Bachelor's project

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Electrification of offshore fish farms

Bachelor's project in Renewable energy
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Preface

This bachelor thesis is written by four students in the subject TFNE3001 - Bachelor thesis Renewable Energy, spring 2020. We are in our last semester at the bachelor engineering program Renewable Energy at Norwegian University of Science and Technology.

The thesis includes an introduction to the fish farming industry in Norway with current status, challenges and regulations, in addition to the power demand at a fish farming site. Further, theory regarding onshore power supply and energy resources will be presented. Three cases will be introduced in the case study, followed by the method regarding simulations and cost calculations. The technologies, cases and simulations will later be used as a basis for the energy solutions and costs, in addition to the discussion. The work load was equally divided between the four students of the group. This thesis has contributed to an increased understanding of important aspects regarding electrification of offshore aquaculture using different energy technologies.

We would like to thank our internal supervisors in the subject, associate professor Håvard Karoliussen and adjunct associate professor Federico Zenith, for help and guidance during the project. We would also like to thank our two external supervisors, Niclas Forsberg at BKK AS and Tor Didrik Krog at Siemens AS, for help, information gathering and feedback during the whole process. Further, we would like to thank Ocean Farming AS, Aker Solutions AS and Viewpoint AS for cooperating and sharing valuable information. Lastly, we would like to thank master student Asle Handro Nybakk for help with the simulations. Other important contributors to the thesis are mentioned in chapter 1.3.

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Abstract

The fishing and aquaculture industry is a major industry in Norway today. Half of the fish farms close to land are electrified with shore power. The remaining fish farms are currently operating with diesel generators. The usage of diesel generators can be reduced by implementing more eco-friendly solutions. Electrification of this industry will therefore play an important role in the reduction of greenhouse gas emissions.

In 2015, the Norwegian Directorate of Fisheries opened up applications for development licences, to contribute solving the area and environmental problems facing the industry today. This has led to an exploration of more offshore areas that have previously not been suitable for fish farming. Offshore sea farming is a new industry, and is defined as fish farms in exposed areas away from sheltered waters. In this assignment, Ocean Farm 1, Arctic Offshore Farming and Spidercage, which have received development licenses, are described based on offshore design solutions, annual power demand and locations. The case regarding Arctic Offshore Farming will focus on a full offshore version of the facility.

The thesis addresses how different renewable energy solutions can meet the power demand of the fish farms planned at sea, and fully or partly replace the current diesel generator in the most cost efficient and eco-friendly manner. Calculations and simulations for all the solutions were performed using Matlab. The thesis takes six different hybrid solutions into consideration, each of which will have a certain number of diesel generators and batteries. In addition, shore power is considered as the only solution without storage capacity.

The results related to costs are presented as CAPEX, OPEX and LCOE plots for each of the facilities, where the solution with the lowest LCOE is considered the most cost efficient. In addition, CO_2 emissions are used to find the most eco-friendly solution.

There is not enough exploitable area at the farms for the solar cells to cover the annual power demand significantly. Both the onshore and floating wind turbines are oversized, which lead to high costs and a great amount of surplus power. The fuel cell hybrid solution will only be relevant for Ocean Farm 1, as hydrogen production is planned close by. The solution will have low emissions, although a high LCOE.

The best hybrid solution for all three cases is batteries in combination with optimized diesel generators. This is due to the diesel generators always being kept at a constant optimal load, while reducing CO_2 emissions. As the diesel generators are still used 100 % of the time, this will only be a short-term solution.

It has been concluded that shore power is the best solution considering LCOE and CO_2 emissions for Spidercage and a full offshore version of Arctic Offshore Farming. On the other hand, the solution will contain some uncertainty as the diesel generators will operate during maintenance or ambient conditions, which are not included in the thesis. This solution will not be cost efficient if the fish farms are placed further offshore.

If the facilities are placed further from shore, the battery and diesel generator solutions will be the most suitable considering costs, as it already is for Ocean Farm 1. The most eco-friendly hybrid solution for Ocean Farm 1 is the fuel cell solution. For Spidercage and a full offshore version of Arctic Offshore Farming, the hybrid solutions for, respectively, floating and onshore turbines will be the most eco-friendly solutions. As the power demand data received is in an hourly resolution, it will lead to uncertainties in the results.

Sammendrag

Fiskeri- og havbruksnæringen er en stor industri i Norge i dag. Halvparten av oppdrettsanleggene nærmere land er elektrifisert med landstrøm. De resterende oppdrettsanleggene er i dag driftet med dieselaggregat. Bruken av dieselaggregat kan reduseres kraftig ved å implementere mer miljøvennlige løsninger. Elektrifisering av denne industrien vil derfor spille en viktig rolle i reduksjonen av klimagassutslipp.

Fiskeridirektoratet åpnet opp for søknader for utviklingstillatelser i 2015, for å bidra til å finne løsninger på areal- og miljøproblemene næringen i dag står ovenfor. Dette har ført til utforskning av flere offshore områder som tidligere ikke har vært passende for fiskeoppdrett. Havbruk til havs er en ny næring, og er definert som fiskeoppdrett i eksponerte områder vekk fra skjermet farvann. I denne oppgaven er Ocean Farm 1, Arctic Offshore Farming og Spidercage, som har fått tildelt utviklingstillatelse, beskrevet ut ifra offshore designløsninger, årlig effektbehov og lokasjoner. Casen som omhandler Arctic Offshore Farming vil fokusere på en full offshore versjon av anlegget.

Oppgaven tar for seg hvordan ulike fornybare energiløsninger kan dekke effektbehovet til oppdrettsanleggene planlagt til havs, og erstatte dagens dieselaggregat helt eller delvis på en kostnadseffektiv og miljøvennlig måte. Beregninger og simuleringer for alle løsningene i oppgaven er utført ved hjelp av Matlab. Oppgaven tar for seg seks forskjellige hybridløsninger som hver vil ha et visst antall dieselaggregat og batterier. I tillegg er landstrøm vurdert, som eneste løsning uten lagringskapasitet.

Resultatene som omhandler kostnader er representert som CAPEX, OPEX og LCOE plott for hvert av anleggene, hvor løsningen med lavest LCOE blir ansett som den mest kostnadseffektive. I tillegg blir CO_2 utslipp lagt til grunn for å finne den mest miljøvennlige løsningen.

Det er ikke nok tilgjengelig areal på oppdrettsanleggene til at solcellene skal kunne dekke effektbehovet betraktelig. Både den landbaserte og flytende vindturbinen er overdimensjonert, som fører til høye kostnader og en stor andel overskuddsenergi. Brenselscelle hybridløsningen vil kun være aktuelt for Ocean Farm 1, da det er planlagt hydrogen produksjon i nærheten. Løsningen vil ha lave utslipp, men en høy LCOE.

Den beste hybridløsningen for alle tre casene er batterier i kombinasjon med optimaliserte dieselaggregat. Dette er som følge av at dieselaggregatene alltid holdes på en konstant optimal last, samtidig som den reduserer CO_2 utslippene. Da dieselaggregatene fortsatt benyttes 100 % av tiden vil dette kun være en kortsiktig løsning.

Det er konkludert med at landstrøm er den beste løsningen med tanke på LCOE og CO_2 utslipp for Spidercage og en full offshore versjon av Arctic Offshore Farming. På en annen side vil løsningen inneholde en usikkerhet da dieselaggregatene som virker under vedlikehold eller ved uforutsette forhold ikke er inkludert. Denne løsningen vil ikke være kostnadseffektiv dersom oppdrettsanleggene plasseres lenger til havs.

Dersom anleggene plasseres lenger til havs, vil batteri- og dieselaggregatløsningene være mest egnet med tanke på kostnader, slik den er for Ocean Farm 1. Den mest miljøvennlig hybridløsningen, for Ocean Farm 1, er brenselscelleløsningen. For Spidercage og en full offshore versjon av Arctic Offshore Farming, vil hybridløsningene for, henholdsvis, flytende og landbaserte turbiner være de mest miljøvennlige løsningene. Ettersom dataene for effektbehov er gitt i timesoppløsning vil dette føre til usikkerhet i resultatene.

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List of terms

Term	Description
Alternator	An electrical generator that converts mechanical energy to electrical energy in the form of alternating current.
Angle of gradient	The angle between the sun's rays and a horizontal plane.
Aquaculture	The farming of fish, shellfish, algae and aquatic plants in either the sea or fresh water.
Bend limiter	Metal construction which ensures controlled inlet of the subsea cable at the feed barge.
Breakers	Device connected between electrical conductors, or ahead of a consumption aperture. It allows or prevents current passage.
Bus-bar	Live bus in electrical circuits for electrical distribution.
Circuit-breaker	A breaker in a current circuit dimensioned to close, lead and break normal load currents and specific short circuit currents.
Cross-linked polyethylene cable	Cables with polyethylene as isolation.
Current transformer	Measurement transformer for electrical current, utilized for measuring, settlement and protective gear.
Development license	A temporary arrangement, which can be given to fish farming projects with considerable innovation and investments.
Electrode	The point at which an electric current enters or leaves an object, for example, a battery.
Greenhouse gasses	Gasses that contribute to the greenhouse effect by absorbing infrared radiation. Carbon dioxide is an example of a greenhouse gas.
Gross domestic product	A monetary measure of the market value of all the final goods and services produced in a specific time period.
Hydraulic piston cylinder	Mechanical actuator that is used to give an unidirectional force trough an unidirectional stroke. Utilized in connection with wave power.

Internal combustion engine	A heat engine. It is called internal because the combustion of the air-fuel mixture occurs inside the engine, in a combustion chamber, and some of the burned gases are part of the new combustion cycle. The engine transforms the thermal energy of the burning air-fuel mixture into mechanical energy.
Lean mixtures	An air-fuel mixture containing a relatively low proportion of fuel.
Levelized cost of energy	Lifetime costs of an energy technology divided by energy production. Calculated present value of the total costs of building and operating a power plant over an assumed lifetime.
License	A set of rights and obligations of the holder of the licence, and is meant to respect environmental and area issues.
Mainland gross domestic product	Includes production from all industries in Norway, except for the extraction of oil and gas, pipeline transport and international maritime transport.
Midnight sun	A phenomenon when the day lasts 24 hours. A phenomenon which applies north of the northern polar circle, and south of the southern polar circle.
Polar night	A phenomenon when the night lasts 24 hours. A phenomenon which applies north of the northern polar circle, and south of the southern polar circle.
Propulsion system	This involves pushing or driving an object forward.
Spark ignition engine	An internal combustion engine, where the combustion process of the air-fuel mixture is ignited by a spark from a spark plug.
Suction anchor	A fixed platform anchor in the form of an open bottomed tube embedded in the sediment and sealed at the top.
Surge arrest	Utilized in electrical installations to protect the connected equipment against harmful transient overvoltage.
Terra Neutral	A type of distribution grid where the neutral point at the transformer is earthed.
Winterization	The process of preparing the fish farm for the winter.

