunlight to harvest the energy indirectly through heat (Foster, et al., 2009). The focus when investigating solar energy for the aquaculture industry will be PV panels.

Similar to wind power there has been a rapid growth in installed PV capacity. The growth has followed an exponential curve for two decades arriving at a total installed capacity of 233GW by 2015. With decreasing prices for PV panels and energy storage solutions, PV is expected to play an important role in the future energy mix (Shah & Booream-Phelps, 2015).

Similar to wind turbines, PV panels can be installed in different locations to provide power for a salmon farm. The simplest option is to place the PV panels directly on the feed barge, but a nearby island or as floating modules at sea are also possibilities. However, to get a substantial power production, a relatively large area is needed, particularly in Norway where the average solar insolation is low, especially in winter.

Another problem would occur for salmon farms located in the northern parts of Norway. In Tromsø for example, the sun does not rise above the horizon between 25. November and the 17. January. Having almost two months where no power will be produced at all will lead to power deficiency issues if the salmon farm is too dependent on solar power. PV panels on a salmon farm would have certain advantages; they normally require less maintenance than wind turbines. Also, the power is produced during the day, when the electrical demand is highest at the farm.

The next section will explore the power potential from PV panels installed directly on the feed barge, as this is seen as the cheapest and simplest solution.

3.3.1 Adding PV panels to the Feed Barge

Returning to the feed barge shown in Figure 13, and outlined in Table 1, it is clear that the space for installing PV panels are limited. The feed barge measures 22x12 metres, making the total area 264 m^2. The whole of this area could not be fitted with PV panels, as the roof has eight hatches where the silos are filled with feed through the hose of a supply boat. Pathways between the panels would also be needed, and the foundation for a possible wind turbine would take up space. An estimate for how much of the roof area that could be covered with PV panels were found by evaluating the plan view of the feed barge. Taking the mentioned considerations into account, a maximum of 70% of the total area could be covered with PV panels. This translates to 185 m^2 of available space for PV-panel installation.

The next step is to see how much capacity could potentially be installed on the roof of the feed barge. A typical 250W PV-panel measures around 1.7 m^2 (Solar World, 2016). With a total surface area of 185 m^2 a total of 108 of these panels could be fitted on the feed barge, making the total installed capacity 27.2 kW. This estimate shows that there is limited space for PV panels on the feed barge. Because of this, other options should be investigated in order to increase the potential PV capacity.

3.3.2 PV panels on Floating Modules

If more PV capacity is to be installed, there is not going to be enough space on the feed barge. Similar to the wind turbines, the PV panels could be installed on a nearby island. There would however only be a handful of places where this could be a solution, so it is not an option for most salmon farms.

Figure 17 PV panels on floating modules on the Queen Elizabeth II reservoir outside London. This is a possible solution for salmon farms (Godwin, 2016).

A second option could be floating PV panels, similar to the ones deployed on the Queen Elizabeth II reservoir outside London (Figure 17). This would remove the problem of not having enough available space, but will result in some other challenges.

The first problem is that floating PV panels are more prone to damage because of waves and saltwater. The queen Elizabeth II reservoir is a freshwater manmade reservoir, only

18 metres deep. The environmental strain inflicted on panels in the open waters of the North-Sea would be much higher than for the relatively protected waters in the reservoir.

Floating PV panels could be a solution for salmon farms that is well protected from waves. It is nevertheless a more expensive solution than fitting the panels directly on the feed barge. There is an added risk of damage from waves and saltwater which should be carefully evaluated before such a system is created.

3.3.3 Cost of PV panels

There are many factors that determine the final cost of a PV-installation; Which type of PV panels chosen for the installation is one factor. The general rule is the higher efficiency, the higher is the cost. Other factors, like the quality of the panels, and the installation also play a role (IEA, 2014). The biggest uncertainty factor in the case of salmon farms, are where the PV panels could be fitted.

There are a lot of uncertainties tied up to the cost of having floating PV panels. The system in Figure 17 is delivered by a French company called Ciel & Terre. The system is made to survive storms, but only waves up to one metre (Ciel & Terre, 2016). The waves at an exposed salmon farm location can be substantially higher than this. As a result, most feed barges are made to tolerate four-metre-high waves. (AKVAgroup, 2016) According to Ciel & Terre the system can be reinforced, but it is not known how much more resilient the system can be made.

The cost of domestic PV systems is normally between £1500-£2500 per kW installed capacity (ECOex, 2016). Larger installations can be cheaper, a 200kW floating solar farm in Berkshire UK had an investment cost of £250 000, equalling only £1250 per kW installed capacity (The Guardian, 2014). However, this included some governmental tariffs bringing the investment cost down.

When investigating PV panels for salmon farms, a price per kW of installed capacity had to be set. This needed to reflect that up to approximately 27.2 kW capacity, the panels could be placed on the feed barge. If more PV capacity is to be added it would have to be placed on floating modules, or a separate barge.

Capital cost for PV panels was estimated to be 2,500 £/kW (ECOex, 2016). The annual O&M cost was set at 4% after doubling the 2% estimate from the report "*Technology Roadmap - Solar Photovoltaic Energy"* (IEA, 2014). This was done to incorporate the added cost from operating offshore. Table 4 summarises all the parameters used:

Capital cost (£/kW)	O&M (%)	O&M (£/kW/year)	Derating Factor (%)	Efficiency (%)	Lifetime (years)
2500	4	100	80	13	20

Table 4 The costs and parameters used for modelling PV panels

The derating factor is the percentage of the rated capacity that is actually available as electric power after system losses. The efficiency is the percentage of the solar radiation that is turned into electrical energy, before the derating factor is accounted for.

3.4 Wave Power

Figure 18 The 750 kW Pelamis P1 wave energy converter, located outside the Orkney Islands (Wikimedia public domain, 2014).

The energy in the ocean waves can be converted to electrical power through a wave energy converter (WEC). There has been attempts to harvest wave energy since around 1890, but wave-power generation is still in the research stage. A number of different designs have been tested, without any device emerging as a clear winner (Miller, 2004).

The most common reasons listed for the absence of commercialised WECs are; lack of large scale research, the complexity of finding an efficient design to harvest wave energy, and the difficulty of creating devices that can survive in the harsh offshore climate (Levitan, 2014).

The 2.25MW Aguçadoura Wave Farm was the world's first multiple machine wave power project. It was located outside Portugal, and consisted of three Pelamis machines (Figure 18), which is a cylindrical wave power device. The farm was opened in September 2008, but was closed down only two months later due to technical issues and problems with further financing (Kanellos, 2009). The company behind the Pelamis WEC, Pelamis Wave Power, went out of business in November 2014, underlining the challenges of developing commercial wave power systems.

Even though larger scale projects like Pelamis have had a rough time there are other small scale tests taking place. One of the most interesting projects was the one undertaken by the Scottish company Albatern Wave Energy outside the Isle of Muck.

3.4.1 Albatern Wave Energy Field Test for Salmon Farming

Figure 19 Albatern wave power project for a salmon farm in Scotland owned by Marine Harvest. A 22 kW wave energy converter device (WEC) was tested for 14 weeks in 2014 (Albatern Wave Energy, 2014).

In the spring of 2014 the Edinburgh based company Albatern installed a 22 kW capacity WEC system at one of Marine Harvest' salmon farms outside the Isle of Muck (Albatern Wave Energy, 2014). This project is the only larger scale renewable energy project at a fish farm that has been discovered so far in this work. To learn more about the project, Albatern Wave Energy was contacted.

David Campbell, the commercial director at Albatern could provide some insights into the project. The project ran for a total of 14 weeks during the summer of 2014. The aim of this project was mainly to test the equipment in relatively calm waters. Albatern could not provide any specific energy production data for the field test. It is however reason to believe that the power production was relatively low, due to the calm waters the field test took place in.

The next field test will take place at Mingay, Ardnamurchan, where a broader range of wave conditions will be present. This will also give more data on the actual power output. The cost of this system is however relatively high. According to a newspaper article the project cost was £720 000 (Scottish Energy News, 2014). This translates to £32 727 per kW of installed capacity.

This project shows that there is potential for wave energy solutions in the future, but there is still a long way to commercialised solutions. As of today the cost of wave energy is substantially higher than wind and solar. The maintenance and lifespans of such systems are relatively unknown as well. Because of this it was chosen to discard wave energy as a potential renewable energy source in this thesis. That said, wave energy will be an interesting option in the future when more field tests and data are available.

3.5 Tidal Power

Figure 20 Two different concepts for harvesting tidal energy. To the left is a 1.2MW Sea Gen tidal stream generator (Sea Gen, 2013). To the right is the 240 MW Rance tidal power station in France (REUK, 1998)

Tidal power is the conversion of the energy in the tides to electricity. The two main concepts for doing so are shown in Figure 20. The design to the left is a turbine type design, which works similar to a wind turbine, just underwater. When the tidal current passes through, the turbine blades are rotated, and power is produced. The turbine in the photo is the 1.2 MW capacity SeaGen, which was the first commercialised large scale tidal stream generator (TSG) (Douglas & Harrison, 2008).

The other way to harvest tidal energy is through the creation of barrages where the tidal forces makes the water pass through generators on a barrage. The photo to the right in Figure 20 shows the Rance Tidal Power Station in France, which has an installed capacity of 240 MW.

When deciding on possible tidal power options for standalone salmon farms, it is clear that the TSG is the most applicable technology. Larger constructions that involve barrages and lagoons would be too expensive for single salmon farms. Multiple salmon farms could of course go together to undertake such a project, but this would require cooperation between multiple smaller companies, or one of the larger companies getting involved.

The question is then, how well could a TSG could work for a salmon farm? Similar to wave power, high costs and lack of commercialised solutions are the first problems that face a potential installation. Scale is another issue, and according to Marine Current Turbines, the company behind SeaGen, a TSG needs to be above 1 MW to be economically viable (MCT Ltd, 2008). The numbers could of course be different for other designs, but a typical salmon farm would need a TSG in the 50-100kW range. There exist no such turbines in the marked today, and developing a suitable turbine would be expensive.

As mentioned in section 2.2, salmon farms are placed in locations with moderate current conditions, to ensure sufficient water circulation. However, if the current is too strong the salmons will be stressed and have a hard time consuming food (Aarset, 2007). For TSGs this is reversed, stronger current conditions are favourable because more power will be produced. Because of this, an optimal location for a salmon farm will probably never be the optimal location for a TSG. An alternative is to place the TSG in a strait with strong currents, and the salmon farm in a nearby location with moderate current conditions. This would however lead to the necessity of underwater power cables, adding additional costs to this solution.

There is a lot of future potential in tidal power, but as the scale of the turbine is crucial for the economics, it is unlikely that it would be a good solution for salmon farms in the near future. There is also problem of non-coinciding current requirements between TSGs and salmon farms. Because of these two problems it was decided to discard TSGs as a potential power resource for salmon farms for now.

3.6 Diesel Generators

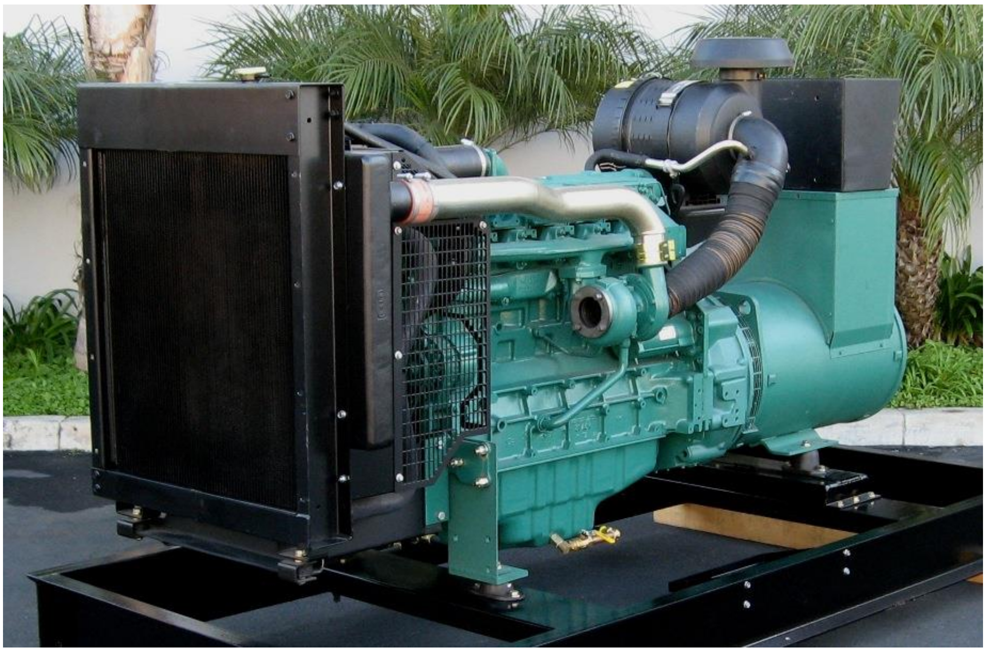

Figure 21 A 100 kW Volvo diesel generator. Generates electricity from diesel, half of all fish farms use diesel generators (Hardy Diesel Generators, 2016).

As mentioned in the introduction, more than half of all fish farms use diesel generators to supply their electricity. Diesel generators work similar to a car engine, but instead of driving the wheels, a generator is turned, and electric power is produced. There are a number of reasons why so many fish farms rely on diesel generators (GeneratorJoe, 2016):

- Low investment cost
- Dispatchable generation (power can be produced when needed)
- Takes up relatively small space on the feed barge
- Well proven technology

There are also disadvantages to diesel generators:

- High fuel costs, especially for long term use
- Fossil fuels are burned which emits CO_2, NO_x and particle pollution
- Leads to vibration and noise on the feed barge
- Risk of spilling diesel to the ocean
- Fuel cost is exposed to fluctuating oil prices

- High maintenance cost (requires reliable equipment to ensure a stable power feed)

The costs for diesel generators were taken from (Lazard, 2014). The operation & maintenance (O&M) cost is normally assumed to be 1.5 pence per hour of operation (HOMER knowledgebase, 2010). It was chosen to double this cost similar to the O&M cost for PV and wind turbines because of the salmon farms offshore location. Table 5 summarises the parameters used for modelling a diesel generator.

Capital cost (£/kW)	O&M (%)	O&M (£/hour)	Minimum load ratio (%)	Lifetime (hours)	Fuel price (£/litre)
500	0.06	0.030	25	15,000	0.81

Table 5 Diesel generator cost and modelling parameters

When simulating the diesel generator, it was chosen to let the computer modelling tool auto-size the generator to meet the electrical demand. Additionally, a smaller diesel generator with a capacity of 10 kW was added to the system. This is because the efficiency of a generator is dependent on what percentage of maximum output power the generator runs at. Most generators are made to have a peak efficiency near their peak power output. This means that if a diesel generator with a capacity of 110 kW is supplying a load of only 5 kW, it will become very inefficient. However, most generators will never run that low, as they have a minimum load ratio, in this case set to 25% of the peak power output to extend the lifetime of the generator. What this means for a 110 kW diesel generator is that the it will never have a power output less than 27.5 kW. If then only meeting a load of 5 kW, fuel will be wasted and excess electricity occurs.

The second smaller 10 kW diesel generator will run when the electrical demand is low, and thereby minimise fuel waste. This is a normal set up at for pure diesel electric system, which will save maintenance and fuel costs.

The fuel price used in the simulation is the 3-year average in Norway, 0.81£/litre. In Norway the tax for diesel is 0.29 £/litre (Regjeringen, 2015), however this tax does not apply to boats, construction machines and stationary equipment. As of today Fish farms fall under the category of consumers that does not have to pay a diesel tax, meaning that they pay marked price for the diesel. With these parameters in place, a diesel generator can be modelled.

3.7 Grid Connection

Approximately half of all fish farms have a grid connection (Bore, 2014). However, many of these fish farms are located close to shore, often less than 100 metres (fiskeridirektoratet, 2016). If the distance is that short, it is relatively inexpensive to connect the fish farm to the national grid. Also, there is no added cost of high voltage cables as the losses are relatively insignificant over short distances. For short distances, a grid connection is the cheapest solution, and it is also a good alternative from an environmental viewpoint. For longer distances where a high voltage cable is needed, the cost increases substantially.

There are also potential problems of having a grid connected fish farm. According to Kjetil Ørnes in Grieg Seafood, there is the risk of problems with the electrical cable. At their salmon farm Laupland which has a low voltage cable, they had three incidents in one year where the power was lost at the salmon farm. This happened because of damage to the subsea cable.

3.7.1 Cost of Subsea Cable

As mentioned in section 2.5, the total cost of electricity from diesel generators can be almost 20 times higher than from the electricity grid. The question is then, why do so many fish farms rely on diesel generators instead of a grid connection?

The main reason is the large capital cost of connecting the fish farm to the grid using a high voltage cable. A high voltage cable is needed for transferring electricity more than a few kilometres to avoid losses. If a high voltage cable is used, transformers are needed at both ends of the subsea cable, dramatically increasing the cost (Beels, et al., 2011). The Norwegian company Måsøval salmon farming has a plan to remove all their diesel generators by 2016, and replace them by a grid connection using high voltage cables. Most of their salmon farms require approximately 5 km of subsea cable (Ramfjord & Toftaker, 2014).

To understand the costs of installing a grid connection, Monicha Seternes at Måsøval salmon farming was contacted. She could tell that currently two of their salmon farms have installed a grid connection. The total cost of connecting these two farms were approximately £860,000, with approximately half of the cost for each of the two farms. Both of these two farms are located 5 km from shore.

Monicha could also tell that a large portion of the cost was not linked to deploying the actual high voltage cable, but the cost of transformers and labour cost on land. In this specific instance the electric cable on land had to be extended to reach the place where it went out into the sea. In addition, high voltage transformer had to be installed on land, driving up the cost. The Norwegian public enterprise ENOVA SF decided to back this specific project, and awarded Måsøval £430,000, this amounted to half of the project cost.

It is difficult to put a specific price on the cost of a high voltage subsea cable, as it is dependent on a number of factors like length of cable, depth, current infrastructure, seabed conditions, transfer capacity, and possible funding received. Nevertheless, a rough estimate from the information provided by Monicha is approximately £86,000 per km of cable. For shorter distances, less than 1-2 km, a high voltage cable might not be needed, and the cost would in those instances be much lower.

For salmon farms close to shore a grid connection is normally the best solution. For longer distances the costs go up substantially. With a possible future solution of moving fish farms further offshore, as described in 2.8.3, the distances will be too long for subsea cables to be feasible. In those cases, renewable off-grid energy systems are likely to be a better solution.

3.8 Storage Solutions

Figure 22 A battery bank is an example of a storage option. In this picture, Lead-Acid batteries are used to store the electricity of a renewable energy system (Schauberger, 2015).

Both wind and solar are non-dispatchable resources, meaning that they cannot be switched on or off to meet a fluctuating electricity demand. Because of this, storage is needed for load matching, and to take advantage of the energy produced when there is no demand (Harack, 2010). It is also possible to create energy systems without any storage, and save the cost of batteries. In the computer modelling the cost of including storage will be weighed against the losses in unexploited electricity and extra diesel generator use. Three different storage options were evaluated: Lead-Acid Batteries, Li-Ion batteries and compressed air storage.

3.8.1 Lead-Acid Batteries

For many years Lead-Acid batteries has been the main type of batteries used for energy storage. They are relatively cheap, but they have a lower energy density and a lower efficiency than Lithium-Ion batteries (Breen, 2015). A potential problem of using Lead-Acid batteries on a floating structure like a feed barge, is the safety aspect. Lead-Acid batteries can generate hydrogen gas, which is highly flammable (O'Donnel & Schiemann, 2008). This could create a safety problem if the batteries are located close to a diesel generator in a hybrid system. Nevertheless, it was chosen to include Lead -

Acid batteries in the analysis to investigate if they provided storage at a lower cost than other solutions.

Table 6 summarise the cost and parameters used for modelling Lead-Acid batteries. The capital cost used is taken from the report *"Energy Storage System Costs*" (EPRI, 2011). O&M cost for battery systems are often set to 2% of the capital cost yearly (EPRI, 2011). Because the salmon farm is located offshore, it was doubled to 4%.

Capital cost (£/kWh)	O&M (%)	O&M (£/kWh/year)	Throughput (kWh)	Lifetime (years)	Initial state of charge (%)	Min. state of charge (%)
250	4	10	800	10	100	40

Table 6 Costs and parameters used for modelling Lead-acid batteries

3.8.2 Li-Ion Batteries

Lithium-Ion batteries have a much higher energy density than Lead-Acid batteries. They also have a longer lifetime and a higher efficiency because they can accept a lower minimum state of charge. First commercialised by Sony in 1991 for use in compact electronics, but have in later years become more widely used in a range of systems (Breen, 2015). The price of Li-Ion batteries has decreased significantly in recent years, and is expected to do so in the future as well. Their decline in cost is often attributed their wide use in the growing electric car marked (Ayre, 2015).

Table 7 summarise the cost and parameters used for modelling Li-Ion batteries. The capital cost used is estimated with the basis in the Tesla Powerwall. O&M cost for battery systems are often set to 2% of the capital cost yearly (EPRI, 2011). Because the feed barge is located offshore, it was doubled to 4%.

Capital cost (£/kWh)	O&M (%)	O&M (£/kWh/year)	Throughput (kWh)	Lifetime (years)	Initial state of charge (%)	Min. state of charge (%)
350	4	14	3000	15	100	20

Table 7 Costs and parameters used for modelling Li-Ion batteries

3.8.3 Compressed Air Storage

The largest portion of the energy consumption on a salmon farm is normally the feeding system. The feeding system requires energy to run air compressors. The compressed air is in turn used to blow feed pellets through hoses out to the sea cages, where they are spread out. Because of this, it could make sense to store the energy as compressed air that could be used directly to run the feeding system.

The feed barges already have a small tank to store compressed air so that the compressor does not need to run constantly. However, these tanks are relatively small, and only provide short term storage. A larger tank could be installed, but since the space on the feed barge is limited, not a lot of power could be stored this way. This is because compressed air storage has a low energy density. The round trip efficiency of compressed air is also lower than batteries, 40 to 54% is common for large scale plants (EASE and EERA, 2013).

Compressed air storage is nevertheless acknowledged as a potential feasible solution. It could either be in the form of small scale storage in pressure tanks at the feed barge, or larger scale in subsea underground reservoirs.

It was chosen to rule out compressed air storage from the computer modelling, and focus on conventional forms of energy storage in the form of batteries. It is however highlighted as a potential energy storage option that should be studied further. This is highlighted in the future work part.

3.8.4 Other Solutions

There is a lot of ongoing research on different energy storage solutions, which could change the landscape of energy storage dramatically. In today's market, Li-Ion and Lead-Acid batteries are the most common battery type, and was therefore chosen for the modelling study. Additional studies should be carried out to evaluate the potential of storage options like; flow batteries, flywheels, hydrogen storage, compressed air and thermal storage.

3.9 Summary

This chapter has described what differentiates an off-grid system from a normal electricity system. Five potential energy resources that could provide power for salmon farms were assessed. Wind power was found to be a good solution, and it was decided to investigate both HAWTs and VAWTs in the computer modelling. Solar power in the form of PV panels was also included as a potential power source.

Wave power and tidal power was also investigated as potential power resources. Because of non-coinciding optimal wave and current conditions between salmon farms and wave and tidal power devices, they were ruled out. They were also found to be more expensive and immature technologies than wind and PV.

Diesel generators were also described, and the economics and constraints of a grid connection. Three different storage solutions were identified; Lead-Acid batteries, Li-Ion batteries and compressed air storage. It was decided to investigate the two battery types in the computer modelling.

For all the components investigated in the computer modelling, the costs and performance parameters were outlined.

4 Salmon Farm Modelling and Electrical Demand

The experimental part of this thesis is to use a computer modelling tool to find practical renewable energy solutions for the salmon farming industry. The overall goal was to investigate if there existed any hybrid systems that was more economically feasible than diesel generators. Three questions were posed:

- What is the cost of meeting the demand through a diesel generator?
- What is the cost optimal hybrid system?
- What is the cost of meeting the whole demand through renewable resources?

Before going ahead with the computer modelling, a software tool had to be chosen, and the demand profile of a salmon farm created. The next chapters will explore this, before outlining the system schematic and the weather data used.

4.1 Microgrid Software Tools

There exist a number of different energy modelling tools that could be used to model a salmon farm. In Table 8 some of the key aspects of four relevant modelling tools are outlined:

	Merit	**HOMER-energy**	**EnergyPLAN**	**Excel**
Cost	Free (Developed at the University of Strathclyde)	16$ monthly for students	Free	Normally free for students (Part of the office package
Scale	Micro grid systems	Micro grid systems	National grid	N.A.
Customisable	Medium	High	Medium	High
Ease of use	Easy	Medium	Medium	Difficult
Overall	Gives the ability to match electric demands with renewable energy production and find optimal renewable energy systems. Also incorporates energy storage	Gives the same options as merit but with more customisable parameters, and the ability to carry out more detailed cost and sensitivity analysis	Energy systems analysis tool that gives the ability to model energy systems as large as a national grid. However, it is not so customisable at smaller scale analysis	A model could be created in excel, but this would require a lot of extra work. Also the results would be less precise than what can be achieved with a dedicated energy modelling tool
Chosen	✗	✓	✗	✗

Table 8 Comparison of relevant energy modelling tools, it was found that HOMER energy could be a suitable software.

When combining the decision factors in Table 8, it was concluded that HOMER energy would be the best tool for investigating possible renewable energy systems. Many other energy modelling tools exist, but it was chosen to use a software the author had experience with.

4.1.1 HOMER Energy

Figure 23 A screenshot of the HOMER energy interface. Here showing the system schematic in the top left corner, and the demand profile in the centre. Components can be added, demand profiles adjusted and results can be calculated.

HOMER energy is microgrid modelling tool, not to be confused with the well-known Simpson's character. It was originally developed by the National Renewable Energy Laboratory (NREL), but sold and commercialised by the company HOMER Energy LLC in 2009. The name is an acronym for *"Hybrid Optimization Model for Electric Renewables"* (HOMER energy, 2016). A software tool like HOMER will simplify the work of evaluating a range of different system designs. The program gives the ability to simulate both grid-connected, and off-grid systems. In this case, only off-grid systems are modelled. When designing a power system there is a range of decisions to be made: Which power resources are optimal for the specific system? What size should the different components be? What is the optimal amount of storage?

Given so many variables the modelling task will quickly lead to thousands or millions of different system configurations to be considered. With a micropower modelling tool, all these configurations can be simulated simultaneously. The built in optimisation algorithms in HOMER will subsequently categorise the results after the preferences set by the user (NREL, 2011).

4.1.2 How the Simulator Works

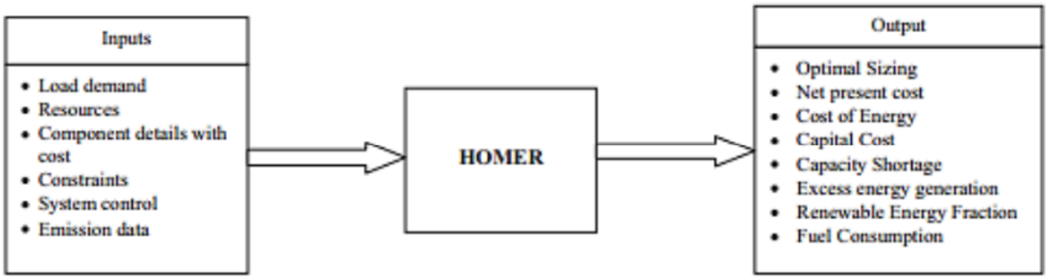

Figure 24 Schematic representation of how HOMER energy works. Component parameters, resources and demand data are inputted. Homer energy will calculate and output; optimal sizing, costs, performance, etc. (Sinha & Chandel, 2014).

An energy modelling simulator works by doing energy balance calculations. In this case on an hourly basis for each of the 8 760 hours in a year. For every hour, HOMER links the electrical demand to the energy produced by the components in a specific system. If a range of different components and sizes have been made available, all possible configurations will be tested.

When including fuel-powered generators or batteries, HOMER will run algorithms to decide when to operate the generator, and when to charge and discharge the batteries. After all the possible configurations have been simulated, HOMER will return all the feasible system configurations. This means all the systems that is able to meet the electrical demand specified (NREL, 2011).

4.2 Energy Demand for a Salmon Farm

To investigate renewable energy systems for salmon farms, a crucial component is the electrical demand profile. This includes both the hourly demand throughout a day, and the changes throughout the farming cycle. During the literature review, no demand profile for a salmon farm was found. Therefore, it had to be created through investigating data from the electricity provider, talking to experts and looking at energy consumption statistics. This chapter will explain how the electrical demand profile used for modelling was established. It will also go into detail on the various equipment and energy reduction measures.

To narrow down the scope of the thesis it was chosen to look at the energy requirement specifically at "Growth in sea phase", which was described in section 2.4. The phases that takes place on land will not be investigated because of the renewable grid connection at the land based phases. Another aspect, which is the transport by boat will not be modelled.

Another thing to decide was whether to model an existing farm, or to try predict the energy usage of one of the potential future salmon farms described in section 2.8. To remove some of the uncertainties it was decided to look at the energy use of an existing farm. This is because it is possible to obtain demand data, and because many of these farms rely on diesel generators, even though they are close to shore. The work that is done by assessing potential off-grid systems could easily be transferred to for example offshore or closed cage farms in the future.

4.2.1 Generating Demand Data

Figure 25 The feed barge at Teistholmen Salmon farm, where the feeding system, crane, monitoring station and kitchen is kept. The electrical demand profile created is based on this salmon farm.

With the help of Kjetil Ørnes at Grieg Seafood electrical demand data was obtained from three of their salmon farms, Teistholmen, Laupland and Dale. These three salmon farms are located in the Rogaland region, in the southwest part of Norway, Teistholmen is only 10 minutes by boat from Stavanger city. The sea cages the salmons are kept in are the same size at all three farms, 150 000 salmons per net cage.

Dale is the smallest with 3 sea cages (450 000 salmons), Teistholmen is larger with 6 sea cages (900 000 salmons) and Laupland is the largest with 8 sea cages (1 200 000 salmons)

The three farms already have a grid connection, making these specific farms unsuitable for installing an off-grid renewable energy system. However, because they all have a grid connection, it was possible to obtain demand data with an hourly resolution from the electricity provider. The problem was only that the electricity provider started recording hourly demand data in February 2016, so it was only available for the five months between February and June.

The demand data was then analysed for all of the three farms, both on an hourly basis and a day to day basis. The plan was to build a synthetic demand profile for a typical farm with basis in these three farms. The process of analysis was not straightforward, as only a limited set of data was available, and the salmon farms where in different parts of the farming cycle.