List of abbreviation

AOF	Arctic Offshore Farming
AC	Alternating current
BoP	Balance of plant
CAPEX	Capital expenditure
Cu	Copper
DC	Direct current
FERE	Polyethylene isolated cable with wired armoring
FEVE	Polyethylene isolated cable with double wired armoring
GDP	Gross domestic product
GHG	Greenhouse gasses
ICE	Internal combustion engine
ISO	International Organisation for Standardization
LCOE	Levelized cost of energy
MAB	Maximum allowed biomass
MDO	Marine diesel oil
MNOK	Million Norwegian krone
NCCS	Norwegian Centre for Climate Services
NDF	Norwegian Directorate of Fisheries
NMC	Nickel-manganese-cobalt
OAOF	Full offshore version of AOF
OPEX	Operational expenditure
PEMFC	Proton exchange membrane fuel cell
PEX	Cross-linked polyethylene
PV	Photovoltaic
SOC	State of charge
SOCMAX	Maximum state of charge
SOCMIN	Minimum state of charge
SFC	Specific fuel consumption
TN-S	Terra Neutral-Switch system

List of symbols

A	Efficient area $[m^2]$
$cos\phi$	Power factor
I_c	Short circuit current $[A]$
L	Length of cable $[m]$
P	Transferred power $[kW]$
P_{in}	Power input $[W]$
P_{load}	Power demand at fish farm $[W]$
P_{max}	Maximum power output $[W]$
R_1	Conductor resistance $[\Omega/km]$
U	Operating voltage $[V]$
X_L	Conductor reactance $[\Omega/km]$
η	Efficiency [%]
θ	Light intensity $[W/m^2]$
ϕ	Angle between the active and apparent power [°]
ΔU	Voltage loss [%]

List of programs

Matlab - Matlab, version 9.7 is a multi-paradigm numerical computing environment and proprietary programming language, developed by MathWorks. Matlab allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python.

PVsyst - PVsyst, version 6.86 is a PC software package used generally for the study, sizing, simulation and data analysis of complete PV systems. This software deals with grid-connected, stand-alone, pumping and DC-grid PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools. The program gathers meteorological data from several sources available on the web. The meteorological data available in the free version includes the databases Meteonorm 7.2, NASA-SSE, WRDC and RETscreen.

The database Meteonorm 7.2 is utilized in this thesis, where data is extracted from 2 500 terrestrial stations and complemented by satellite. Values from all over the world can be extracted within a period from 1961 and up to 2015 for some countries. In this thesis, the data is based on measurements from 1990, as this was the data available in the program for relevant locations.

1 Introduction

The aquaculture industry is one of the largest businesses in Norway and is currently mostly operated by diesel generators, which contributes to emissions of GHG. In order to satisfy the power demand at fish farms in Norway in an eco-friendly manner, both current and advanced technology should be considered. A cost efficient solution is necessary to compete with the current inexpensive diesel generator solution. Several sea farmers are exploring offshore farming to solve some of the issues facing the industry.

The purpose of the thesis is to find an environmentally friendly and suitable solution to meet the power demand of offshore fish farms. In this chapter, a description of the background and purpose is elaborated. The problem definition is described including simplifications, and a brief overview of contributors is presented. The thesis is written in collaboration with BKK AS and Siemens AS.

1.1 Background

Norway is committed to reduce their emissions of greenhouse gasses, GHG, of at least 50 % by 2030, compared to the reference year 1990. This is a direct effect of the Paris Agreement, where the countries in the world will try to limit the temperature rise to 1.5 °C. By 2050, Norway is expected to be a low carbon society with GHG reduced by 80 to 85 %.[1, 2]

Furthermore, the world population is expanding at a rapid rate, and is expected to exceed 9 billion by 2050 [3]. The world is facing a challenging future, where climate change and environmental degradation are of the biggest challenges for the upcoming generation. Providing adequate food supply for a growing population, while preserving limited natural resources, will be problematic. While only 2 % of the food energy in the world is retrieved from the sea, the demand of seafood is increasing with a rising middle income group. There is hence a need to increase seafood production in an efficient and sustainable manner.[4]

Norway has a close connection to the sea, as it has a coastline of nearly 103 000 km. The country has a rich history of fish farming due to its optimal landscape, including fjords and islands. The aquaculture in Norway is located in sheltered coastal areas close to land, and is one of the major industries in Norway today. In the last decade however, the industry has fluctuated. Between 2007 and 2018, the value of slaughter fish in the aquaculture industry in Norway had nearly quadrupled. The volume of production has however not increased significantly since 2012.[5, 6]

According to ABB and Bellona, the fish farming sites in Norway, including boats associated with the farms, have a calculated emission of 453 972 tonnes of CO_2 per year. In order to keep up with the political agendas, the fish farm industry must reduce its emissions. Half of the farms located in sheltered areas are already electrified, but there is still a long way to go before all future offshore fishing farms adopt more renewable energy solutions.[7]

To resolve these issues, the Norwegian Directorate of Fisheries, NDF, introduced a new concession in 2015. This initiative was proposed to motivate the industry to invest in more innovative and technology-enabled solutions, that could help solve both the environmental and area challenges facing the aquaculture industry.[8]

1.2 Problem definition

Several sea farmers are exploring offshore fish farming in order to resolve some of the area and environmental issues facing the industry today. Offshore sea farming is a new industry, and is defined as fish farms in exposed areas away from sheltered waters. Electrification of these offshore farms can be more complicated than the farms located near land, due to rougher weather and increased distance from shore. The problem examined in this thesis is as following:

Which energy technologies are the most suitable and can be combined to satisfy the power demand on an offshore fish farm, in an eco-friendly and cost efficient manner? How will these solutions compare to the traditional diesel generator solution?

1.2.1 Simplifications

Several simplifications are done in this thesis due to limited time. Technical and design changes the different energy solutions might lead to, for the fish farms, are not taken into account. This includes the required space and weight of battery cabinets, fuel cells and diesel generators. The simulations are hence based on the power demand, and not practical reasoning.

To limit the thesis, not every renewable energy resource is taken into consideration. Possible technologies which are not included are nuclear power, tidal power or geothermal energy, among others. A specific model for each technology is chosen based on costs and offshore conditions, and the same model is used in simulations and calculations for each case. Several models will hence not be tested. The power demand of the aquaculture service vessels which are frequently visiting a typical fish farm will not be included in the simulations of energy solutions. In addition, the production time of the fish farms at the locations is not taken into account.

Another simplification is done regarding calculations of CO_2 emissions, where only the emissions from the diesel generators are taken into account. The renewable energy sources will also have emissions, though these are not considered in the calculations. In addition, the simulations of the energy solutions do not include an optimal load for the diesel generator, with the exception of the battery and diesel generator solution.

A simplification considering the battery cabinets is the c-rate not being accounted for during charging or discharging. The connection between each battery cabinet is also not included for, and the cabinets will be viewed as a whole, rather than separate cabinets.

An uncertainty analysis will not be performed regarding the results presented, though the possible uncertainties will be mentioned and discussed. The three cases included in this thesis will not be compared to each other as this was requested. The energy solutions for each case will be presented separately.

1.3 Contributors

The list below acknowledges people who have contributed with valuable information for this thesis. The answering of questions and shared information within their study of field is received with great gratitude.

Name	**Position**	**Company**
Alstad, Sandra	Bid Manager	Siemens AS
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BKK AS
BKK AS is a renewable energy company located in Bergen, and is the largest power company in western Norway. They produce, distribute and trade the produced power. In addition, they deliver district heating and broadband systems.

BKK AS is one of the employers for this thesis. They want to map the potential for electrification of offshore aquaculture, considering concepts which have received development licenses. They can potentially have a central role concerning electrification of the aquaculture in Norway and in the transition to a more sustainable society.

Siemens AS
Siemens AS is a global powerhouse that develops high-tech and innovative solutions for industry, energy, cities and transport. Their focus areas are electrification, automation and digitization.

Siemens AS is one of the employers for this thesis. They have an interest in the electrification of the aquaculture industry as their technology can contribute to a sustainable energy solution.

1.4 Information gathering

The information gathered in the thesis is information received from several corporations, articles, books and reports. All the information constitutes an overall view of the fish farming industry, different energy resources and technologies.

The case study and simulations are based on values and data received from the offshore aquaculture industry. This data was crucial in order to conduct realistic calculations and simulations, which will be presented. In addition, in order to gather updated and realistic information and data about necessary equipment, other industries and firms have been contacted. Most of the information gathered was received by e-mail correspondence.

There was a difference in how much information each company could or would like to share. A reason for this could be the concealment and competition within the fish farming industry. The offshore fish farming industry is in the initial stages of development, and sharing of information about innovative and new technologies can potentially harm their projects.

In order to increase the knowledge about the fish farming industry, it was planned to go on a field trip to a facility. This had to be cancelled due to the outbreak of Covid-19. There was also a lack of e-mail responses after the outbreak. In addition, some information was not received as the contact persons, at the different firms, did not have access to the specific information when working from home.

2 Fish farming industry in Norway

Norwegian fish farming is one of the foremost export industries, and the annual income of farmed fish in Norway is 65 billion NOK [9]. The Norwegian Government aims to increase and develop the industry further. However, with this development challenges may occur. These challenges will be described in the following chapter. Furthermore, the history and current status will be briefly explained, followed by the construction of a fish farm and the production chain.[10]

2.1 The development of fish farming in Norway

Aquaculture in Norway dates back to 1850, when the first brown trout were hatched. Aquaculture is farming of fish, shellfish, algae and aquatic plants in either the sea or in fresh water. The different species and organisms are bred to a certain size before they are harvested and used for different purposes.[11, 12]

During the 19th century, several fish farms attempted to establish in Norway. Figure 2.1 is an example of one of the earliest technologies used for fish farming. Early initiatives failed, and current modern sea-based aquaculture dates back to 1969 when the first salmon smolts were successfully raised in cages. Knowledge and technology spread rapidly to firms all along the Norwegian coast, primarily in the southwest. High profitability resulted in rising production rates.[13]

Figure 2.1: *Fish caging made by linen, rigged up by wooden poles in the sea, one of the earliest technologies used for fish farming. The picture is from the 1950s and taken in Bjordal in Høyanger municipality.[14]*

The development included moving the fish from onshore farming tanks to cages in the sea. Rainbow trout and salmon production in floating net cages provided better growth and lower capital and operating costs compared to the previously onshore farming tanks. The salmon developed to be the most important species of the fish farming industry. The salmon was easy to market with a competitive price, which resulted in a more economically solid industry.[15]