The demand data from the salmon farm Dale was not included in the assessment because of a faulty electrical cable. When the demand data from this specific farm was analysed it was noticed a sudden drop in the energy use in the middle of May, effectively cutting the electrical demand in half. When discussing the electrical demand of the farms with Kjetil Ørnes it was discovered that this drop coincided with the changing of the faulty cable. The dramatic effect of changing the faulty cable lead to a surprise, and stands as a remainder of the importance of monitoring the electrical consumption to reduce energy waste.

The initial analysis of the data was to look at the average daily demand profile, both for a weekly average, and monthly average. This produced graphs like the one shown in figure 7:

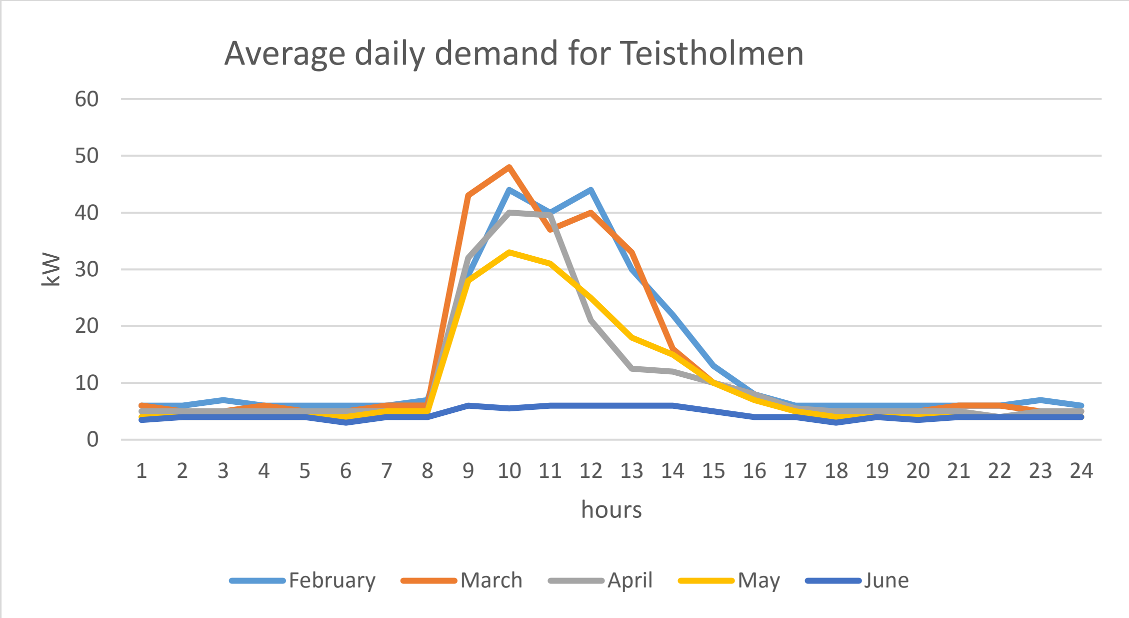

Figure 26 Average daily demand at Teistholmen Salmon farm. The coloured curves shows the average daily energy consumption for that specific month. There is a base demand of 4-5 kW and a peak of 40-50 kW in the day. In June (dark blue curve), the demand stays flat throughout the day. This is because the salmons have been slaughtered, and there is no feeding taking place.

The graph in Figure 26 shows the average daily demand for the salmon farm Teistholmen for the months February to June. The salmons where slaughtered towards the end of May, explaining why the energy use is lower this month (yellow line). In June there is no feeding taking place, and the energy use stays constant throughout the day without, the peak in the middle of the day (dark blue line). As we will see the feeding system is the most energy intensive equipment on the farm.

However, the average daily profile for each month does not show the whole picture of when, and how much energy is being used at the facilities. When plotting the total daily energy use for each of the months, it is clear that there is quite a lot of variation from day to day (Figure 27). The jumps in energy usage could be because equipment like the crane is used a lot on that specific day due to cleaning or other maintenance. The dips in the graph could be explained by bad weather or service intervals preventing normal feeding. The downward trend that starts in the end of May is due to the slaughtering of the fish happening in this period.

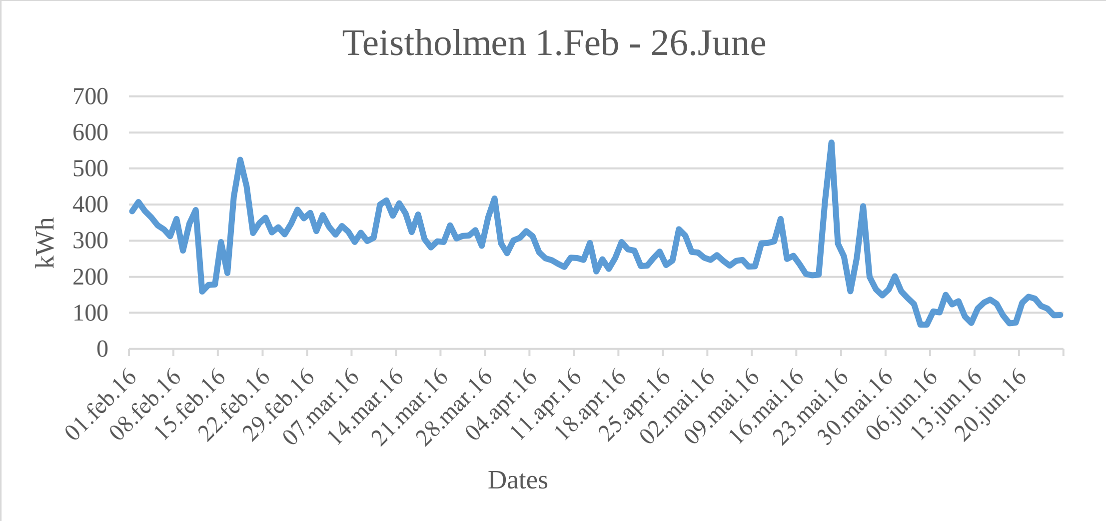

Figure 27 Daily energy demand for the salmon farm Teistholmen. The average demand decreases in the end of May, because the salmons are slaughtered.

4.2.2 Understanding the Electrical Demand

To understand what drives the demand throughout the day and farming cycle, all the components installed at the salmon farm had to be mapped out. This was done by first visiting the salmon farm Teistholmen. All the electrical components were written down and photographed. In addition to the demand investigation an interview with Kjetil Ørnes was scheduled to evaluate the energy usage of the different components, and their operation times. Finally, the electrical consumption from the household equipment like the fridge, oven and coffee machine was taken from: (EnokGuiden, 2016).

A breakdown of the electrical consumption of the components at the salmon farm Teistholmen is found in Table 9. In the far right column the daily average can be found, which shows that the daily consumption can vary substantially, as shown in Figure 27.

	Peak power (kW)	Average power (estimated kW)	Operation time	Hours per day	Daily average (calculated) (kWh)
Feeding system (Compressor)	4*22 = 88	30	08:00-16:00	3-8	90-240
Feeding system (Progressive cavity pump)	4*1.2 = 4.8	2	08:00-16:00	4-8	8-16
Crane	30	5	08:00-16:00	0.5	2.5
Monitoring equipment (Cameras, Sensors, computers, etc.)	3	1	00:00-00:00	24	24
Dead fish handling system (Grinder)	22	5	08:00-16:00	1-2	5-10
Dead fish handling system (compressor)	6	2.5	08:00-16:00	3-5	7.5-12.5
Underwater lighting	6*1 = 6	6	00:00 (December – June if multi-year cycle)	0 or 24	0 or 144
Indoor lighting	0.5	0.5	08:00-16:00	2-10	1-5
Outside lighting (Safety lanterns, etc.)	1	0.5	16:00-08:00	6-16	3-8
Electronic Heating (Panel ovens)	8	2	00:00-00:00	0-24	0-48
Hot water tank	2	1	00:00-00:00	4-10	4-10
Coffee maker	1.5	1	08:00-16:00	0.5	0.5
Fridge	0.16	0.05	00:00-00:00	24	1.2
Freezer	0.175	0.07	00:00-00:00	24	1.68
Oven	2.2	2.2	08:00-16:00	0-1	0-2.2
Microwave oven	0.7	0.7	08:00-16:00	0.1	0.07
Toaster	1	1	08:00-16:00	0.1	0.1
Dishwasher	2	2	08:00-16:00	0.5	1
Other (Removable equipment, etc.)	10	1	08:00-16:00	0-8	0-8
Total	189				239-534

Table 9 Electrical components at Teistholmen salmon farm. Created from an interview and consumption data. This highlights the different components, and how much overall energy they use.

As we can see from Table 9, the feeding system is normally responsible for more than 50% of the energy use on the farm. The question is then, why is this part of the process so energy intensive, and can it be reduced? To answer this, we need to look at the scale of feed involved, and the possible complications of not having an optimal feeding system.

4.2.3 Feeding System

A salmon farm like Teistholmen contains approximately 900 000 salmons. An adult salmon requires approximately 1.2 kg of feed daily (Marine Harvest, 2015). Without accounting for losses, this alone amounts to 1.08 tons of feed daily. The feeding system consists of large silos where feed in the form of small pellets are kept. These silos can contain more than 50 tons of feed each, and each barge can have multiple silos. Figure 28 shows the bottom of the feed silo at Teistholmen, with the progressive cavity pump connected at the end of the pipe pointing vertically out from the bottom of the silo. To the right is the compressor unit. As seen from Table 9, there are a total of 4 compressors and progressive cavity pumps on this salmon farm.

Figure 28 Feeding system at Teistholmen salmon farm. Left: Bottom of the feed silo and the progressive cavity pump. Right: compressor unit, driving the feeding system.

The feeding system works by blowing the feed pellets through hoses that can be several hundred meters long, using compressed air. The hoses are stretched out to each of the sea cages with a spreader connected at the end which distributes the feed pellets evenly inside the net cage. Figure 29 shows the hoses transporting feed pellets out to the sea cages.

Figure 29 The hoses transporting the feed pellets out to the sea cages. The feed pellets are blown through the hoses using compressed air, before being spread out inside the sea cages.

The second part of the question is whether or not the energy use from the feeding system can be reduced. The focus of the systems that are used today is to avoid wasting feed pellets. Trond Severinsen at AKVA group provided more information on this. According to him, decades of research have taken place to create feeding systems that minimize the number of pellets that are crumbled or creates blockages along the way. As shown in Figure 7 in section 2.6 the salmon feed is responsible for more than 96% of the energy usage of the salmon farm. Because of this, a system that uses less energy would in the larger picture end up wasting more energy if any increase in crumbled pellets occur. There could be solutions that reduced the energy use without increasing feed waste. However, as long as there are not any strong incentives in doing so, it is unlikely that such systems will be developed.

One way the energy use could be reduced is to minimise the length of the feed hoses. This could for example be done by placing the sea cages in a circle around the feed barge, instead of in a line. Shorter hoses would lead to less friction, but it is uncertain if this would have any noticeable effect. This could be an interesting topic to research in future work.

4.2.4 Components and Energy Efficiency

As shown in Table 9 there is a range of different components necessary on a salmon farm. Some of these components are difficult to substantially reduce the energy use of, like the ones in Figure 30 below:

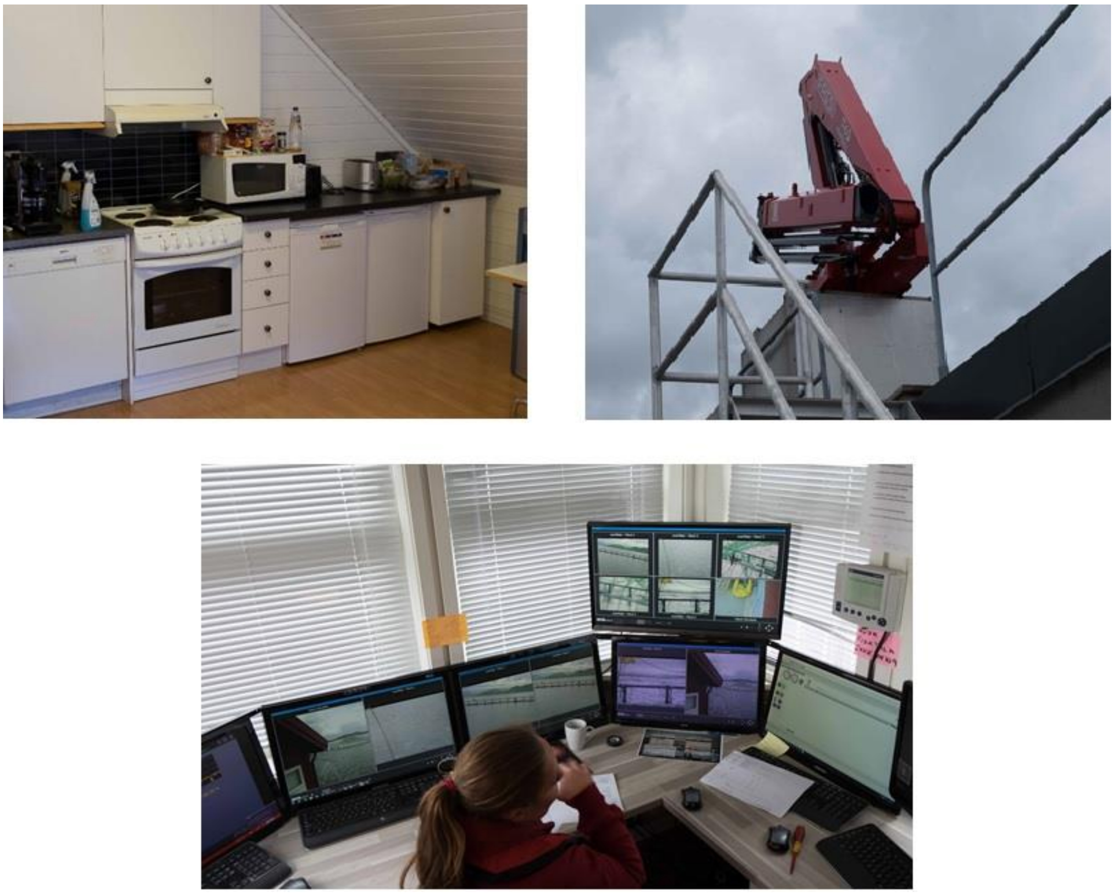

Figure 30 ***Top left****: The kitchen at Teistholmen salmon farm where employees prepare food.* ***Top right****: A crane which is used sporadically for lifting salmons or equipment.* ***Bottom****: Monitoring equipment, here the employees can monitor the salmons through underwater cameras. There are also sensors to monitor oxygen levels and potential emissions.*

Some improvements could be made by investing in more energy efficient appliances, but the overall energy use of the kitchen is already relatively low. The crane and the monitoring equipment is on the other side difficult to make more energy efficient.

For other components at the salmon farm it is easier to reduce the energy consumption. One such component is the underwater lighting system. This system is used if the salmons are kept in the sea for more than one year, to avoid the salmons maturing. Matured salmons grow slower, and is therefore unwanted. When the underwater lighting system is used, it is kept on 24 hours a day between December and June. If the underwater lights where switched to LED-lights, this system would require 60% less energy (Ørnes, 2016). This is likely to be a very cost effective energy reduction measure if implemented. The outdoor and indoor lighting could also be changed to LEDs, but the overall energy savings from this would be substantially less than from changing the underwater lights.

Another component at the salmon farm is the heating system, which today consists of electrical panel ovens, or diesel heating system at some feed barges. A water source heat pump is likely to be a good alternative for most salmon farms, and could reduce the energy required for heating by up to 70% (Haugerud & Lien, 2015). Alternatively, the excess heat from compressing the air could be used for heating, if compressed air energy storage is implemented.