2.2 Current status

Most fish farms are currently located near land, taking up space of valuable coastal areas. The growth of fish farming along the coastal areas are limited by some challenges. This involve lack of available locations for future farms, discharge of antibiotics and harmful algae blooms. Furthermore, build-up waste feed and faeces on the seabed, escaped fish, sea lice and transmission of disease between farmed and wild fish will also be contributing factors.[16]

Today most fish farms utilize diesel generators as power supply, because it is a reliable and effective energy source. On the other hand, these diesel generators are contributing to emissions, which affects the environment. Therefore, the process of substituting the diesel generators have started. Of the farms located near land, 50 % are already electrified trough shore power, but there is still a long way to go before all fish farms utilize renewable energy solutions.[7]

The most produced fish species considering the fish farm industry in 2017 are illustrated in Figure 2.2. In addition to trout and Atlantic salmon there are several species which have achieved a commercialised stadium involving Atlantic halibut, mussels, charr and lump fish. Further, some species are under an up-scaling phase to be commercialised. These species are spotted wolf-fish, cod and sugar kelp. The production of cod had a collapse in both development and production in 2013, though have been between 300 to 400 tonnes the last few years. In addition, cultivation of seaweed and sea tangle are still in the initial phase, but are expected to increase in the next decades.[11, 17, 18]

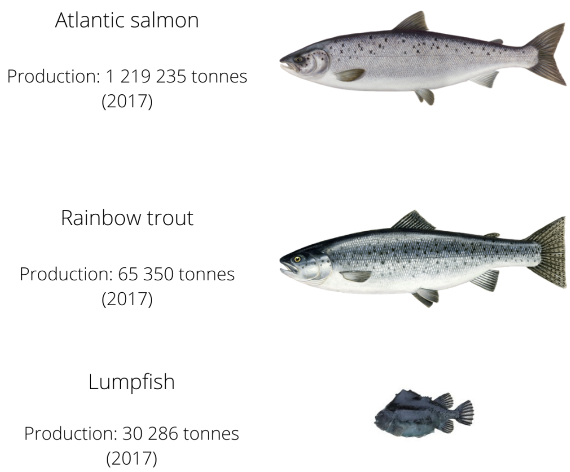


Figure 2.2: *The number of tonnes for the most produced species considering the fish farming industry in Norway. These are Atlantic salmon, rainbow trout and lumpfish for 2017. Lumpfish is a species which eats sea lice and are used to reduce the sea lice population at the fish farm.[11]*

In 2018, there were a total of 1 041 seawater licences for salmon and trout, according to MOWI. A licence is a set of rights and obligations of the holder of the licence, and is meant to respect environmental and area issues. The industry contributed to around 8 000 employments in 2017, distributed along the Norwegian coastal areas, as illustrated in Figure 2.3.[10, 19]

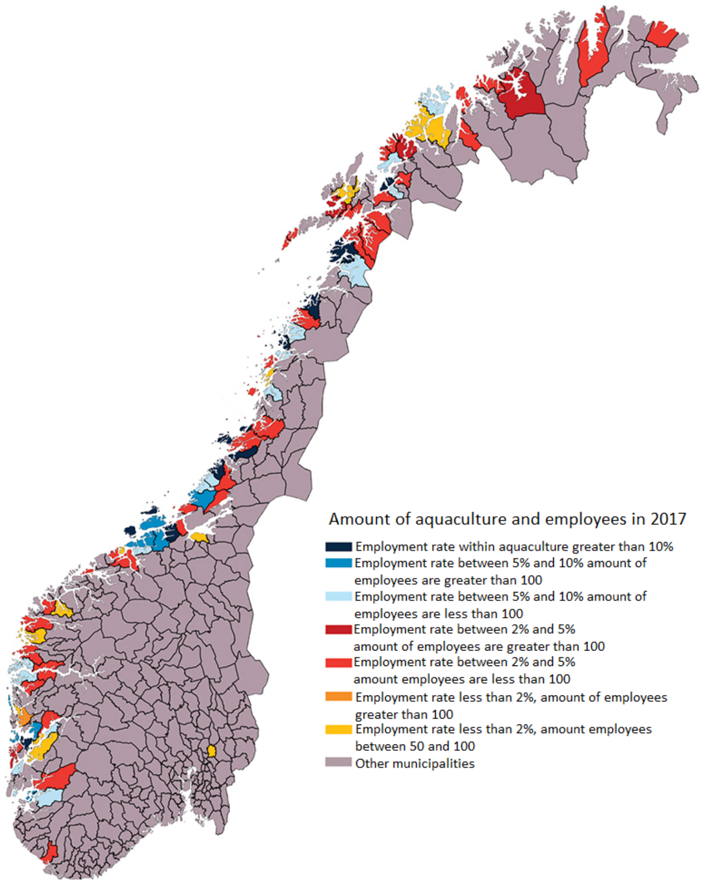


Figure 2.3: *The aquaculture industry in Norwegian municipalities. The percentage and number of employees distributed along both coastal and urban areas, in a total of 8 000, sorted by colours.[10]*

The production in Norwegian aquaculture have increased the last decade, from 0.15 million tonnes in 1990 to around 1.3 million tonnes in 2018 for salmon, trout and rainbow trout. In 2018, the fish farming industry contributed to gross domestic product, GDP, of 32 billion NOK, which corresponds to about 1.3 % of mainland GDP. By comparison, the contribution from the wild fish industry was 13 billion NOK, corresponding to 0.5 % of mainland GDP.[10]

Since 2012, the production has stagnated, because of the limited possibilities for increase in capacity. This is mainly due to environmental concerns. Even tough the production have stagnated, there have been an increase in profit due to higher pricing of the produced fish, as shown in Figure 2.4. The sold fish and value are presented for each year from 2007 to 2018 to illustrate the increase in marked price, and a more stable production of fish over the last few years. The increase in price and profit from 2007 may be a consequence of higher demand and interest in the industry.[10]

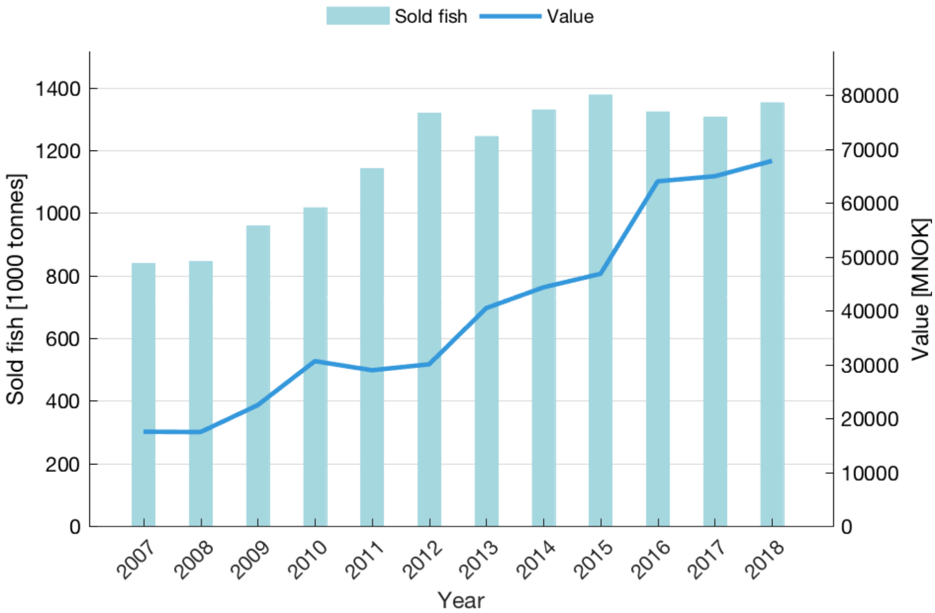


Figure 2.4: *The amount of sold fish is illustrated as bars, compared to the increased value of sold fish plotted as a line. The sold fish and the value are represented for each year from 2007 to 2018 to show the increase in marked price, and a more stable production of fish over the last few years.[20]*

The industry creates growth in both the supplier and processing business. In addition, this stimulates growth, both outside and inside urban areas. The technology and biology need to develop if the production of fish is going to increase. By moving the aquaculture operation offshore, the regulations will become stricter due to environmental concerns. On the other hand, it will obtain more space making it possible to achieve higher production in a sustainable manner.[16, 21]

In November 2015, the NDF opened up applications for development licenses regarding aquaculture projects. A development license is a temporary arrangement, which can be given to projects with considerable innovation and investments. The licenses are meant to facilitate development of technology, which can contribute to solutions of the environmental and area problems the industry is facing.[8]

The Norwegian Government has, through development licenses, facilitated new aquaculture technology. Within the deadline for applications in 2017, the NDF received 104 concept applications. 18 concepts were approved and 82 concepts were denied, per May 2020. The approved concepts vary in exposure to the sea, with different solutions for structure, either open or closed, and if it is submerged or not. Some concepts are being tested, others are under construction and a few are still at the design stage. One of the approved concepts, Ocean Farm 1, is in operation and testing outside Frøya, in Frohavet. This is the first offshore facility in the world per today.[4, 19]

The outcome of the new innovative concepts may contribute to production at locations previously unsuitable. On the other hand, the concepts need time before they can contribute with a production of larger scale. Three of the new innovative projects will be described further in chapter 6.[19]

2.3 Environmental problems

Sea lice and escaped fish are of the biggest challenges the industry faces today. This has a negative effect on both the profit and the marine habitat. Escaped farm fish migrate to the sea or river, and spawn with wild salmon. This affects the diversity of wild salmon, and may cause eradication of certain species. In addition, diseases within the farmed fish can spread to the rest of the marine habitat.[22]

Sea lice are parasites who prefer salt water, and hence thrive in the fish cages along the fjords in Norway. These parasites are a threat to the aquaculture industry as they weaken the quality of the fish, and prevents the farmers from selling it. In addition, nutrients from the farmed fish and fish feed cause reduction in oxygen levels and impact the habitat negatively.[23, 24]

The fishing industry is slowly moving from the fjords to more exposed areas in the sea. The offshore fish farms are utilizing new and innovative technology to avoid several of the problems the conventional fish farms have experienced. This involves further development of sensors to detect when fish have escaped or when they are infected by sea lice. Several of the cages are submersible or semi-submersible, hence the occurrence of sea lice is expected to diminish, as the salt concentration decreases with sea depth.[24]

The stronger currents and deeper waters offshore, wash away and dilute discharged nutrients and faeces. The waste materials can be assimilated back into the ecosystem. This will make the production more sustainable, while the currents also reduce the risk of algae bloom and contaminants associated with coastal aquaculture. On the other hand, there are some challenges by moving the production offshore. Tougher weather conditions will affect the fish, construction complexity and cost compared to current platforms. In addition, the greater distance from shore will increase the complexity of shore power possibilities and more demanding conditions for the aquaculture service vessels.[10, 16]