As seen there are a number of energy reduction measures that could be carried out to make salmon farming more energy efficient. Carrying out these actions are likely to be much cheaper than installing extra renewable capacity and storage to accommodate inefficient components. On the other side it is important to keep in mind that the energy efficiency measures do not negatively impact the farming process in any way. Training of the personnel to be more aware of the energy consumption would also be important.

Length of Farming Cycle

The 1.5-2-year farming cycle that has taken place on the analysed salmon farms is the most common farming cycle today. This is also the one described in section 2.4. There is however a new method that is gaining popularity. Grieg Seafood will test it out on some of their farms already this year. The current method involves growing the smolt (young salmon) in water tanks on land until they reach a weight of 60-120 grams. The fish is then transported to the saltwater location where it is fed and kept for 14-24 months until it reaches the slaughter weight of 4.5-5.5 kg (Nesfossen, 2016).

The new method involves keeping the salmons in the water tanks on land for a longer time, until they reach a weight of around 1 kg. The salmons are then transported to the sea cages and farmed at sea for less than a year. There are multiple advantages for doing this (Ørnes, 2016; Berge, 2015):

- The farming period in the open sea is reduced to approximately 10 months, instead of 14-24 months.
- The larger fish are more resilient towards infections and sea lice and have an overall higher survival rate
- It is easier to monitor the fish on land and thereby reducing the spread of parasites and diseases.
- No need for underwater lighting system to avoid the fish maturing
- Considerably lower energy use in the phase where fossil fuels are used to produce electricity

There are also some potential downsides and uncertainties to this new technique:

- Higher overall energy usage, as the fish is kept for a longer time in the energy intensive growth on land phase. The water needs to be recirculated with pumps constantly. However, renewable energy from the grid is available.
- Uncertainties with regards to overall cost, but predictions show that this method could be cheaper

4.2.5 Farming Cycle Chosen for Modelling

As mentioned in the start, the aim of analysing the demand is to be able to use it for computer modelling. When carrying out microgrid modelling it is important to use realistic and suitable demand data. The first plan was to input the hourly demand data from Teistholmen or Laupland directly into the microgrid modelling software. This turned out not to be the optimal solution, as there was only available data from the last five months of the farming cycle. The other problem was the timespan of the farming cycle at the two salmon farms.

At Teistholmen the salmons were transferred to saltwater in October 2014 and slaughtered in May 2016, totalling an 18-19-month production cycle at sea. At Laupland the salmons were transferred in April 2015, and it will be slaughtered between July and December 2016, totalling 15-20 months. This shows that farming cycles vary from farm to farm, depending on the initial weight of the salmons, and amount of feed given.

Electrical demand profiles for use in computer modelling has to be 1-year demand profiles, which is then repeated throughout the project lifetime of 20 years. Trying to input a 1.5-2-year cycle into HOMER-energy proved to be a difficult task, and after conversations with Kjetil Ørnes at Grieg Seafood it was decided to create a 1-year farming cycle. The 1-year farming cycle used for modelling is shown in Figure 31:

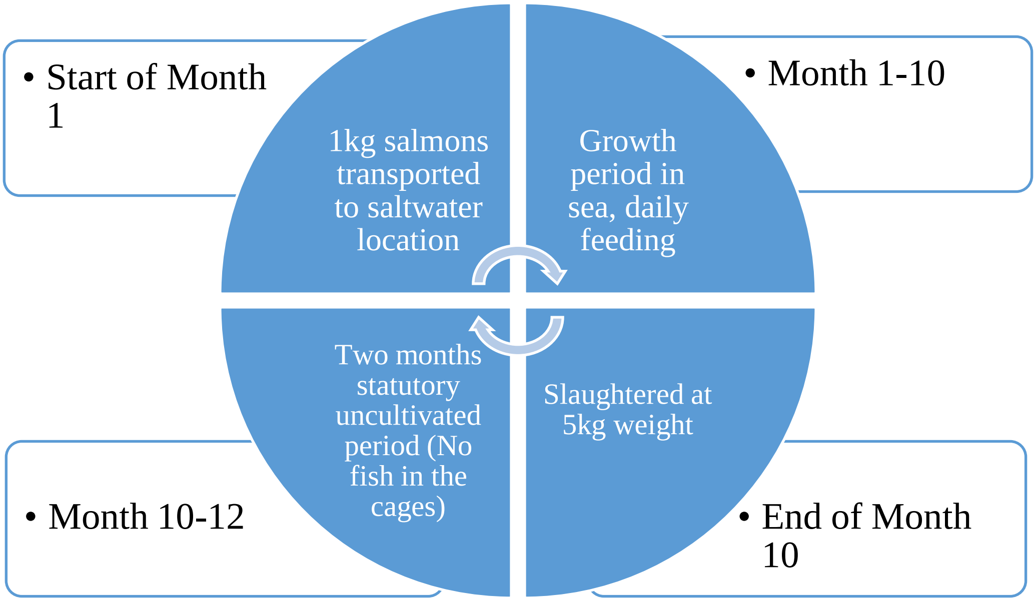

Figure 31 Breakdown of the 1-year farming cycle used in the computer modelling. The salmons are kept in the sea cages for a total of 10 months.

This one year farming cycle with a 10-month growth phase, is the one that will be used to build a demand profile for modelling. Electrical demand data from the salmon farms Teistholmen and Laupland and interviews will be used to establish a synthetic demand profile for a salmon farm of similar size as Teistholmen, but with a shorter cultivation period.

Choosing to model a one-year cycle while the current industry standard is 14-24 months might at first come through as a substandard solution, but there are good reasons for doing so, except from the software limitations. As mentioned there is an industry trend of growing the fish larger before transferring it to the sea cages. This would also be relevant in the case of moving the salmon farms further offshore. Larger and more vigorous salmons are likely to have a lower mortality rate in the harsher offshore conditions.

Figure 32 shows the final 12-month farming cycle that was used for the modelling.

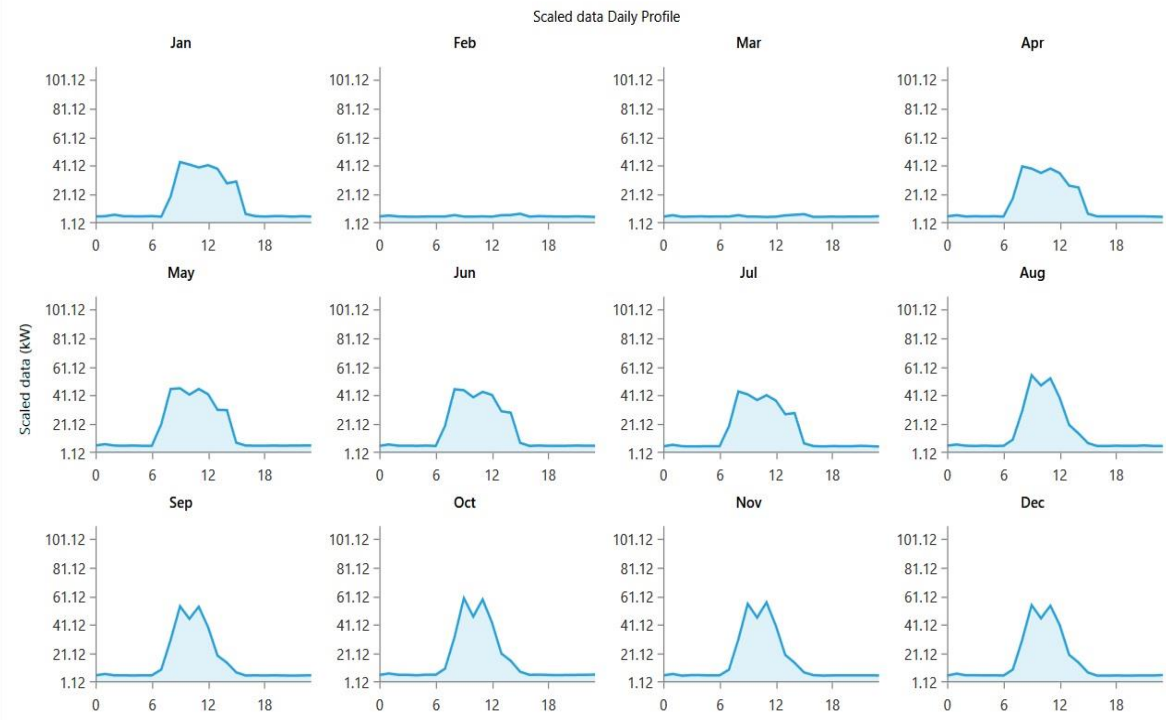

Figure 32 Monthly electrical demand profile used for computer modelling as inputted into HOMER energy. Between April and January there are salmons being fed daily, which is reflected in the electrical demand. In February and March there are no salmons in the sea cages, and the electricity demand stays constant at 5 kW throughout the day.

Figure 32 shows the monthly electrical demand profiles used for modelling a salmon farm in HOMER energy. The hours are plotted on the horizontal axis, and the demand in kW is plotted on the vertical axis. The figure contains a total of 12 graphs, representing the months from January to December.

As described the operation of the feeding system is responsible for the daytime peaks in demand. After advice from Kjetil Ørnes it was decided to have the salmons transferred to sea in the beginning of April when modelling a 1-year farming cycle. The feeding follows the same daily demand profile until November, where at this point the

salmons will have reached a weight of approximately 2.5kg. The feeding profile then changes because the salmons are given around 20% more feed, and it is given over a shorter time period. This is seen from the peaks in energy use being higher between August and December. In January the daily energy use drops of a little because the salmons are given less feed in the weeks before slaughtering. Finally, there is two months of statuary uncultivated period, where there are no salmons in the sea cages, and therefore no peak in energy demand during daytime. These two months are necessary to avoid the spread of parasites and illnesses from previous farming cycles.
Figure 26 shows the average daily demand for each month.

As seen from the hourly demand data from Grieg Seafood's salmon farms the daily demand can change from day to day (Figure 27). To incorporate this into the synthetic demand profile, a random variability factor was added. The day-to-day variability was set to 20% and the hourly time step variability to 10%. What this does is to run a randomising function through all the time steps, which in turn are changed inside the limits of the variability factors. This will ensure that the system that is designed can handle fluctuations in the energy demand.

4.3 System Schematic and Component Search Space

Figure 33 shows the system schematic of the finalised HOMER model. The system schematic shows the AC components, generators and wind turbines to the left, and the DC components, PV and batteries to the right. In the middle we can see the salmon farm load, which has a daily average of 341.92 kWh/day. The peak power during the one-year farming cycle is 92.56 kW. The daily demand profile has a day-to-day variability set to 20% and the hourly time step variability set to 10%. This will give a more realistic daily demand profile throughout the farming cycle.

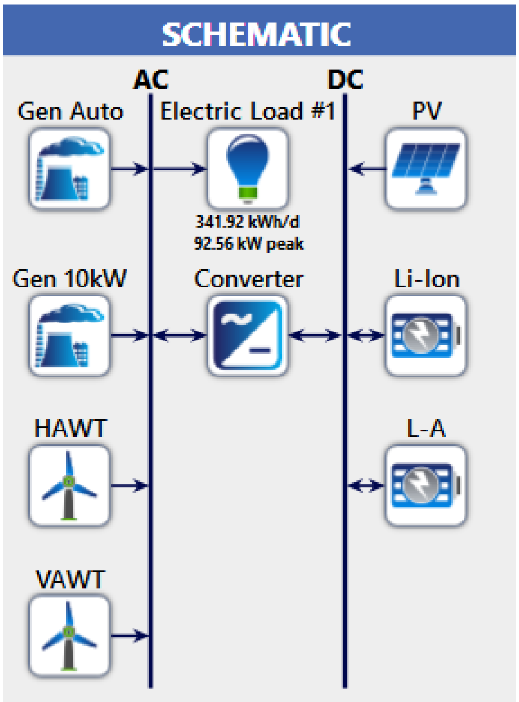

Figure 33 System schematic from HOMER energy showing all the components evaluated in the computer modelling. HOMER will suggest combinations of these components to meet the electrical demand.

Each of the components analysed were given an upper and lower optimising limit. This will ensure that HOMER analyses all the possible configurations in between these two limits. For example, one single PV-panel was set to have a capacity of 1kW. It was then given an upper optimising limit of 300 panels and a lower optimising limit of 0 panels. This would effectively make HOMER search all PV combinations between 0kW and 300kW of installed PV-capacity. The same method was applied to all the other components, and the intervals was adapted to incorporate all reasonable possibilities. For the diesel generator the HOMER function ‘auto-size generator’ was used, this makes the software automatically size the generator to match the peak demand. The search spaces used are listed in Table 10:

Component	Search space
Wind turbine	0-150 kW
PV panels	0-300 kW
Converter	0-100 kW
Li-Ion	0-1500 kWh
Lead Acid	0-1500 kWh

Table 10 Search space for the different renewable resources and storage options

When carrying out the economic analysis the discount rate for the project is assumed to be 6%. This was a suggested estimate for solar and wind projects by the Oxera report, *"Discount rates for low-carbon and renewable generation technologies"* (Oxera, 2011). Project lifetime was set to 20 years, as this is a typical lifetime of components like wind turbines and PV panels. The inflation rate used in the modelling is 2% in accordance with the FED inflation target (FED, 2015). The cost of the converter is estimated at 500 £/kW (HOMER Energy LLC, 2016).

4.4 Weather Data

An important part of modelling a renewable energy system is the weather data used. The performance of PV panels and wind turbines are directly linked to the wind speed and the solar radiation. This thesis does not look at one specific salmon farm, but rather analyses the potential for utilising renewable energy sources in general for salmon farms. Because of this, the location of the modelled salmon farm had to be chosen.

Keeping in mind that future salmon farms are likely to move further offshore, a location approximately 10 km west of Stavanger was chosen. More specifically halfway between Randaberg and Kvitsøy. This could be considered an open offshore location, but nearby islands make it somewhat less exposed. Figure 34 shows the location on the map.

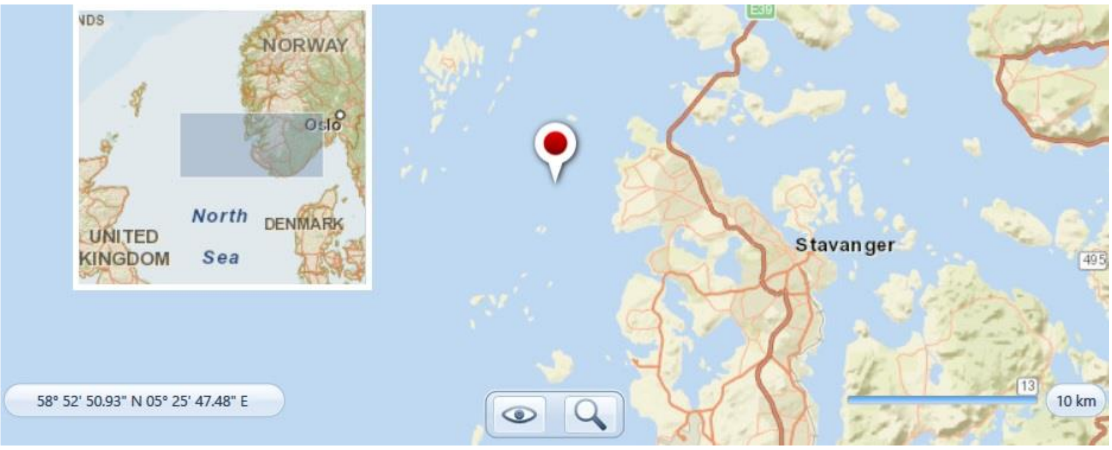

Figure 34 Location of the modelled salmon farm. This is the location the weather data will be taken from. Screenshot from HOMER energy.

HOMER energy uses NASA surface meteorology and Solar energy data. The data set is called the SSE-Renewable Energy data. It is collected from satellite data over a 22-

year period between July 1983 and June 2005. The data has a resolution of 1° latitude by 1° longitude (NASA, 2016). The resolution of the data is hence quite low. However, as the goal is to find a general solution for salmon farms in Norway, not one specific salmon farm, this is not a key requirement in this study.

To get precise wind data it should ideally be measured at the specific site chosen for an installation. This measured data should have at least a 1-hour resolution, and it could then be inputted to the HOMER model. Since this study is seen as a feasibility study, it was chosen not to use measured data. Instead monthly average data from the SSE-Renewable Energy database was used.

The wind speed changes constantly, so if a monthly average was used directly, keeping the wind speed constant from hour to hour, it would give very unprecise results. To avoid this, HOMER energy uses an algorithm to create an hourly wind speed from the average monthly values. This algorithm is based on characteristics of real wind speed data, and it will take into account gust patterns and seasonal and daily variations *(HOMER energy, 2016)*. Figure 35 shows the average monthly wind data that was used in the computer modelling.

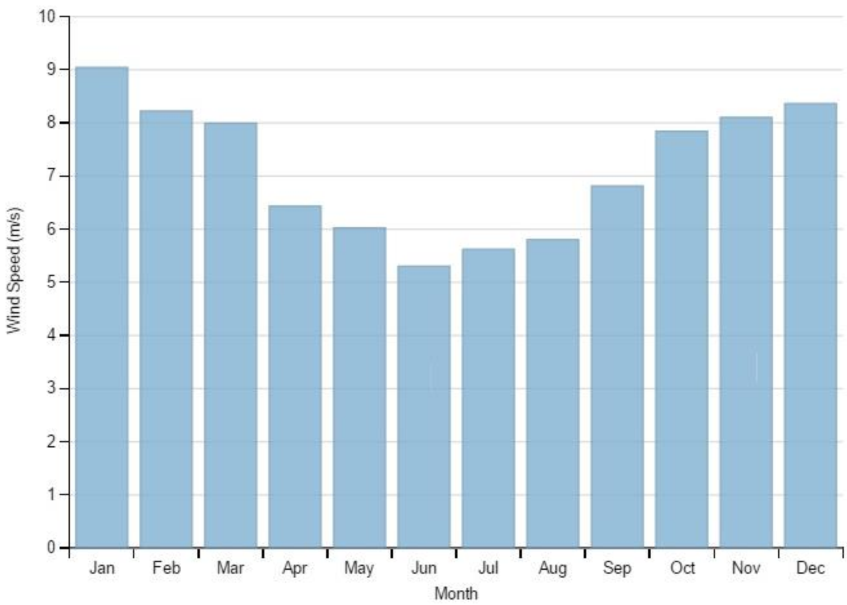

Figure 35 Average monthly wind data from HOMER energy at the location chosen, 50 metres above the surface. Lower wind resource in summer, which will impact the performance of the wind turbine.

Solar radiation data was also taken from the SSE-Renewable Energy data. A similar algorithm as the one HOMER uses for wind translates the average monthly solar radiation into hourly data. Figure 36 shows the average monthly solar radiation used in the computer modelling.

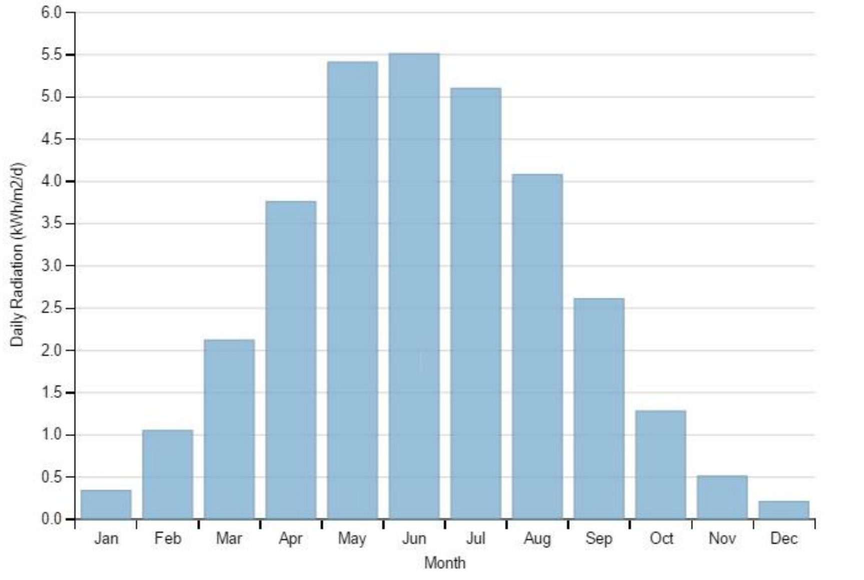

Figure 36 Average monthly solar radiation at the location of the salmon farm. Higher solar radiation in summer than in winter, this will result in PV performing better during the summer months.

The benefit of combining solar and wind in a renewable system is that they complement each other. Wind will provide more power in the winter, while solar will provide more in the summer.

With the costs for all the components, weather data and key parameters defined, the optimisation simulations could be undertaken. The next section will describe the results from the various simulations

4.5 Summary

This chapter has evaluated different energy modelling tools, where HOMER energy was found to be the best suited. Then the process of obtaining a demand data was described. Hourly demand data was obtained from the salmon farming company Grieg Seafood. Through a field trip and an interview, the daily electrical demand was better understood.

A general demand profile was created using data from Teistholmen salmon farm, interviews and equipment consumption data. A one-year farming cycle was chosen for modelling. Special attention was given to the feeding system, which is responsible for around half of the electrical consumption. Then the system schematic and weather data used was described.

5 Results

When evaluating the results, it was chosen to look at both cost and performance. One of the central cost figures is the net present cost (NPC) of an investment. Which in HOMER is defined as; *"The present value of all the costs that the system incurs over its lifetime"* Another figure that will be used for assessing the economics of a system is the cost of electricity (COE), which is define as; *"The average cost per kWh of useful electrical energy produced by the system"*. The capital cost (CC) will also be stated for the systems, and can be defined as; "*The total cost of components at the beginning of the project"*

The performance of the system is also an important characteristic and this will be expressed by the use of the renewable fraction (RF). RF is defined as; *"The fraction of the energy delivered to the load that originated from renewable power sources"*. The higher the RF of a system, the more of the energy load is met by a renewable source. Another important figure is the excess electricity (EE) produced by each system. EE can be defined as; *"Surplus electrical energy that must be dumped because it cannot be used to serve a load or charge the batteries"* If a system has a high EE fraction, this means that a lot of the electricity produced is not put to use.

The monthly average electrical production divided into components will be shown graphically for each of the systems. Also a detailed breakdown of the costs for each of the systems will be shown. Details about the components used in the modelling can be found in chapter 3. For the initial simulations the medium cost estimate was used for all the components.

5.1 Pure Diesel Generator System

Figure 37 Illustration showing how a salmon farm can look today with a diesel generator. To the left is the net cage where the salmons are kept. To the right is the feed barge. The diesel generator and fuel is located below deck (Akva Group, 2015).

In order to have a baseline cost, a simulation was undertaken to investigate the costs of producing all the electricity from a diesel generator. The option ‘auto-size generator’ was chosen in HOMER-energy, which makes the simulator choose an ideal generator to match the demand. In this case a 110 kW diesel generator was chosen by HOMER. As described, the demand profile is built with a basis in Teistholmen, which uses a grid connection to supply power. Teistholmen have always had a grid connection, so it is not possible to verify if this would be the correct generator size to meet this demand. However, according to Kjetil Ørnes at Grieg Seafood, one of their salmon farms, which is larger than Teistholmen has a 160 kW main diesel generator. This gives an indication that the turbine size is reasonable.

As mentioned in section 3.6 about diesel generators, the efficiency of a generator is dependent on what percentage of maximum output power the generator runs at. Most generators are made to have a peak efficiency near their peak power output. This means that if a diesel generator with a capacity of 110 kW is supplying a load of only 5 kW they will become very inefficient. However, most generators will never run that low, as they have a minimum load ratio, in this case set to 25% of the peak power output. What this means for this specific generator is that the it will never have a power output less than 27.5 kW. If then only meeting a load of 5 kW, fuel will be wasted and excess energy occurs.

In addition to the 110kW diesel generator, a second 10 kW generator was added to the system. This smaller generator will run when the electrical demand is low, and thereby minimise fuel waste. Pure Diesel generator systems are normally set up this way to minimise fuel waste and maintenance. The highest hourly electrical demand is 93kW, however, HOMER choses a diesel generator with extra capacity available to be able to meet peak happening inside the 1-hour time steps.

Meeting the electrical demand with a pure diesel generator system yielded the following costs and system characteristics:

NPC (£)	COE (£/kWh)	RF (%)	EE (%)
837,860	0.491	0	7.5

Table 11 Main characteristics of ***pure diesel*** *system with a 20-year lifetime. NPC – net present cost, COE – cost of electricity, RF – renewable Fraction, EE – excess electricity.*

The pure diesel generator system has a low initial capital cost, of only £60 000. There are however other costs that makes the NPC as high as it is. A cost summary is shown in Figure 38 below:

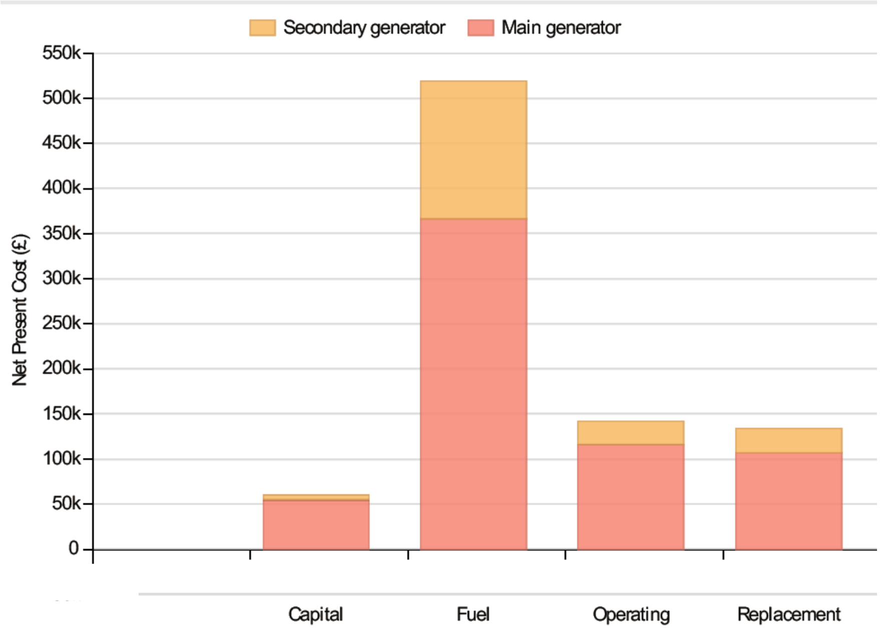

Figure 38 Cost summary for the ***pure diesel system****. The diesel generator system has a low capital cost, but a very high fuel cost. Operating cost is relatively high, and so is the replacement cost due to the diesel generators lifetime.*

The fuel is responsible for 62% of the NPC, showing that diesel generators are expensive to use for long periods. Because the diesel generator runs constantly in the 20-year lifetime of the project, the operating and maintenance costs are also high. O&M costs amount to 35% of the NPC. Another interesting figure is the excess energy of the diesel generator system. The reason for this number not being zero, but 7.5% is because the diesel generator does not match the demand exactly. Also, the efficiency of the generator drops off when the generator runs at lower output power than maximum, which is why the minimum load ratios is set to 25%.

With a cost for a pure diesel system established, the next step is to investigate the cost of a hybrid system.

5.2 Hybrid System

Figure 39 The feed barge with the cost optimal **hybrid system**. *The wind turbine has a capacity of 14 kW, and there is a total of 35 kW of PV capacity. Below deck there are Li-Ion batteries with a total capacity of 146 kWh and diesel generators. Some PV panels are placed on floating modules as there is not enough space on the feed barge.*

When trying to find a cost optimal hybrid system, the overall goal has to be decided. One way to define the cost optimal system could be the system that provides the highest renewable fraction for the lowest cost. However, the definition used here will be the system with the lowest NPC and COE, without taking into account the renewable fraction. The system outlined in Table 12 is the system that provides the lowest cost of electricity:

NPC (£)	COE (£/kWh)	RF (%)	EE (%)
701,176	0.411	34	4.6

Table 12 Main characteristics of the cost optimal ***hybrid system*** *over a 20-year lifetime. NPC – net present cost, COE – cost of electricity, RF – renewable Fraction, EE – excess electricity*

This system would actually have a 16% lower NPC and COE than the diesel generator system. The renewable fraction is at 34%, which is fairly low, but with a cost lower than the diesel system, this is acceptable. The system is also quite efficient, as only 4.6% excess energy occurs. This is actually lower than the pure diesel system, which has 7.5% excess energy.

The components of the cost optimal system are outlined in Table 13:

Wind turbine (kW)	PV panels (kW)	Li-Ion batteries (kWh)	Converter (kW)	Diesel generator (kW)
14	35	146	48	110 + 10

Table 13 All the components in the cost optimal ***hybrid system****, which provided electricity for the lowest cost.*

The optimal wind turbine size was found to be a 14 kW HAWT. In addition to the wind turbine, this system includes 35 kW of PV capacity. The reason for this system having more PV-capacity than wind capacity is partly because of the capital and O&M cost for each of the power sources. It could also be because the energy demand is at its lowest in February and March, when there are no fishes in the sea cages, and therefore no feeding. Looking at the wind resource in Figure 35 we can see that these two months are the second and fourth windiest. The system also includes both a 130 kW and a 10 kW diesel generator, which provides electricity when not enough renewable energy is available.

For the cost optimal solution Li-Ion batteries where found to be cheaper than L-A batteries, even though they have a higher capital cost. The higher cost is however outweighed by the longer lifetime and higher efficiency of the Li-Ion batteries.