Aquaculture in Norway consists mainly of mono culture with fed fish. A synergy with fish farms and cultivation of other species can potentially decrease the environmental impact without the need for more energy.Integrated aquaculture involve intercropping of different species at different levels in the food chain. A balanced integrated system operates like a natural ecosystem, where excess nutrition from, for instance, fed salmon works as a natural fertiliser or feed for species lower down on the food chain, such as mussels and seaweed. The complexity of the system is dependent of the cultivated species.[25]

2.4 Political regulations and aspects

In Norway, fish farming companies are limited to a number of regulations and laws. The Aquaculture Act from 2006 is a law intended to promote the profitability and competitiveness of the aquaculture industry, while ensuring a sustainable development. Another important law is the Food Safety Act from 2004, which is intended to provide secure food and sustainable production. The purpose of the Act is also to promote sound plant and animal health.[19, 26, 27]

In addition to national laws, Norway is obligated to follow international agreements. In 2015, the Paris Agreement was endorsed by the United Nations to ensure limited climate change in the world. As a result of this agreement, the Norwegian Government passed a climate law in 2018. The climate goal of Norway is to reduce GHG emissions by at least 40 % from the reference year 1990 within 2030. The climate law constitutes the framework for Norwegian climate policy, and will facilitate the transition to a low carbon society. In February 2020, the climate goal was proposed to increase from 40 % up to 55 %.[1, 2, 28]

To engage in aquaculture and sea ranching activities in Norway, a licence is required. The licence regulates the limitation of production, called maximum allowed biomass, MAB. This is defined as the maximum volume of fish a company can hold at sea at all times. The MAB of one licence equals 945 tonnes in Troms and Finnmark, and 780 tonnes for the rest of the country. Each production site has its own MAB, and is determined by the carrying capacity of the site, which regulates the limit for the total amount of fish. This varies, but is in general between 2 340 to 4 680 tonnes.[19, 26]

The coast of Norway is divided into 13 geographical production areas. The MAB regulations are determined by the level of sea lice in these areas. The Government evaluates this every second year. This is called the traffic light system, where green areas are offered growth, yellow areas stay the same and red areas have to reduce production. Sites with strict environmental standards can be offered additional growth in MAB. In 2020, two production areas were given red light, two areas were given yellow and the remaining nine areas were given green.[19, 29]

The farmers are obliged to report any suspicion or awareness of escaped fish to the NDF. This applies regardless of the escaped fish being their own or from other facilities. The NDF, in cooperation with the industry, have conducted a systematic approach to the challenge of escaped fish. This includes the NDF monitoring water systems in the country and registration of the escaped fish in a national registry. In addition, the industry has to take responsibility for removing the escaped fish from water systems.[30, 31]

There is an ongoing debate in Norway regarding taxes in the aquaculture industry. In April 2018, the Norwegian Government announced that an Aquaculture tax committee would be put together. The committee will review, and possibly recommend, economic rent tax for the aquaculture industry. The Norwegian Parliament decided that one of the goals of the review, was to ensure stable and predictable income for the municipalities with aquaculture. In November 2019, the committee delivered their report to the Minister of Finance. The Government has yet to decide on the proposals in the report, although the Parliament has requested an evaluation during spring 2020.[32, 33]

The NDF has mapped and identified areas suitable for offshore aquaculture. In collaboration with the Institute of Marine Research, the NDF has recommended 11 areas relevant for consequence analysis, shown as dark-covered areas in Figure 2.5. In addition, the NDF identified 12 other areas that can be relevant for consequence analysis in the future, shown as light-covered areas in the figure.[34]

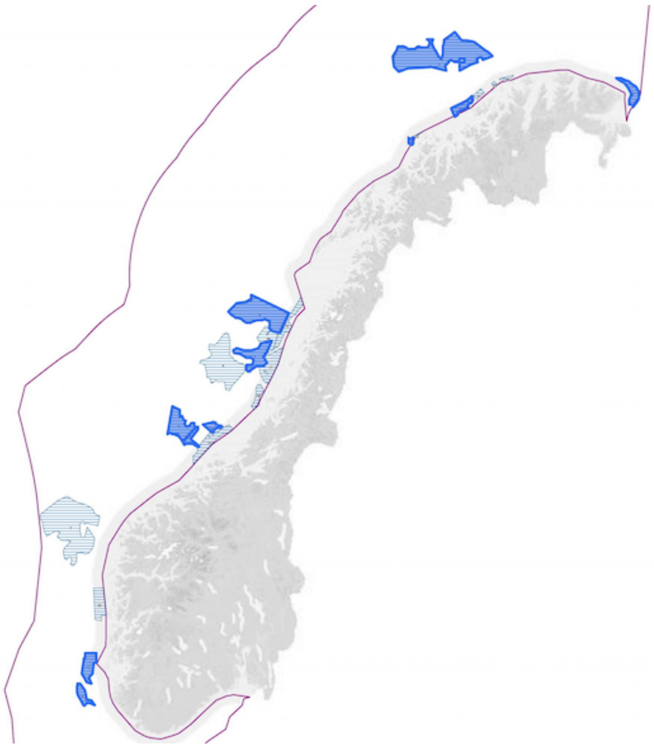


Figure 2.5: *Mapped and identified areas suitable for offshore aquaculture. The dark-covered areas are recommended for consequence analysis by the NDF. The light-covered areas can be relevant for consequence analysis in the future. The line defines the opportunity set for offshore aquaculture.[35]*

2.5 Construction and production chain

To understand the power demand at a fish farm, it is important to have an overview of the construction and production chain. The total production chain is briefly illustrated in Figure 2.6. It consists of feed production, smolt production, breeding in net cages and the slaughtering process. Different kinds of vessels are attached to the process depending on the assignment.[36]

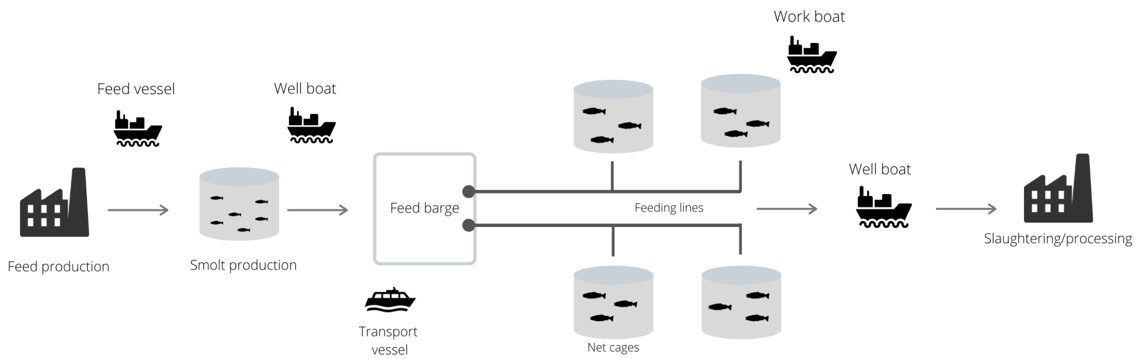


Figure 2.6: *The total production chain consists of feed production, smolt production and the growing process at the fish farm, before the fish get slaughtered and processed. Several aquaculture service vessels are attached to the production chain depending on the operation.[36]*

The production chain with more information about the power demanding equipment is illustrated in Figure 2.7. A salmon farm is constructed around the feed barge. Usually, a fish farm consists of between six and ten cages. The cage is constructed of a buoyancy element on the surface, and a net bag in which the fish swim. A typical net bag is between 20 to 50 m deep, and has a diameter of 50 m. The net cages are connected to the feed barge through feeding hoses. Typical equipment in the cages are cage lights, underwater camera system and environmental sensors.[5, 37]

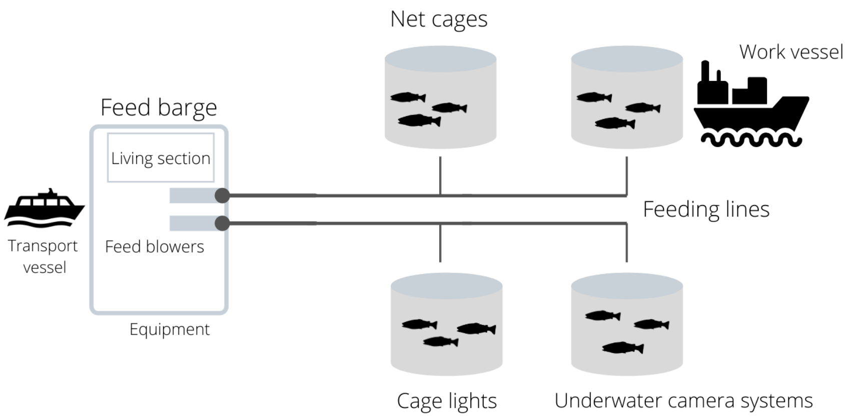


Figure 2.7: *Typical construction of a fish farm. The net cages are centred around the feed barge connected to feeding lines. Different equipment is placed in the cages to control the breeding of the fish. The feed barge often contains feed blowers, a living section and equipment. Aquaculture service vessels are used for transportation of personnel and work at the site.[36]*

The feed barge is designed depending on the location, climate and size of production. The main objective of the feed barge is to secure reliable, effective and optimal feeding of the fish. The installation contains a living section, control room, feeding system with silos, and different equipment like generators, net cleaning system and crane systems. The living section contains utilities according to different requirements.[37]

The fish undergo several stages from roe to the market. In total, the process can last for three years. The complete process is illustrated in Figure 2.8. Intensive farming of the Atlantic salmon will be used as an example, considering it is the most common species in the Norwegian fish farming industry.[19]

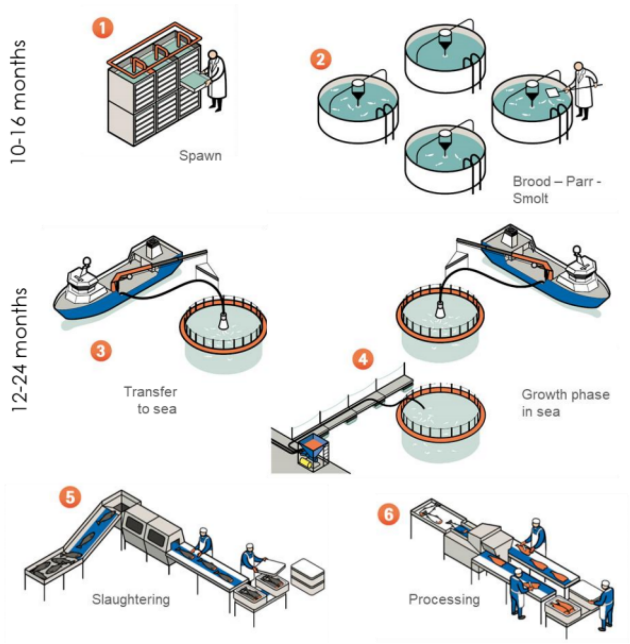


Figure 2.8: *The production chain of salmon fish farming, from spawn to processing. Firstly, the roe is fertilised in fresh water, before it hatches and can be moved to larger tanks. Furthermore, when the fish have reached a certain size it is moved to cages in the sea, and undergoes a growth phase. Further, when the fish weigh 4 to 5 kg, they are retrieved and transported and ready for slaughtering. Finally, they are stunned, gutted, washed, sorted and laid on ice.[19]*