Figure 40 shows the breakdown of the costs for this system, the light blue box called "component" is the system converter:

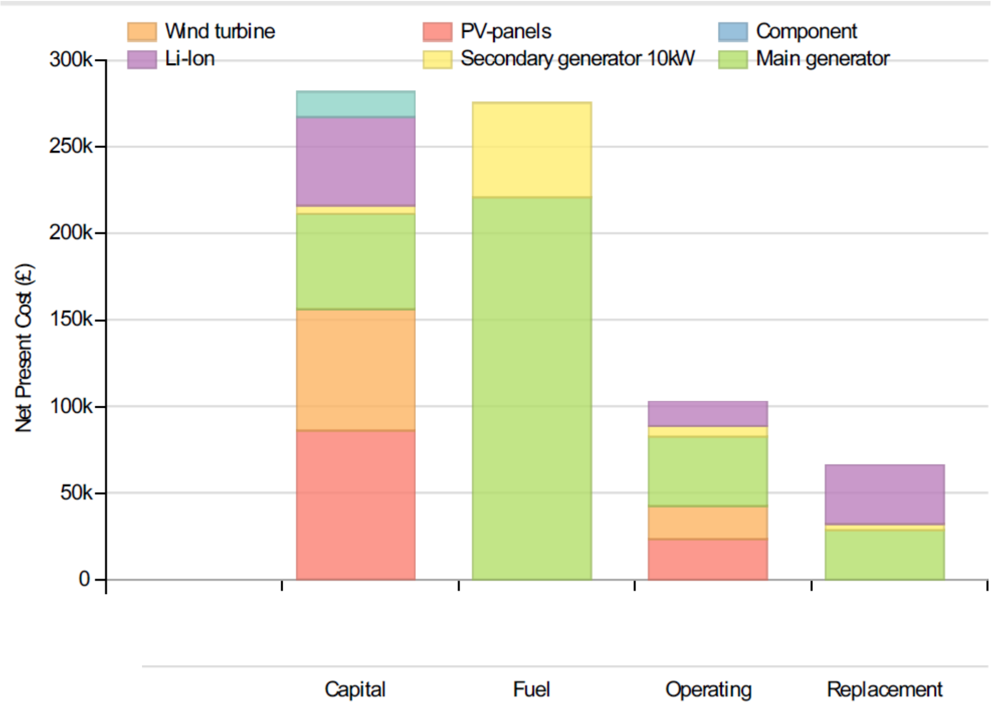

*Figure 40 Cost summary for the **hybrid system**. This system configuration has a much higher capital cost than the pure diesel system, however, the fuel cost is reduced.*

Comparing the system cost in Figure 40 to the pure diesel system in Figure 38, the cost categories are very different. While the diesel system has a capital cost of £60,000, the hybrid system has a capital cost of nearly £282,000, almost a five-time increase. The fuel category on the other side has been reduced from £519,000 to £275,000, a 47% decrease. We can say the hybrid system is capital intensive, while the diesel system is fuel intensive.

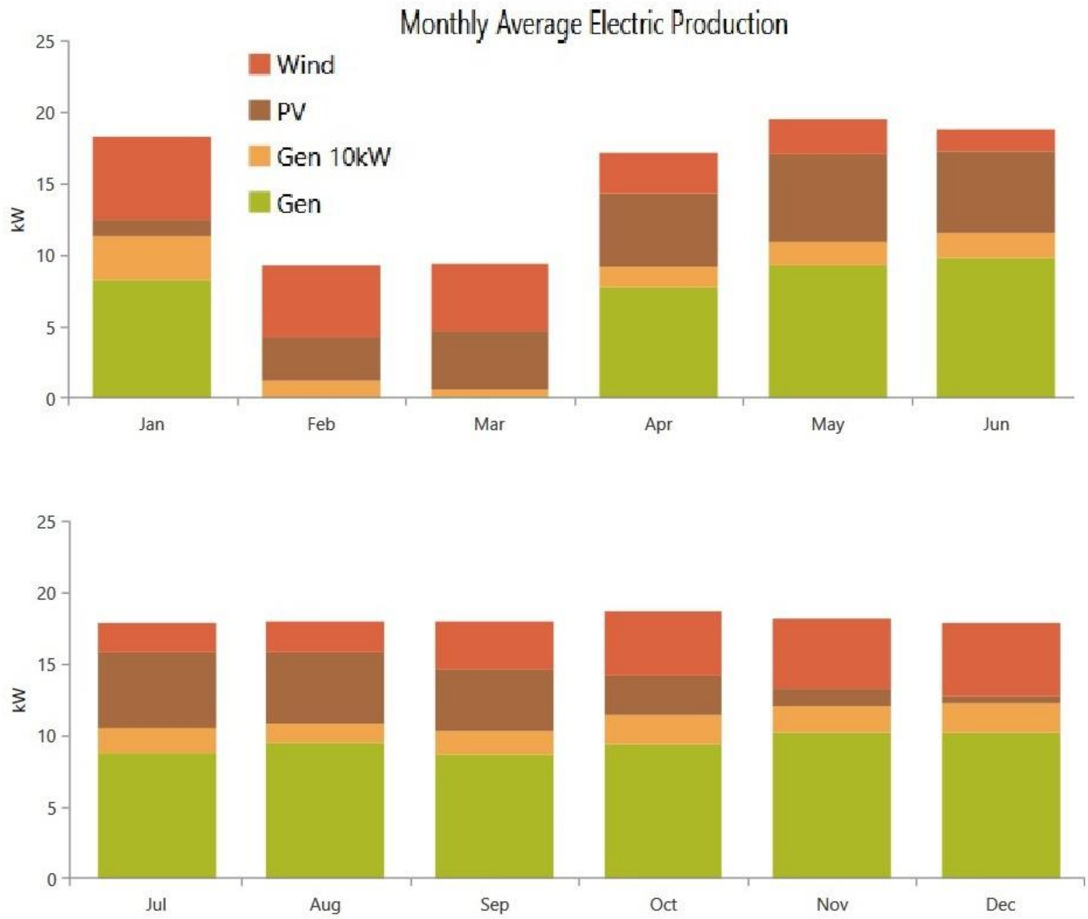

Figure 41 This graph shows the monthly average electrical production for each of the components in the cost optimal ***hybrid system****. In the two months with no salmons in the sea cages, there is almost no need for the diesel generator.*

The graph in Figure 41 shows the monthly average electrical production. The green part of the columns shows the average production from the 110 kW diesel generator, light brown – 10 kW generator, brown – PV and red – wind. Examining the average monthly production from PV and wind, it is clear that during winter, most of the renewable energy produced comes from wind. During the summer months, it is the opposite, and the PV- panels produce more power. This coincides with the weather data used. Another realisation from this is that an optimal hybrid system is likely to include both PV panels and a wind turbine, as they complement one another.

5.3 100% Renewable System

*Figure 42 The feed barge with the **100% renewable** system. The wind turbine has a capacity of 59 kW, and there is a total of 109 kW of PV capacity. Below deck there are Li-Ion batteries with a total capacity of 1,183 kWh and diesel generators. A lot of the PV panels are placed on floating modules as there is not enough space on the feed barge.*

It would be possible to create a system which relies 100% on renewable resources. Running the simulation with the same parameters as earlier, but removing the diesel generators, following costs and system characteristics were found to be the optimal:

NPC (£)	COE (£/kWh)	RF (%)	EE (%)
1,382,559	0.810	100	41.4

*Table 14 Main characteristics of the **100% renewable system** with a 20-year lifetime. NPC – net present cost, COE – cost of electricity, RF – renewable Fraction, EE – excess electricity.*

Looking at the figures in

NPC (£)	COE (£/kWh)	RF (%)	EE (%)
1,382,559	0.810	100	41.4

Table 14, and comparing them to the cost optimal hybrid system in Table 12, we can calculate that the NPC increases by 49% when going from 34% RF to 100% RF. This shows that a 100% renewable systems have a much higher cost compared to the hybrid system alternative. The excess energy, EE for the 100% renewable system is substantially higher than for the two other systems. This is one of the factors that drive up the cost of this system. Table 15 shows the components of the 100% renewable system:

Wind turbine (kW)	PV panels (kW)	Li-Ion batteries (kWh)	Converter (kW)	Diesel generator (kW)
59	109	1,183	97	0

Table 15 Components in the 100% renewable system, which yielded the highest cost of electricity.

To achieve a 100% renewable system, a lot of PV-capacity needs to be added to provide enough electricity throughout the summer. The 109 kW of PV panels would translate to approximately 763 m^2. This could not be fitted to the feed barge, so floating modules or a nearby island would have to be used to accommodate the panels. This adds uncertainty to the cost estimate because of the potential floating PV modules. A relatively large wind turbine of 59kW would be needed as well, and it is uncertain if it could be added to the feed barge without causing instability.

Another aspect is the batteries, and the weight of them. The weight per 1 kWh Li-Ion battery is approximately 7 kg, this would mean a total weight of 8.2 tons for the 1,183 kWh's of batteries. This is a relatively small weight compared to the 450 tons' capacity feed silo and 30 tons' diesel tank on a typical feed barge. It should not be any issue with regards to the weight of the batteries. Space could however be a constraint.

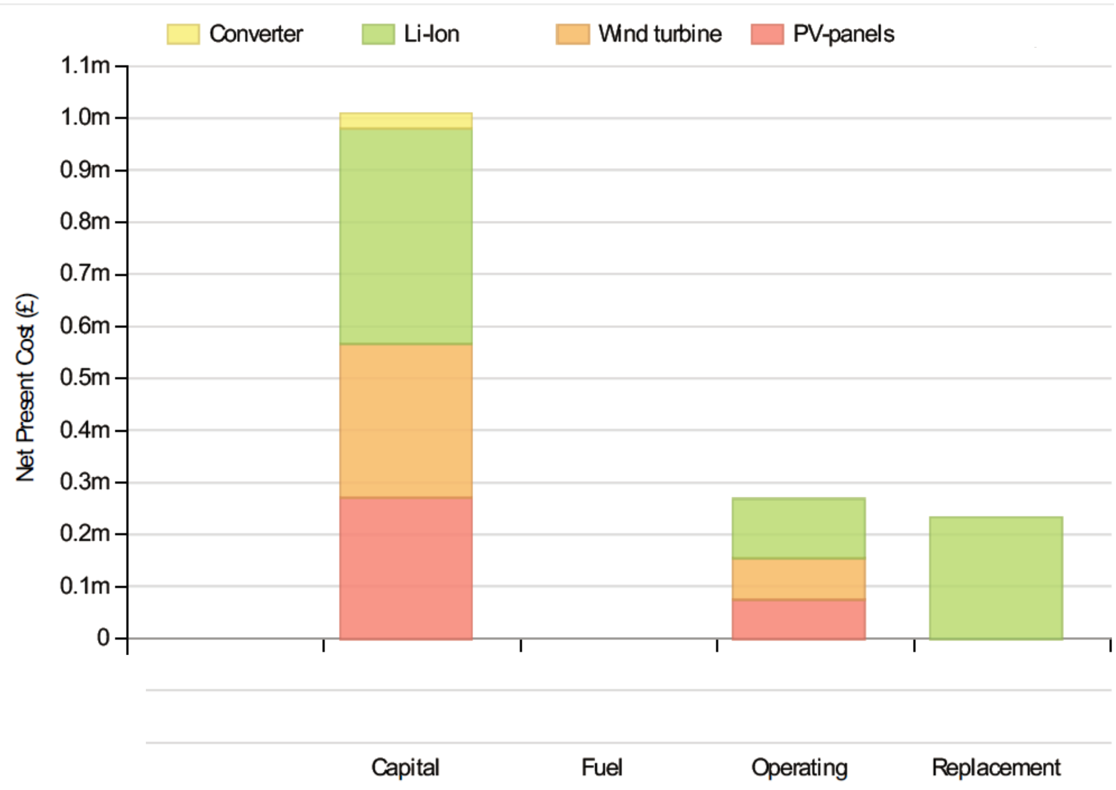

Figure 43 Cost summary for a 100% renewable system. An interesting detail is how the capital cost almost quadruples compared to the hybrid system. It takes a lot of components to make a reliable 100% renewable system without backup generation. The largest portion of the capital cost is the batteries.

As can be seen from the cost summary in Figure 43 the largest cost is the Li-Ion batteries. Without any back-up diesel generator, the system, which relies on two non-dispatchable power resources needs large amounts of storage capacity to deliver electricity when no wind and solar is available. With no diesel generators installed, there is no need for fuel, and this cost drops to zero. The operation and maintenance cost is also relatively high, 48% higher than the pure diesel system and 63% higher than the cost optimal hybrid system.

There is a relatively high replacement cost to this system as well, because approximately half of the batteries need to be changed during the 20-year lifetime of the system. One of the problems by having a 100% renewable energy system is that there is no backup power available. This would make such a system less reliable, which is a crucial element for a salmon farm power system.

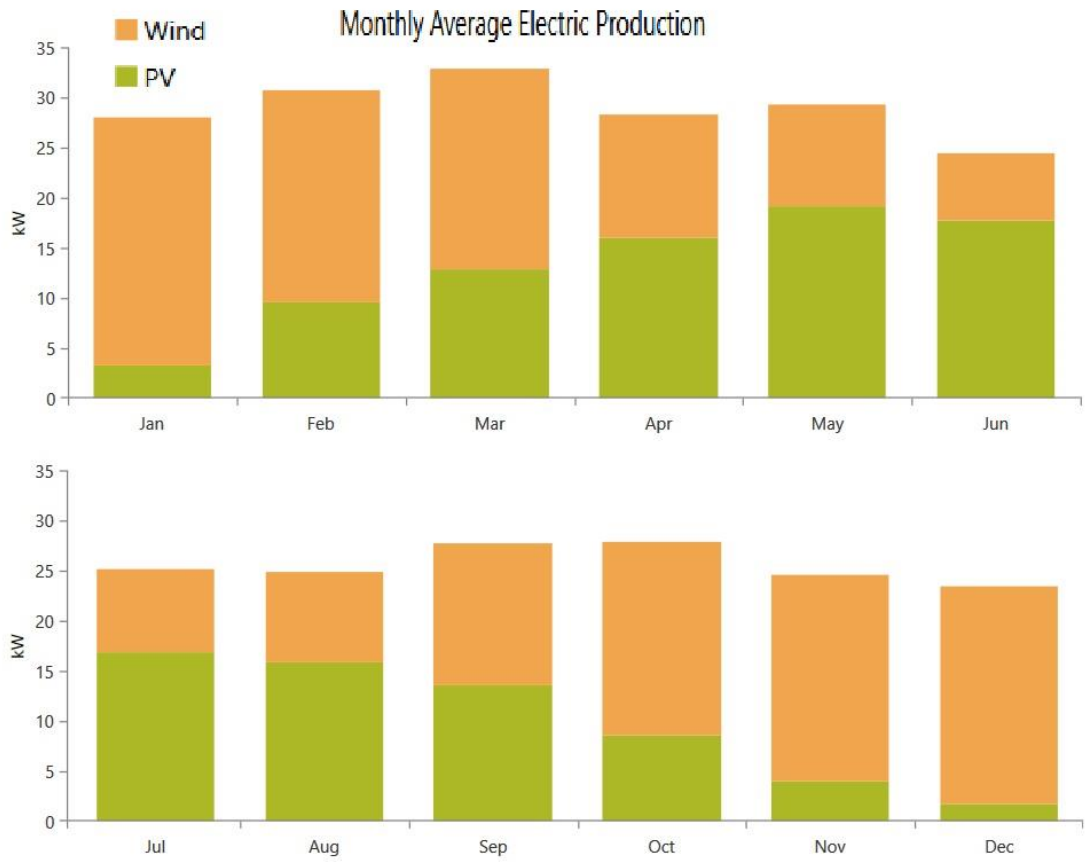

Figure 44 Monthly average electrical production for a 100% renewable system. Note how the 59 kW wind turbine provides most of the electricity in winter, while the 109 kW of PV panels delivers most of the electricity in summer.

The graph in Figure 44 shows the monthly average electrical production. The brown part of the columns indicates the average production from the 80kW wind turbine, and the green part the electricity produced by the PV panels. Wind dominates the energy production in the winter, while the PV is more important during the less windy summer months.

5.4 Overall Comparison

An overview of the NPC, CC, COE, RF and EE of the three systems described are found in Table 16:

	NPC (£)	CC (£)	COE (£/kWh)	RF (%)	EE (%)
Pure diesel system	837,860	60,000	0.491	0	7.5
Hybrid system	701,176	281,769	0.411	34	4.7
100% renewable system	1,382,559	1,009,590	0.810	100	41.4

Table 16 Overview of system characteristics for the three different system configurations. The pure renewable system has the highest NPC – Net present cost and COE – cost of electricity. It also has the highest CC – capital cost, and a lot more electricity is wasted as the EE – excess electricity is higher than the two other systems.