The process begins onshore, step 1, in an incubator tray. Hatching takes place after approximately 60 days. Four to six weeks after hatching, the spawn begin to eat feed and can be moved to larger freshwater tanks, in step 2. Fish are bred to approximately 100 to 150 grams in a controlled freshwater environment, and the total freshwater production cycle takes about 10 to 16 months.[19]

The fish undergo major changes in a process called smoltification. These changes are necessary for the salmon to be able to live in seawater. Producers can speed up the smoltification by up to six months with light manipulation. The fish are known as smolt.[9]

After 10 to 16 months the fish are at a certain size, and is ready to be transferred to cages in the sea, in step 3. The salmon are kept in cages where they are bred to around 4 to 5 kg over a period of 12 to 24 months. This is known as the growth phase, in step 4.[19]

After the growth phase, the fish are ready for processing. The salmon is retrieved by well-boats and transported to the fish-processing facility for slaughtering, in step 5. They are then stunned, gutted, washed, sorted according to size and quality and finally laid on ice in step 6. In Norway, smolts are mainly released into seawater twice a year. Most harvesting takes place in the last quarter of the year. The location is fallowed for between 2 and 6 months after the site is harvested, before the next generation is put to sea at the same location.[9, 19]

3 Power demand at a fish farm

Electrical power is a substantial factor in the fish farming industry. The power covers the demand of the feeding system, lightning and control system. Average consumption for a typical fish farm is between 300 and 500 MWh annually, depending on the size of production. Several farmers are looking to expand the industry offshore to utilize more space and increase the production. An increase in the production will lead to an increase in the power demand at the fish farm, due to, among other factors, longer feeding hours.[37, 38]

This chapter will describe the power demanding equipment on a fish farm, briefly explain how they work and what they are used for. The seasonal and daily variations of the power demand at the fish farm will be described. In addition, the aquaculture service vessels which are frequently visiting a typical fish farm, will be described. Potentially, the aquaculture service vessels can have an impact on the power demand of a future fish farm, if the vessels are electrified.

3.1 Loads and seasonal variations

Table 3.1 gives a description of the most common power demanding components of a conventional salmon farming facility. In addition to the power demanding equipment listed in the table, the feed barge has a steady power demand at approximately 5 to 6 kW, due to base load. This increases when personnel arrive at the site for work.[38, 39]

Table 3.1: *Description of the energy demanding components on the feed barge of a salmon farming facility.*

Components	Description	Power demand	Source
Feeding system	Three main systems: *Electrically operated automatic feeders* *Airborne feeding system* *Water-borne feeding system* Pellets stored in silos are blown trough plastic feeding hoses by pumps. The hose is laid out to each cage and has spreaders at the end, which distribute the feed. One feed blower per feeding line is required.	Per feed blower: 11 to 32 kW	[39]
Cage lights	Underwater lightning is used to increase growth, repress pubescence and increase the appetite. The lights are mainly used in the winter months.	Per light: 6 kW	[39]
Living section	The living section of the feed barge requires heat and lighting. The heat is delivered through panel ovens and is the most energy requiring element. Other power demanding equipment is typically kitchen supplies and hot water tank.	Total: 10 to 20 kW	[39]
Camera system	Used to monitor the feeding activity, fish behavior and sea lice.	1 to 3 kW	[39]
Dead fish handling system	Used to grind dead fish from the cages.	2.5 to 26 kW	[39]
Crane	Used for various lifts and other work.	5 to 30 kW	[39]
Ballast pumps	Used to elevate and lower submersible and semi-submersible facilities.	22 to 33 kW	[40]

The biggest power demanding equipment are the feeding system and the ballast pumps. The activity of the ballast pumps is determined by the frequency of operations related to maintenance work, transfer of smolt and harvest of fish. During normal operation, they are used once a month during the production cycle. The power demand of the feeding system is dependent on which system is utilized on the feed barge. Water-borne feeding systems are, in general, more efficient than airborne feeding systems, and will therefore have a lower power demand. The activity of the feeding system constitutes for more than 50 % of the total activity on the feed barge. This can be seen in Figure 3.1, which illustrates the average activity of the different power demanding equipment for a normal day of operation.[37, 40, 41]

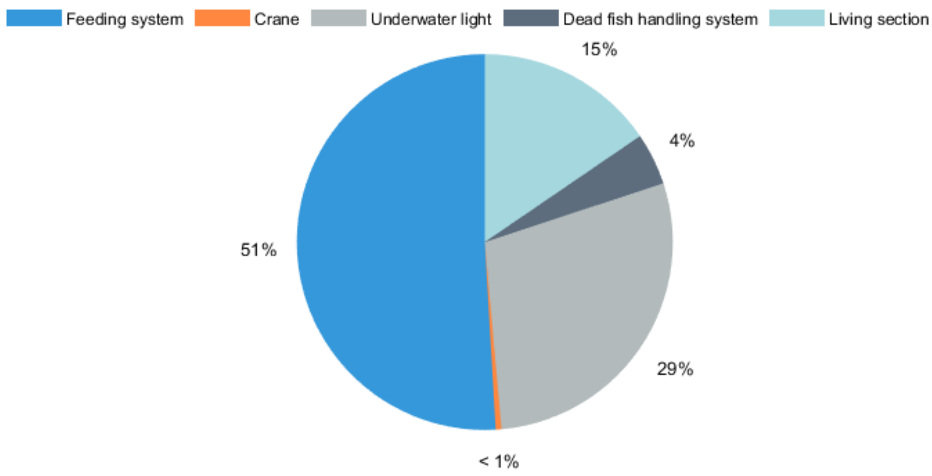


Figure 3.1: *Average activity of different power demanding equipment for a normal day of operation. The feeding system is the most operative.[39]*

The energy consumption on the feed barge varies with the seasons. The growth rate of the salmon is strongly correlated to sea water temperature, which is highest in the summer. This results in longer feeding hours and thereby a higher power demand for the feeding system in the summer. The cage light system and residential systems have a decreased power demand in the summer due to increased temperatures and longer light hours.[36]

The application of the equipment on the feed barge varies with the activity load, such as handling dead fish. Sea lice, as explained in chapter 2.3, is a threat to the fish farming industry. The lice reproduce most rapid in the summer, and can cause an increase in the amount of dead fish [42]. Therefore, the dead fish handling system is more operative during the summer months, causing a higher power demand.[36]

The energy consumption on the feed barge also varies throughout the production chain. If the steps in Figure 2.8 are taken into consideration, the main consumer of energy is in step 4, the growth phase. Step 1 and 2 both happens at land connected to the grid. The same applies for the slaughtering and processing steps. The power demand at the feed barge increase simultaneously with the size of the salmon, as they consume more feed.[19, 36]

The power demand of the living section is mainly determined by the size of the feed barge. In addition, it is affected by the different periods personnel are placed on the feed barge using the equipment in the living section. The equipment has a stable power demand, as there are few variations in the power consuming equipment on the market.[36]

Another factor that determine the power demand at the feed barge is the number of cages, hence the scale of the production. Increasing the number of cages leads to a higher power demand of cage lights and feeding systems. The position of the cages may also determine the power needed at the feed barge. If a cage is placed far away from the feed barge, long feeding lines are required. This cause a higher power demand in order to carry the feed, compared to the cages placed closer to the feed barge.[43]

Different loads for an offshore fish farm are presented in Figure 3.2. The values in the figure is received from the industry. The figure also gives a comparison of the power demand for a typical winter and summer day, in order to illustrate the seasonal variations.[44]

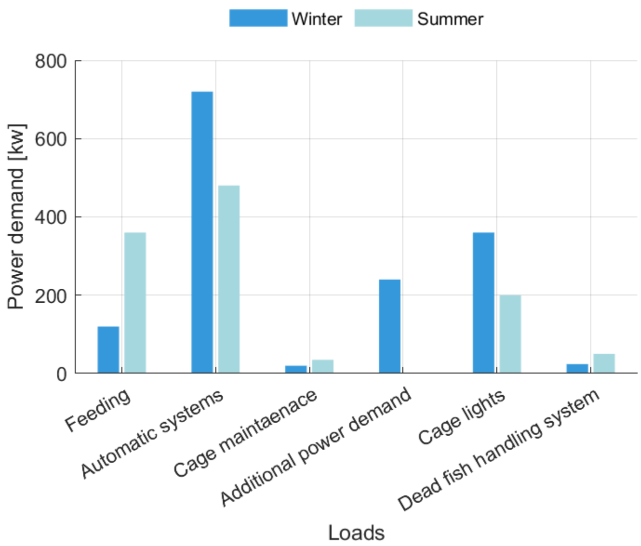


Figure 3.2: *Power demand for an offshore fish farm comparing a summer and winter day. The largest power demanding equipment is the automatic systems, as it is a total of a minor loads at the fish farm. The additional power demand is mainly due to winterization, which does not apply in the summer.[44]*

Figure 3.2 shows a higher power demand of automatic systems in the winter compared to the summer. In addition, this load is the highest among the other loads at the feed barge. The automatic systems represent minor loads at the feed barge. For instance, it includes the loads in the living section, such as heating and ventilation, and censoring systems. For the winter, an additional power demand is added. This is mainly due to winterization, which is not applied during summer.[41]

3.2 Aquaculture service vessels

Several supporting vessels are included in the production cycle. In accordance with the system illustrated i Figure 2.6, the supporting vessels include maintenance, live fish carries, transport and fish feed carriers. If the vessels are electrified and charged at site, they can have an impact on the power demand. However, the aquaculture vessels are currently not suited to connect to an offshore farm for charging.[36, 43, 45]

Most support vessels have combustion engines with diesel fuel. To reduce the consequences of fossil fuel, electric vessels are being developed. The technology for electric service vessels are available, however it is expensive. Service vessels in operation, with a diesel generator, have currently an average age of 30 years. When building new vessels to substitute the old ones, they might need to replace the diesel engine completely or partly with batteries, or other solutions to reduce emissions. The first electric maintenance vessel in the world, Elfrida, was put into operation by SalMar in 2017, and more electric vessels are being developed by other Norwegian dockyards. Elfrida is expected to operate electrically 90 to 95 % of the time.[36, 46]

Elfrida is equipped with two batteries of 90 kWh. In addition, the vessel has a diesel engine as backup. The maintenance vessel can both charge at the fish farm and onshore. At it can charge at fish farm it can charge with 440 V, and onshore with 230 V. Currently, Elfrida operates at a fish farm located near shore outside of Frøya, in Trøndelag county, and is illustrated in Figure 3.3.[46]

Figure 3.3: *The first electric maintenance vessel, Elfrida, for the aquaculture industry in Norway, put in operation by SalMar.[47]*

Under normal operating conditions, a fish feed carrier supplies the farm with water, fish feed and marine diesel oil, MDO, visiting once a week, according to SalMar. The feed carrier can possible carry the load of 2 030 m^3, and unload the fish feed with a capacity of 200 tonnes per hour.[45, 48]

Furthermore, a live fish carrier is built for transportation and processing of live fish. These vessels visit the fish farm when transporting smolt, harvesting, size sorting of salmon or when handling diseases. Usually they visit around three to four times during the production cycle. These boats can possibly hold 4 000 m^3 of fish. A fish-pump system and crane, used to handle and positioning of the two fish-pump hoses into the net cage, are installed to perform the tasks. By assuming the fish-pump system being similar to the one used for onshore systems the capacity for the fish-pump hose is between 30 to 55 kW. There are two fish-pump hoses which work simultaneously at the site. An example of a live fish carrier is illustrated in Figure 3.4.[43, 49, 50]

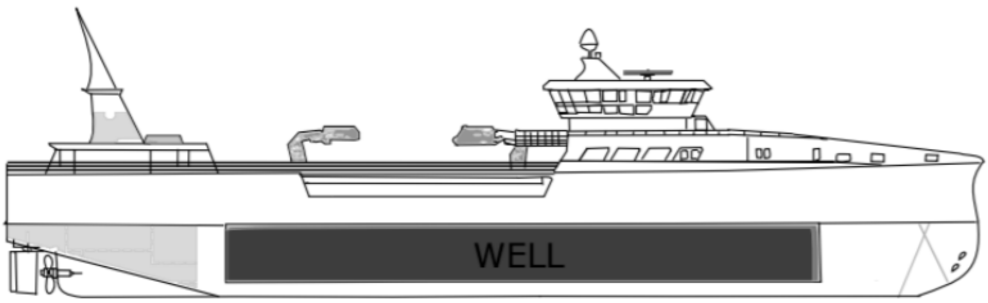


Figure 3.4: *A modern live fish carrier. The well is a compartment room for fish, constituting for a large part of the carrier.[51]*

Transport and maintenance vessels demand less power than the live fish carrier and fish feed carrier, thus can be electrified regardless of the energy resource of the fish farm. Therefore, by utilizing outboard engines and battery cabinets, the transport and maintenance vessel can be charged onshore and be electrified sufficiently. Transport vessels of personnel are small boats and will not contribute to a significantly increase in the power demand, when potentially charging at the offshore fish farm. These vessels may not be suitable for offshore farming due to rough weather conditions.[7, 36, 43]

If electric vessels are put into operation, a charging point at the location may be needed. This leads to a higher power demand at the feed barge. On the other hand, if the fish farm is not electrified, a hybrid solution for the work vessel, with charging onshore, can be a possibility to reduce emissions. An alternative to reduce emissions is to utilize a connection point at the fish farm as a power source when the vessels are operating at the facility, and diesel generators as a propulsion system. However, this would cause large power peaks when docked to the facility, which will increase the network tariff as it is determined by the highest power peak for each month. This applies when the facility is electrified trough shore power.[7, 36, 43]

4 Electrification using onshore power supply

In Norway, the mainland energy production is primarily renewable. Shore power is the technology where this renewable power can cover the demand at an aquaculture site, or other marine constructions. The necessary technology for onshore power supply is well developed, and it contributes to a more climate friendly solution, reducing CO_2 and NO_X emissions compared to diesel generators. In addition, it ensures operational security, reduces operational and maintenance costs, OPEX, and increases the unit operating time. On the other hand, the necessary equipment is expensive, and results in a large investment cost, CAPEX. Even though the theoretical principal is easy, the practical part involves different challenges.[38]

To understand shore power technology and the profitability of using it, a description of the most important electrical components and their costs are necessary. An overview of the Norwegian electricity grid, regulations and challenges for new grid connections and shore power technology will be explained in this chapter. In addition, subsea cable technology and costs for onshore power supply will be presented. The chapter will focus on grid connection considering offshore fish farms.

4.1 The Norwegian electricity grid

Availability of grid power is a prerequisite for electrification using shore power. In order to analyse the shore power potential for offshore fish farms, the barriers of the power grid must be understood. The electricity grid enables transport of electricity from generating resources to end users and households. Traditionally, the electricity grid in Norway is spilt between three voltage levels, the transmission grid, the regional grid and the distribution grid, as seen in Figure 4.1.[52]

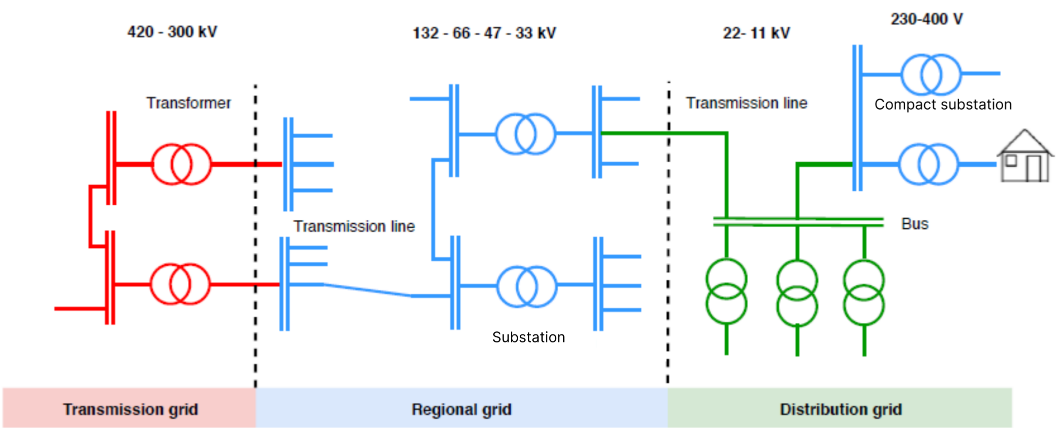


Figure 4.1: *The electricity grid in Norway is divided into three voltage levels, the transmission, regional and distribution grid connected by transmission lines. They cover different voltage levels. The different grid levels are interconnected with substations and compact substations, which reduce and increase the voltage.[36]*

The transmission grid is the backbone for the power grid in Norway, and represents the highest voltage levels. It allows transportation of electricity over large distances, due to high levels of voltage, and connects producers and consumers. The regional grid has a lower voltage level and is the interconnection between the transmission and the distribution grid. Industries with a high electricity demand can connect directly to the regional grid.[52, 53]

The distribution grid supplies end users, households, industry and services with electricity. A section of the electrical grid in Norway is shown in Figure 4.2. The different grid levels are interconnected with substations and compact substations, which reduce and increase the voltage. From the stations, several transmission lines emerge and distribute power to end users.[36, 53]

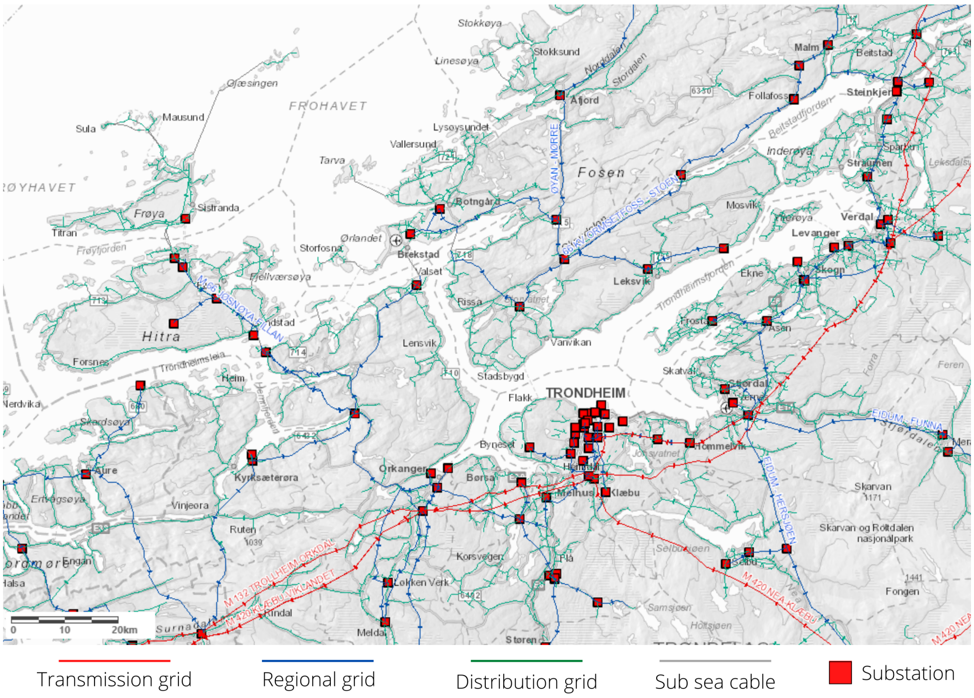


Figure 4.2: *The transmission, regional and distribution grid in the areas around Trondheim. The different grid levels are interconnected with transformer stations, illustrated as squares in the map.[54].*

In Norway, Statnett is responsible for running the transmission lines. Norway is further divided into geographical areas, where different network companies own and operate the electrical distribution networks with voltage up to 22 kV. The network companies have monopoly on transmission of electricity in an area, and this monopoly is matched by a delivery obligation. When new customers connect to the grid, the required power of their load must be known. This is due to power being the dimensioning factor for the grid.[36, 55, 56]

4.2 Regulations and challenges for new grid connections

There are no specific regulations considering implementation of onshore power supply to offshore fish farms. However, there are two central laws related to new grid connection, both offshore and onshore. The first law is the Energy Act. It provides regulations considering electrical facilities onshore, including reefs and islets along the coast within the baseline. The baseline is the coastal states delimitation towards the sea, illustrated in Figure 4.3. It is the foundation to determine zones in coastal states.[57–59]

Figure 4.3: *The line outside the cost represents the baseline for Norwegian coastal areas. The Norwegian coastline constitutes 102 936 km.[35]*

The second law is the Offshore Energy Act, which applies for territorial waters outside the baseline and to the continental shelf. In addition, individual provisions of this act can also be made applicable to internal waters. This law is a more general concession law, which is primarily adjusted for the future development of offshore renewable energy production. Hence, power demand for offshore fish farms is not included properly in regulations per today. There are also other regulatory acts that require both adjustments in the law and clarifications towards jurisdiction. Providing power to offshore fish farms can both be a political and bureaucratic obstacle that must be solved.[57, 59]

The network companies are obligated to deliver power according to the Energy Act. However, they demand new customers of the grid to pay an investment contribution of the necessary initial expenses up to 100 %. The investment cost is primarily dependent on the customers power requirement. In addition, it depends on how the new connection reduces the ability for the network companies to continuously supply end users. The electricity must maintain a specified quality identified by the supply quality regulation.[52, 57, 60]