The hybrid system was found to be the most cost effective system to meet the electrical demand of a salmon farm. It would deliver the lowest COE, and also less excess electricity than the two other systems. However, it has a substantially higher capital cost than the pure diesel system, and therefore a higher initial investment is needed. There are some uncertainties associated with the costs. Especially the capital cost and O&M cost for PV panels and wind turbines. This will be addressed in the sensitivity analysis in 5.5.

	Wind turbine (kW)	PV panels (kW)	Li-Ion batteries (kWh)	Converter (kW)	Diesel generator (kW)
Pure diesel system	0	0	0	0	110 + 10
Hybrid System	14	35	146	48	110 + 10
100% renewable system	59	109	1,183	97	0

Table 17 Overview of the components for the three different systems. The number of components increase dramatically when going from a hybrid system to a 100% renewable system.

Another interesting aspect to look at for the different systems are the emissions associated with them. Table 18 summarises the emissions for each of the systems.

	Pure diesel system	Hybrid system	100% renewable system
	kg/year	*kg/year*	*kg/year*
Carbon dioxide	123,229	65,432	0
Carbon monoxide	304	162	0
Unburnt hydrocarbons	34	18	0
Particulate matter	23	12	0
Sulphur dioxide	247	131	0
Nitrogen oxides	2714	1441	0

Table 18 Emission comparison for the different systems. The pure diesel system has the highest emissions, the hybrid system has approximately half of the emissions, and the 100% renewable system has no emissions.

Reducing the use of diesel would also lead to significant emission reductions. Table 18 shows the emissions of pollutants for each of the systems. Going from a pure diesel to a hybrid system could reduce the yearly CO_2 emissions by 46.9% while reducing the cost of electricity by 16.3%. The table only lists emissions from the burning of fuels, which means that the emissions linked to for example the production of the wind turbines, batteries and PV panels are not included.

5.5 Horizontal Axis Wind Turbines (HAWTs) vs Vertical Axis Wind Turbines (VAWTs)

Figure 45 The feed barge with a floating vertical axis wind turbine (VAWT). Because of the different power curves for VAWTs and HAWTs, the systems with a HAWT were found to have a lower cost of electricity. However, VAWTs have a lower centre of mass, and as described in section 3.2.2, this could have benefits it the turbine is floating.

In the computer modelling VAWTs were also tested, to evaluate if they could provide electricity for a lower cost than HAWTs. When evaluating the VAWTs the same costs and parameters were used as for HAWT. The only difference was the power curve of the two turbines, which can be found in Figure 15 in section 3.2. For the hybrid system, and for the 100% renewable system the HAWT was preferred. This is because the HAWT produces more power per kW of installed capacity.

A specific simulation was carried out to investigate the cost of creating the same hybrid system as the cost optimal system found previously, but with a 14kW VAWT instead of the chosen 14kW HAWT as the only difference. This yielded the following results:

Wind turbine type	NPC (£)	CC (£)	COE (£/kWh)	RF (%)	EE (%)
14 kW VAWT	757,036	281,769	0.443	27	2.6
14 kW HAWT	701,176	281,769	0.411	34	4.6

Table 19 Main characteristics of the ***hybrid system*** *with a VAWT and a HAWT. All the components stayed the same size and the number of units were the same. The only difference is the wind turbine type. The NPC – net present cost is higher because the RF – renewable fraction is lower for the VAWT system. With a lower RF, more diesel is used.*

Table 19 shows that a hybrid system with a VAWT would perform different from a system with a HAWT. One would at first think that these two systems would have the same NPC, as the only thing that has been changed is the power curve of the wind turbine. However, the NPC also includes fuel cost, and since the RF is decreased by 7%, more fuel is used in the VAWT system. The capital cost of the two systems is exactly the same. Excess electricity is actually decreased. This is because the wind turbine produces less energy, with the same amount of batteries installed.

The reason for the VAWT having a higher NPC and a lower RF is because of the different power curves for the two turbine types. While the VAWT has a higher efficiency in strong winds, it is less efficient in medium strong winds. Since medium strong winds occur more often throughout the year, the overall energy production is higher from the HAWT. The conclusion from these calculations is that a VAWT needs to have a lower capital cost to compete with a HAWT. However, there exist wind turbines with different power curves than the ones used, so different wind turbine designs could produce other results.

It could be that a VAWT could be better suited to place on the feed barge, or place on a separate floating foundation. This is because of the lower centre of mass would make the turbine with foundation more stable. It could also be easier to maintain as the alternator is placed at the base of the mast. These possible advantages are not taken into account in these calculations. More detailed studies would have to be carried out to investigate the stability of the feed barge with different turbine concepts.

5.6 Sensitivity Analysis

There is a high grade of uncertainty linked to the costs for these systems. Especially the cost of Photovoltaic (PV) panels and wind turbines. This is because there exist very little data on small scale offshore renewable systems. It was decided to focus the sensitivity analysis on the hybrid system, which would provide electricity for the lowest cost. When experimenting with different values in HOMER, it was found that the two most crucial figures for the overall cost, was the cost associated with the PV panels and the wind turbine. A sensitivity analysis was carried out to evaluate what impact changing costs for these two components had to the overall NPC of the hybrid system. It was always assumed that the capital cost was linked to the O&M cost, so that a doubling in capital cost also lead to a doubling in O&M cost. Table 20 shows how the NPC of the hybrid system changes with varying costs for PV panels and the wind turbine:

PV	2.0	*786,306*	*812,886*	*857,466*	*902,045*
	1.5	*712,582*	*757,161*	*801,741*	*846,321*
	1.0	*656,857*	*701,176*	*746,016*	*790,596*
	0.5	*601,133*	*645,712*	*690,292*	*734,872*
	Multiplication values	0.5	1.0	1.5	2.0
	Wind turbine				

Table 20 Cost sensitivity analysis for the ***hybrid system****. This table can be used to evaluate what happens to the NPC – net present cost when the cost of PV and wind turbine changes. Blue cells are the cost multiplier and white cells shows the NPC in £. The green cell highlights the initial cost estimate outlined in chapter 5.2.*

When examining Table 20 we can evaluate what impact changing the costs for PV panels and wind turbines does to the NPC of this system. An example could be: "*What happens if the cost of wind turbines goes up by 50%, and because of the need for floating modules, the PV cost doubles?"*

To answer this question, we can use Table 20. This is done by following the horizontal wind axis until the blue cell with the value 1.5, then going up vertically on the PV axis until the value 2.0, we then find the new cost. The new NPC with the increased component costs is £857,466. This would effectively increase the cost of the wind turbine from £5,000 to £7,500 per kW of installed capacity, and the yearly O&M cost would go from 4-6%. The cost of PV panels would increase from the estimated £2,500 to £5,000 per kW of installed capacity. Yearly O&M would go from 4% to 8%.

The example above shows that the NPC of the hybrid system is quite sensitive to changes in the PV panels and wind turbine costs. However, since the renewable hybrid system already has a 16.3% lower NPC than the pure diesel system, the component cost can increase without eliminating the profitability. Even with this substantial cost increase, the renewable hybrid system is still only £19,606 or 2.2% more expensive than the pure diesel system. An estimate from the sensitivity analysis indicates that the PV-panel cost and the wind turbine cost can both go up at least 50% each, without giving the hybrid system a higher NPC than the pure diesel system.

Another aspect is that changing the PV and wind turbine cost separately would yield completely different system configurations. If the PV cost is lower than the wind turbine cost, PV dominated systems would be favoured, and vice versa. Also, the higher the cost of the renewable technologies, the more economical is a diesel generator dominated system. This can be shown by plotting PV cost against wind turbine cost and renewable fraction, as shown in Figure 46:

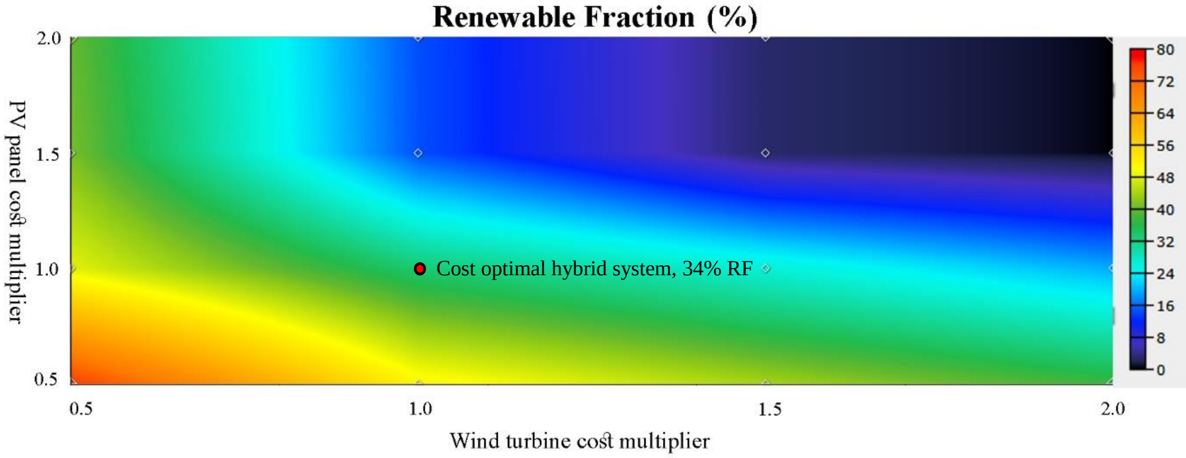

Figure 46 Renewable fraction (RF) in relation with PV and wind turbine cost multiplication values. The colours illustrate the RF in % as a function of changing PV and wind turbine cost. If the cost of PV and wind turbine is reduced by 50%, another system configuration would be optimal. In this case, a system including a lot more renewable generation, having an 80% RF. If the cost doubles, a system incorporating no renewables will be the cost optimal, thereby yielding 0% RF.

Figure 46 illustrates how sensitive the system configuration is to changing costs for the two most crucial components, PV and the wind turbine. As a logical response to increasing the price of these two components, the RF will decrease as systems with more diesel generated electricity is preferred. To better understand how the costs impacts the system configuration, we can make a plot using the same two axis, but having the surface plot display the resulting PV capacity. This is done in Figure 47:

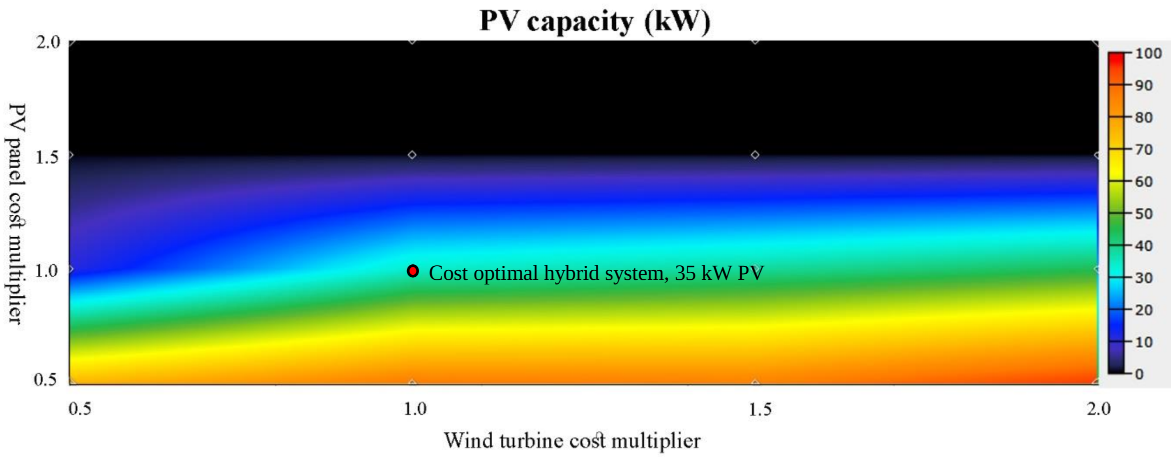

Figure 47 PV capacity in relation with PV and wind turbine cost multiplication values. The colours illustrate the installed PV capacity in kW as a function of changing PV and wind turbine cost. We can see that the cost of PV is quite sensitive, a 50% increase in PV costs, results in systems including no PV.

By examining Figure 47, we can see how a relatively small increase in PV cost, rules out PV from the cost optimal system configurations. The initial costs that was used for PV was £2,500 per kW of installed capacity. A 50% price increase would result in a price of £3,750 per kW of installed capacity. The yearly O&M would go from 4% to 6%. The conclusion that can be drawn from this is that for PV to be feasible, the cost needs to be kept lower than approximately 3,750 per kW of installed capacity. This might rule out floating PV panels as a feasible solution, as this would increase the cost substantially.

The same exercise can be carried out to evaluate the sensitivity of the wind turbine cost. Using the same axis as previously, but having the surface plot display the resulting wind turbine capacity, we can evaluate the cost sensitivity of this component as well. This is done in Figure 48:

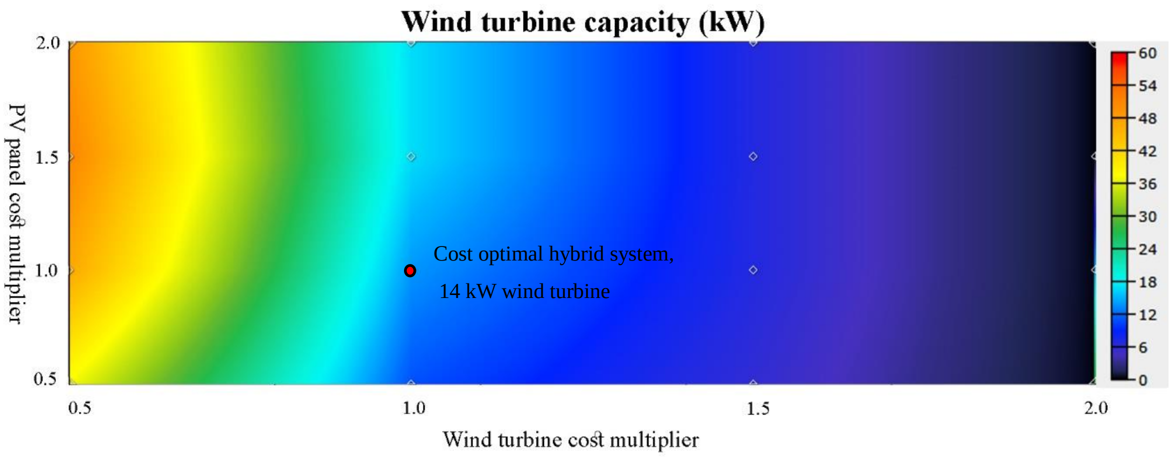

Figure 48 Wind turbine capacity in relation with PV and wind turbine cost multiplication values. The colours illustrate the installed wind turbine capacity in kW as a function of changing PV and wind turbine cost. The wind turbine capacity is little less sensitive to changing costs than the PV panels.

Looking at Figure 48, we can see that the wind turbine capacity is a little less sensitive to change than the PV capacity. A 50% cost increase for wind turbines, would result in the cost optimal hybrid system having a 7 kW wind turbine, compared to the 14 kW when using the original cost of £5,000 per kW of installed capacity. However, if the cost doubles to £10,000 per kW of installed capacity, and 8% O&M cost, wind turbines are ruled out as a potential solution as well.