Technical challenges may occur by establishing onshore power supply to a fish farming site. A new grid connection will influence the security of supply, especially when there are several customers connected to the same transmission line. The consequences of a new connection point depend on the power requirement and quality of the grid at the connection point. Challenges occur when connection points are far away from a transformer or in areas where the grid is weak. In addition, connections with a high power demand can cause difficulties.[36, 57]

A consequence when a connection point is far away from a transformer, is voltage drop in the transmission line. The voltage drop is proportional to the power demand and the length of the line. If the voltage drop surpasses the specified allowed level in the supply quality, grid investments are needed.[60, 61]

Connection points in areas where the grid is weak, lead to other challenges. These challenges include low voltage, instantaneous voltage changes and excessive loads. The grid is often weak in areas far from the generating source and transformers, typically in less populated areas close to shore. The impact of a new connection point on the grid, is dependent on the power demand and voltage loss and changes.[36]

There is no shortage of energy supply in Norway. However, new connection points can trigger grid investments. This occurs when the power demand at new connections are not available from the grid. The transmission infrastructure determines the boundary for the instantaneous energy. If a load is connected where this limit is reached, new grid investments are needed.[36]

Fish farms are often located in areas which may not have easy access to the power grid, or in rural areas along the coastline where the grid is weak. In addition, the production chain requires power demanding equipment, as described in chapter 3. These factors can, in addition to an increasing demand for power in other electrification initiatives, contribute to triggering grid investments if shore power is used as an energy source. Beyond these challenges, the electricity supply at sea will function as a normal industry on land.[36]

4.3 Technical description of onshore power supply

The equipment needed for onshore power supply for a fish farm include an onshore transformer, subsea cable from shore to the facility, switch gear and offshore transformer. Figure 4.4 illustrates these components.[36]

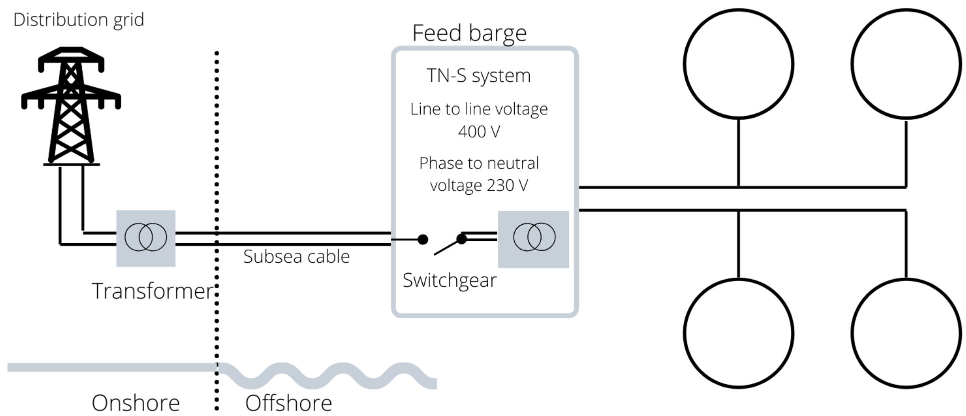


Figure 4.4: *Onshore power supply to a fish farming site with typical voltage levels at the feed barge. The cable is connected to an onshore transformer which transforms voltage from the power grid to the necessary voltage level in the cable. A switch gear is utilized to ensure isolation of the electrical equipment. The transformer on the feed barge transform the voltage to the applied voltage at the feed barge.[36]*

The subsea cable needs an attachment point onshore. This is typically a circuit-breaker or a transformer, depending on the voltage level in the grid. A transformer transforms the voltage level in the onshore grid to the applied voltage in the subsea cable. Transformers has a life expectancy of 30 years, which is a design criteria. The transformer is connected to the distribution grid and is part of a compact substation, which is constructed with switch and control gear. The switch and control gear consists of cables, bus bar, breakers and surge arrest. In addition, it includes a current transformer utilized for electrical current measurements, which is demanded by the network companies.[36, 62, 63]

Most feed barges have a Terra Neutral-Switch system, TN-S, as shown in Figure 4.4. A switch gear on the feed barge is connected to the subsea cable. This ensures isolation of the electrical equipment. Furthermore, the switch gear is connected to an offshore transformer which transforms the voltage of the subsea cable to the applied voltage at the feed barge.[36]

For the offshore industry a high voltage solution of 22 kV is the most optimal, due to the distance from shore and size of the facility. If a solution of 22 kV is being used, the feed barge requires a high voltage room where access is limited to high voltage qualified personnel.[39, 64]

4.4 Subsea cable

Special built subsea cables are used to transmit the power to the facility at sea. Connection to the onshore power grid demands cable constructions and concepts designed to withstand the special mechanical and environmental strain. To avoid mechanical stress and cable bends, some cable firms provides equipment like bend limiters [64]. In addition, the construction must be in pursuance of regulations and requirements.[38, 43]

The Norwegian Electrotechnical Committee has the following requirement for installation for cables at an aquaculture site:

Cables shall be selected and erected as to prevent mechanical damage due to movement of floating units. Cables with solid conductors shall not be used. The supply cable from onshore shall not be subject to higher mechanical stresses that prescribed by manufacture. The cable shall withstand mechanical stressed for installation on the sea bed or as floating in the sea/water.[65]

The cable from shore to the site is often armoured hybrid cable solutions. They are constructed with three-phased conductors, one for operation, one for control and one for fiber. Different companies offer subsea cables, among others Nexans. They have different alternatives, for instance FERE and FEVE, which are primarily used between shore and the fish farm. Life expectancy for cables are typically 30 years, but this varies as it is dependent of construction, material, type and if the cable is exposed to ambient conditions.[63, 66]

The length of the cable is determined by the distance between the onshore transformer and the offshore fish farm. In theory, there is no limit in the length of the cable, and they are often custom made to the specific project. However, it is not recommended to joint individual sections of the cable, as it can weaken the structure and increase the cost of the installation. The size of the facility in kVA and length of the cable determine which cable is suited. Voltage loss in a cable is caused by the resistance and reactance, which increases with the length and power demand. It is recommended a maximum voltage loss of 5 %.[64, 66]

To prevent voltage loss in a three phase alternated current cable from exceeding accepted values, equation 4.1 can be applied. The transferred power is defined by P, given in kW, L is the length of the cable in m, R_1 represents the conductor resistance and X_L is the reactance, both given in Ω/km. Operating voltage, U, is given in V and the voltage loss ΔU is given in %. The power factor, $cos\phi$, is the power factor for the output object.[66]

$$\Delta U = \frac{P \cdot L \cdot (R_1 \cdot cos\phi + X_L \cdot sin\phi)}{U^2 \cdot cos\phi} \cdot 100\% \tag{4.1}$$

In addition to the voltage loss, two other criteria are of importance in order to select the right cable. The first criterion is transmission capacity, which is dependent on the cross section of the conductor. The second criterion is the short circuit current, I_c, which must be known in order to dimension the correct protective gear. If I_c is unknown, the protective gear will not register error and the error will be persistent, until it gets detected.[39]

It is recommended to have an AC cable, rather than a DC. This is due to the cost of the AC/DC inverter needed both onshore and on board the feed barge. DC cabling systems are used for distances far above the distances presented in this thesis. Today, it exists AC cabling systems at a distance of 16 000 km.[39]

4.5 Costs related to onshore power supply

The most vital cost driver for onshore power supply is the procurement of the subsea cable. The cable cost varies depending on cross-sectional area, isolation type, conductor material and voltage level. Aluminium type cables, Al-cables, are often cheaper than cobber type cables, Cu-cables. However, Cu-cables are recommended for cabling systems in water, to avoid corrosion.[67]

Historical figures from Enova shows that this cost will constitute 40 to 90 % of the total CAPEX. This depends on the sufficiency of the onshore grid, developed infrastructure, and the distance from shore. The distance between the infrastructure and fish farm is crucial to the profitability of using onshore power supply. For some localities, the distance will be too long for a profitable investment of shore power technology.[7, 52]

In addition to the cable, it is necessary to invest in other infrastructure when implementing onshore power supply. This applies both onshore and at the fish farming site, as explained in chapter 4.3. These costs will vary depending on the power demand and voltage level.[7]

Table 4.1 gives an overview of the necessary equipment for onshore power supply with a technical description and its corresponding investment cost for a high voltage system. The compact substations are prefabricated and the cost includes material, installation, machinery, construction, projecting and additional costs. However, the cost varies depending on size, capacity, voltage level and if the substation is to be placed offshore or onshore. Other costs for additional equipment and installation are given in Appendix A.

Table 4.1: *The equipment with technical description and investment cost for onshore power supply for a high voltage system.*

Equipment	Technical description	CAPEX	Source
Subsea cable	High voltage AC cable	400 to 1 000 NOK/m	[64]
Overhead cost subsea cable		200 000 NOK	[7]
Ditching/laying of cable		300 NOK/m	[7]
Compact substation	High voltage	600 000 to 2 000 000 NOK	[39]
Transformer	315 kVA	75 000 NOK	[68]
Circuit-breaker	High voltage	300 000 NOK	[69]
Installation		600 000 NOK	[7]
Unspecified		10 %	[7]

The cost of installation related to the subsea cable will vary according to weather conditions, seabed conditions, access to laying vessel and other conditions. SINTEF and data from NVE imply that the cost for laying of a subsea cable will constitute approximately 35 % of the subsea cable cost for voltage levels at 24 and 33 kV.[67, 70]

OPEX related to shore power, includes material, transport and work. Historical figures for an equivalent facility can be utilized to find annual OPEX. Another alternative is to estimate annual OPEX as a percentage of the total investment cost.[71]

OPEX for onshore power supply is given in Table 4.2. There is a limited extent of OPEX for subsea cables. The OPEX is related to cathodic protective gear in addition to control of the grip at the connection point, with a few years interval. This cost includes transportation of personnel, administration and remaining cost. OPEX for substations is minimal and due to an annually inspection of the substations. This cost is dependent on the type and size.[70, 72]

Other OPEX for onshore power supply includes electricity cost and network tariff. The network tariff consists of an annual fixed component, one component dependent on the consumption of energy which comes in an addition to the electricity cost, and one component dependent on the power peak value for each month. Both the electricity price and network tariff will vary, depending on the power situation, network company and market.[43, 73]

Table 4.2: *OPEX for a subsea cable, substations and electricity prices with network tariff. The network tariff for the summer includes the months from April to October, and the winter network tariff includes the remaining months.[73]*

Operation and maintenance	OPEX	Source
Maintenance subsea cable	2 000 NOK/km	[70]
Annual inspection of substation	500 to 900 NOK/substation	[72]
Electricity tariff	0.020 NOK/kWh	[73]
Network tariff summer	50.1 NOK/kW/month	[73]
Network tariff winter	63.30 NOK/kW/month	[73]
Overhead cost network tariff	25 000 NOK/year	[73]
Electricity price	0.400 NOK/kWh	[74]

5 Energy resources

Considering fish farms projected offshore, shore power is currently very expensive, due to the distance from shore. In the following chapter, technologies able to substitute the diesel generators, are presented. This involves hydrogen generator, fuel cell, solar power, wind power, both offshore and onshore, and wave power. Storage solutions with batteries and hydrogen are also included. In addition, diesel generator technology is described.