On the other side would a decrease in wind turbine cost lead to a cost optimal hybrid system incorporating a lot more wind turbine capacity. If the price fell by 50%, to £2,500 per kW of installed capacity, the cost optimal hybrid system would include a 48 kW wind turbine. This is almost 7 times more wind turbine capacity than the initial estimate.

This sensitivity analysis illustrates how it is almost impossible to design an optimal hybrid system without knowing the costs exactly. Relatively small changes can alter the cost optimal hybrid configuration dramatically. Other factors like battery cost, fuel cost and diesel generator cost could also be evaluated the same way to. However, it was found that PV and wind turbine cost were the two most uncertain variables, that also had the largest impact on the hybrid system configuration and overall cost. It was therefore decided to focus the sensitivity analysis on these two elements.

5.7 Summary

During the simulation study, three different electricity systems were found, that could supply power to the salmon farm. One relying solely on diesel generated electricity, the next incorporating renewable generation in addition to the diesel generator, and the last depending only on renewable resources. The hybrid system was found to deliver electricity at the lowest cost of the three. It consists of 14 kW of installed wind capacity, 35 kW of PV, 146 kWh's of Li-Ion batteries, and two diesel generators (130kW and 10 kW).

HAWTs was compared to VAWTs, and it was found that HAWTs delivered electricity at a lower cost than VAWTs. A sensitivity analysis was carried out, highlighting how sensitive the cost optimal hybrid system is to changes in PV and wind turbine costs.

6 Discussion

The discussion part of this thesis will focus on uncertainties tied up to cost and simplifications that were made. A review of the objectives is then carried out, before recommendations are outlined. Lastly, future work to be undertaken is recommended.

6.1 Uncertainties

There will always be uncertainties when planning a project ahead. This is especially true for this specific project, as there are few, if any similar projects in operation. The largest uncertainty is associated with the cost of different components, and the O&M costs. Other uncertainties arise because simplifications are made, or because alternatives are scoped out of the analysis. The following sub-chapters will go into detail on these issues.

6.1.1 Costs

Costs for PV panels and wind turbines were evaluated in the sensitivity analysis. This revealed that changes to these components impacts the overall cost. Another aspect of the cost perspective, is how the cost of PV panels and the wind turbine separately impacts the system configuration.

The specific renewable hybrid system found in this analysis is only the cost optimal solution, if the costs estimated turn out to be exactly the same in a real world project, as shown in Figure 46. It is highly unlikely that all the costs have been estimated correctly, and thus, a different system configurations might be optimal in a real life scenario. Because of this, a more throughout investigation that includes cost data from for example a pilot project should to be evaluated before a full scale project is commenced.

The sensitivity analysis has also been simplified. It was chosen to look only at the hybrid system, and only at changing costs for the PV panels and the wind turbine. The reason for only examining the renewable hybrid system in the sensitivity analysis is because it is seen as the optimal solution. It was therefore the most important to investigate in detail. All the costs used are subject to change. Battery prices can change, and many estimate that Li-Ion batteries will be cheaper in the future, because of larger scale production. This is also the case for PV panels. The company Tesla has a goal to cut Li-Ion battery costs by 50% by 2018 from 2014 prices (Ayre, 2015). This could favour a system with more storage, and less generation capacity.

Fuel costs are also subject to change. The oil price has experienced large fluctuations over the last 10 years, and is likely to do so in the future as well. Another aspect with regards to fuel cost is that salmon farms do not pay a fuel tax on the diesel they use. If a fuel tax is introduced for the aquaculture industry, the cost of fuel would go up by approximately 26%. An increased fuel price will favour more renewable generation, and less use of diesel generators.

For all the components it was used a fixed cost per kW of installed capacity. Most components follow the rule of “economics of scale” to a varying degree. What this means in practice is that larger, higher capacity components give a lower COE than smaller components. E.g. a 3 MW wind turbine will deliver electricity at a much lower cost than a 3 kW turbine per kWh.

The price for HAWTs and VAWTs was set to be equal in the computer modelling. In reality VAWT normally have a higher cost than HAWT for the turbine itself. However, because of the possible advantages outlined in 3.2.2 they could have a lower installation cost. Because of these uncertainties, it was chosen to use the same price estimate for the two turbine design, so that they could be compared from a pure technical viewpoint.

6.1.2 Effects of adverse weather conditions and corrosion

All offshore installations face extreme stresses from the environment. Looking at the history of previous renewable offshore projects, many of them have run into problems quickly. The Pelamis Aguçadoura wave farm (section 3.4) is one example of a project that failed after only two months of operation.

There are many reasons for why operating offshore is so difficult. The constant stresses from wind and waves will over time break down equipment. Additionally, the saltwater makes equipment corrode much faster than on land. Corrosion and rust is not only a problem for equipment directly in contact with the saltwater. With strong winds the salt particles get into the air, and will damage equipment high above the water surface as well.

Many of the effects of weather damage and corrosion can be mitigated by proper planning and by using equipment specifically made for offshore use. The problem is only that the seriousness of operating offshore is often not taken properly into account. Since this is a pilot study, the main focus has been to investigate potential energy systems. In future studies, more attention should be given to the challenges of operating offshore.

It could also be beneficial to share knowledge with the offshore oil and gas industry. The Norwegian offshore oil and gas industry has 50-years of experience operating in offshore conditions. The lessons learned from their projects could be invaluable for offshore renewable installations.

6.1.3 Simplifications

In addition to costs, other simplifications and estimates had to be made. The bullet-points below summarise these, and the possible effects they can have:

- The weather data was obtained from the HOMER database, which calculates the hourly weather data from a 22- year average. This does not yield very precise data, but can be used as an estimate to evaluate the feasibility of renewable energy systems for salmon farms.

- All wind turbine sizes were said to have the same tower height of 25 metres. Using different tower heights would give other results, as the wind resource is dependent on the distance from the ground.

- This study is only looking at a salmon farm in one location using estimated weather data. More precise weather data, and salmon farms in different geographical areas would give other optimal system configurations.

- Looking at an hourly demand does not take into account power fluctuations shorter than 1 hour. If this is not investigated in more detail, an unreliable system could be designed.

- It was decided not to incorporate some of the advanced input parameters in the HOMER modelling. This includes temperature effects for PV panels, wind turbine losses and wake effects. This would have some effect on the overall results, but was considered unimportant because of the other uncertainties involved.

- A limited number of storage options were evaluated. Compressed air storage could provide certain benefits, but it was chosen not to include this type of storage in the computer modelling. Hydrogen fuel cells and storage should also be evaluated

- The technical aspect of where to fit the different components has only been briefly discussed. A study focusing on where to place components like wind turbines and PV panels should be carried out.

6.2 Reviewing the objectives

Returning to the introduction of this thesis, a number of objectives was set. This chapter will summarise how the objectives were met, and if not, how they can be met in future work.

- **Get an overview of the aquaculture industry, with special focus on the rapid growing salmon farming industry in Norway**

The history of aquaculture and the salmon farming industry in Norway was outlined. The current status of the industry, with special focus on the production chain, environmental problems and energy use was described. Additionally, possible future designs for salmon farms were investigated.

- **Obtain demand data from an offshore salmon farm**

A demand profile had to be created from scratch. This was done by contacting the salmon farming company, Grieg seafood. They provided four months of demand data for three of their salmon farms. This data, combined with interviews was used to generate a reference electrical demand for an offshore salmon farm.

- **Understand what drives the demand, and investigate demand reduction measures**

The salmon farm Teistholmen outside Stavanger was visited. This provided important information on the feeding process, and the installed equipment on a salmon farm. An interview with Kjetil Ørnes at Grieg Seafood provided more information on the electricity use of the different components. A range of demand reduction measures like, LED-lights, heat pumps and more efficient feeding systems were described.

- **Assess possible renewable energy sources and storage solutions**

Wind power, solar power, wave power, tidal power and diesel generators were investigated as possible energy solutions. The storage solutions Lead-acid batteries, Li-Ion batteries and compressed air storage were evaluated. It was decided to include wind power, solar power, diesel generators, Lead-acid batteries and Li-Ion batteries in the computer modelling.

- **Use a computer modelling tool to make a microgrid model for an offshore salmon farm**

The computer modelling tool HOMER energy was found to be the optimal microgrid modelling tool for this purpose. The demand profile that was created was combined with the energy sources and storage solutions. This resulted in a HOMER model where different scenarios could be simulated.

- **Investigate different combinations of wind turbines, PV panels, batteries and diesel generators**

Since HOMER energy was set to optimise for systems with the lowest NPC, cost estimates had to be made. Different system configurations could then be simulated and investigated. It was chosen to model a pure diesel generator system, a cost optimal hybrid system and a 100% renewable system.

- **Recommend a renewable energy system, and do a sensitivity analysis to understand the cost uncertainties**

The hybrid system was found to have the lowest cost and highest reliability. It also reduces CO_2 emissions by almost 50% compared to the pure diesel system. A limited sensitivity analysis was carried out on this system, investigating the impact of changes to PV and wind turbine costs, to the NPC and system configuration.

6.3 Recommendations

The hybrid system has the lowest COE of all the systems analysed. In addition to having the lowest cost, a hybrid system will have a higher reliability than a pure diesel system, or a 100% renewable system. The pure diesel system relies on a single component for all the electricity produced. A pure renewable system on the other hand relies solely on intermittent renewable resources, without any possibility for dispatchable back-up generation. A hybrid system combines the two systems to create an overall more reliable system. In addition to possibly reducing the cost of electricity, it will cut CO_2 emissions substantially.

The recommendations from this pilot study is to find a salmon farm to do a pilot project on. Electrical demand data with a higher resolution than one hour could then be obtained. In addition, the wind and solar resource on the actual location could be measured. After obtaining these data, new simulations could be undertaken in HOMER to validate the system proposed here, and then adjust the system configuration. The scale of the pilot system could be smaller than the proposed hybrid system outlined here. For example, a 3 kW wind turbine, 5 kW's of PV panels, and 10 kWh of battery capacity could be installed at the offshore salmon farm.

A pilot project like this would provide crucial knowledge for further development of renewable hybrid systems for the salmon farming industry. This would include better cost estimates, actual knowledge of how the system performs, and maybe even lower electricity costs for the salmon farm. It would also run no risk of having an unstable system, as the diesel generator would be kept as the main power source.

6.4 Future Work

Most of the recommended future work has been described in the previous chapters. The bullet-points below summarise what is thought to be the most important:

- More precise cost estimates for small scale offshore renewables should be obtained. Some manufacturers might have more data, alternatively a pilot project should be carried out.
- A More detailed electrical demand analysis should be done. The 1-hour resolution does not discover short peaks, and a system could become unstable if this is not incorporated.
- Emissions from the wellboats and service equipment has not been addressed. This is also responsible for considerable emissions. Solutions like battery or hydrogen boats should be investigated.
- Compressed air storage should be investigated in more detail, as it could prove to be a good solution for salmon farms.
- Other storage options, like hydrogen and other battery types should be investigated in more detail, as the modelling only included Li-Ion batteries and Lead-Acid batteries.
- Alternatives to generators running on diesel should be investigated. One solution is biodiesel/biogas, if using a closed cage system, the waste could be collected and made into fuel. Another alternative that could be a solution in the future is fuel cells.
- A more detailed sensitivity analysis should be undertaken to understand what changing costs of batteries, fuel, demand profile and weather data does to the system configuration.

7 Conclusion

The literature review revealed that there exist few, if any open studies that investigates the possibility of supplying offshore salmon farms with renewable electricity. Because of this, the electrical demand profile had to be created. This was done by contacting the salmon farming company, Grieg seafood. They provided four months of demand data for three of their salmon farms. This data, combined with interviews was used to generate a reference electrical demand for an offshore salmon farm.

After a reference demand profile had been created, potential energy resources were assessed to decide which had the greatest potential. Wave and tidal was discarded for various reasons as explained in chapter 3.4 and 3.5. This left wind, solar and diesel generators as possible resources. In addition, storage options had to be evaluated because of renewable energy resources intermittent nature. Li-Ion and Lead-Acid batteries were chosen as the storage solutions for the computer modelling. Various configurations were tested in the computer modelling tool, HOMER-energy. Three different system configurations were analysed. Pure diesel generator system, hybrid energy system and a 100% renewable energy system.

The diesel generator system had an NPC of £837 860 and a COE of 0.491 £/kWh, with a project lifetime of 20-years. It includes one 110 kW and one 10 kW diesel generator. This system would have CO_2 emissions equivalent to 123 229 kg/year, and also produce significant amounts of CO, NO_x, SO_2 and particulate matter. Because of these emissions and the government's target of having a sustainable aquaculture industry there is a motivation to avoid fossil fuel systems.

Another option is to create a hybrid system which combines renewable resources with a diesel generator. The cost optimal hybrid system had an NPC of £701,176 and a COE of 0.411 £/kWh, 16% lower than the pure diesel system. It consists of 14 kW of installed wind capacity, 35 kW of PV, 146 kWh's of Li-Ion batteries, and two diesel generators (130kW and 10 kW).

The possibility of producing all the electricity from renewable resources was also investigated. A system that could provide all of the electricity from renewable resources would consist of 59 kW of wind capacity, 109 kW of installed PV-capacity, and 1,183 kWh's of Li-Ion battery capacity. The NPC of this set-up would be £1,382,559, 49% more expensive than the hybrid system. One of the problems by having a 100% renewable energy system is that there is no backup power available. This would make such a system less reliable, which is a crucial element for a salmon farm power system.

The recommended system is the hybrid system, as it greatly reduces the CO_2 emissions, and probably reduces the overall cost of electricity as well. Having a diesel generator also provides security in the case of equipment failure. By first building a hybrid system, costs, maintenance and performance can be logged, so that the different parameters are better understood before possibly building a 100% renewable energy system.

As with all modelling studies there are uncertainties to the results obtained. One of the biggest uncertainties is the cost for the different components. A sensitivity analysis was carried out to investigate what impact changing PV and wind turbine costs had to the overall feasibility. It was found that for the hybrid system, the price of PV and wind turbine could increase by almost 50% each before becoming more expensive than the pure diesel system. However, changing the component costs separately would result in different cost optimal hybrid systems. If the cost of PV panels rises by 50%, a wind turbine is preferred, and no PV capacity. The cost of the wind turbine is somewhat less sensitive, but a cost increase of 50% leads to a cost optimal system including half as much wind turbine capacity.

Because of this, it is almost impossible to design a cost optimal hybrid system without having accurate cost data. Fuel prices change, batteries and PV panels have experienced a price drop, and is likely to continue that trend. There exist little data on the cost of offshore small scale wind turbines, and it has therefore been estimated from the costs of larger scale installations.

Another aspect is the weather data used. For the purpose of investigating general salmon farms, an offshore location, west of Stavanger was chosen. The optimal renewable configuration would change depending on the geographical location. In the case of installing renewables on an actual salmon farm, the wind and solar radiation should be measured at that specific location. The refined weather data could be inputted into the computer model so that an optimal renewable system could be created for that specific location.

It is possible to make large emission cuts and very likely cut energy costs for many of the salmon farms in Norway. With the possibility of receiving governmental funding, investing in renewable hybrid systems for the industry, should carry a relatively low risk. The Norwegian ministry of fisheries and Coastal affairs have an executive goal of: *"An Environmentally Sustainable Aquaculture Industry".* The main focus has been to make the industry biologically sustainable. Now it is time for the industry to aim at producing energy sustainable as well. High marked prices for salmon meat has led to good revenues for the industry in the last years. Because of this it is time that the industry itself takes the lead on this issue, to become leaders on offshore off-grid energy solutions.

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