The presented technologies each have a table including life expectancy, costs and capacity, among other parameters. The purpose is to give an impression of how relevant, available and suitable the different technologies are for the offshore fish farm industry. OPEX and CAPEX are some of the parameters listen in the tables. These parameters do not take the life expectancy or energy production of the technologies into account.

Levelized cost of energy, LCOE, can be calculated based on both OPEX and CAPEX, and takes the life expectancy and energy production into account. This is a method to calculate the energy cost, and allows various technologies to be compared, on an economical basis. LCOE can be calculated from equation 5.1, where CAPEX is the investment cost and OPEX is annual operation and maintenance cost. Both fuel cost and energy produced are also given as annual values. The discount rate is represented by r, and usually varies between 4 % and 6 %. The life expectancy is defined by n, given in years.[75]

$$LCOE = \frac{\sum_{t=0}^{n} \frac{CAPEX\ +\ OPEX\ +\ Fuel\ cost}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Energy\ produced}{(1+r)^t}} \tag{5.1}$$

5.1 Diesel generator

Diesel generators convert fuel energy into mechanical energy, and further on to electrical energy. The diesel generator utilizes an internal combustion engine, ICE, in combination with an alternator. The combustion produces exhaust emission as a waste product. The steps from diesel fuel to produced electricity are described in the simplified flow sheet in Figure 5.1. These generating sets are mostly used in locations without connection to the power grid, as primary power supply, peak shaving and backup.[76–79]

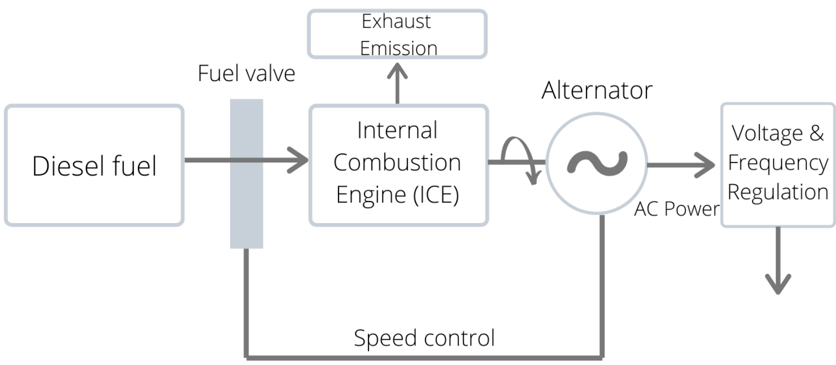


Figure 5.1: *Electric power generation by ICE, and the process from diesel fuel to the electricity power output. This produce the fixed frequency AC voltage output required. Speed regulation provides an indication of the alternator output frequency, which is fed back to control the fuel supply valve.[79]*

The advantages of using a diesel generator are availability, quick start up, reliability, fast ramp up, withstand of heavy loads, low investment cost and durability. On the other hand, the diesel generator has disadvantages. This involve noise pollution, pollutive emissions and a higher fuel cost compared to renewable energy resources. The size of the generator determine both the amount MDO, and the operating cost.[76]

Diesel generators emit carbon dioxide, CO_2, nitrogen oxide, NO_X, and particulate matter, which are released into the atmosphere. For a typical generator set the consumption of fuel is between 0.32 and 0.53 L/kWh at its rated power. This depends on the quality of the engine. It is released approximately 3.2 $kg\ CO_2/L$ into the atmosphere from each liter of diesel consumed. The emissions depend on the size of the generator.[77, 78]

The overall efficiency of a diesel generator is a combination of the efficiency of the diesel engine and alternator, and can range between 30 and 55 %. The standalone efficiency of the diesel engine and alternator are higher when operating separately. There are several parameters that affect the efficiency. This involves the design, capacity, mechanism for fuel control, operating speed and type of cooling mechanism. In addition, the efficiency of a diesel generator during operation deviates from the design value, because of load and ambient conditions. The patterns for efficiency of the generator indicates that it increases with the size of the generator.[76, 77, 80, 81]

Diesel generators are sized to meet the peak demand during the consumption peak hours, to increase reliability. As a result, they run at low power during off-peak consumption hours. This low-power operating mode leads to poor fuel efficiency and increases the maintenance work. A solution to this problem involves implementing several diesel generators, to meet the higher and lower power peaks. Norwegian fish farms have a varying power demand. Therefore, they are operating with several generator sets, to meet the peak demand in the most efficient and economical way. In addition, the life expectancy of the diesel generators increases.[76, 82, 83]

The specific fuel consumption, SFC, is expressed in g/kWh, and indicates the quantity of diesel required to generate one unit of electricity, which relates to the fuel cost to operate the diesel generator. The SFC varies with load, and is typically optimal at 70 to 80 % loading of the rated capacity. Loads of 25 % of rated power or lower decrease the SFC substantially, and can damage the diesel generator. SFC varies with size of the diesel generator and is better for larger sized sets, specially over 500 kVA. A 500 kVA diesel generator at 100 % loading has typically 12 % better SFC than a 25 kVA set at the same loading.[45, 80, 84]

Figure 5.2 illustrates the SFC, of a generator set of 230 kVA and its efficiency. The SFC is based on a data sheet for the specific generator, were the only given points on the graph were at 50, 75 and 100 % load of rated power. There will be some uncertainties regarding the SFC graph, as the rest of the graph was plotted from other SFC trends for different diesel generators.[45, 80, 84]

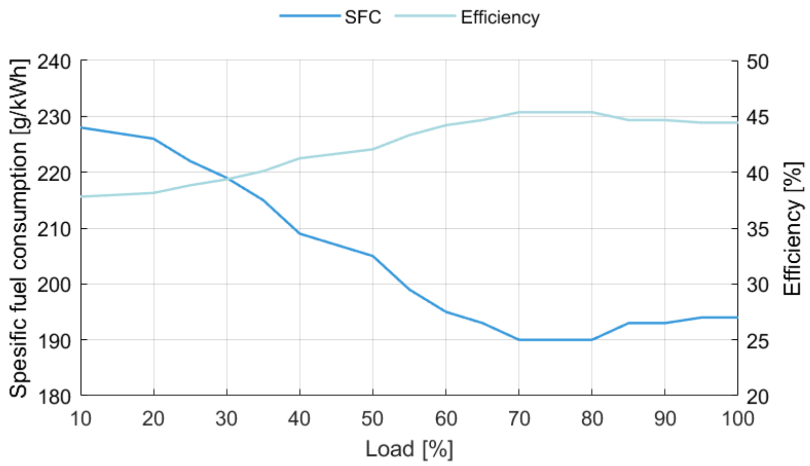


Figure 5.2: *SFC and efficiency of a generator set of 230 kVA. The SFC is based on the data sheet for the specific diesel generator and from other SFC trends for different diesel generators.[83, 84]*

To give an impression of operational lifetime and costs of a diesel generator, an example of a set with 230 kVA is described in Table 5.1. Costs and life expectancy for this diesel generator set is based on general numbers given by Nogva Motor Factory, which delivers generator sets for the marine industry. A diesel generator set with this apparent power is identical to the size of the set utilized on Ocean Farm 1. The OPEX and life expectancy presented in the table are relative to how often, good and thorough the maintenance work is performed on the generator set. In addition, the maintenance work and fuel cost are dependent on the amount of load the generator operates at. Operation hours per year will variate dependent on how much of the power demand the diesel generator is expected to cover.[39, 45, 82]

Table 5.1: *Parameters of a diesel generator set, with the apparent power of 230 kVA, and values considering MDO.*

Parameter	Amount	Unit	Source
Apparent power	230	kVA	[45]
Efficiency	30 to 50	%	[76]
Life expectancy	25 000 to 50 000	h	[82]
Operation hours per year	4000	h/year	[82]
Weight	1 030	kg	[45]
Energy content MDO	11.6	kWh/kg	[39]
Density MDO	0.84	kg/L	[39]
Price MDO	7.70	NOK/L	[85]
CAPEX	300 000	NOK	[82]
OPEX	10 000	NOK/year	[82]

The price of MDO is constantly changing, thus the expenses for an operating diesel generator on a fish farm will variate. Norwegian fish farms are currently paying a tax of 1.45 NOK/L for CO_2 emission, but not taxes on noise and local pollution from road use, although this could change. Table 5.1 presents a value for MDO from May 2020. However, in January 2020 the price was 10.27 NOK/L. These constant changes can have a significant impact on the fuel cost for the fish farms.[45, 85, 86]

5.1.1 Hydrogen generator

Hydrogen can be utilized as fuel in an ICE, as either a single or additional fuel. The hydrogen generator will function similar to a diesel generator, and will have the same efficiency. There will be a difference in cost of fuel and storage of hydrogen. Hydrogen as fuel will not emit CO_2, hence reducing air pollution. This is one of the most important benefits of using hydrogen as fuel. However, NO_X can be produced in combustion with air. A hydrogen generator is also currently cheaper than a fuel cell. In general, it is not difficult to get an ICE to run on hydrogen. However, the challenge is to get an ICE to run sufficiently on hydrogen as a single fuel.[87, 88]

The diesel generator can run on hydrogen as a single fuel with few modifications. Despite the fuel being easy to ignite with an ignition source like a spark, it does not auto-ignite well under compression alone. Therefore, it is usual to inject a small amount of diesel fuel to ignite the hydrogen air mixture. Another solution can be to utilize a spark ignition engine instead, which can ignite pure hydrogen.[89]

Hydrogen has a wide range of flammability and low ignition energy. It can be used in lean mixtures, as a result of the wide range of flammability. The low ignition energy can lead to problems of premature ignition, as hot spots and hot gases in the combustion chamber can serve as sources of ignition. Preventing this is one of the main challenges of running an ICE on hydrogen. The low hydrogen density leads to complications, as a large volume is required in order to store enough energy. In addition, it reduces the energy density, and hence the power output.[87]

Currently, the addition of hydrogen to the fuel of an ICE can be considered as a more suitable method. Hydrogen as an additional fuel is also more preferred in a diesel generator. If hydrogen is to be used with other fuels, it has to be stored separately and mixed immediately before ignition. Hydrogen gas can not be stored in the same tank as liquid fuel, due to its low density. This will result in the hydrogen to remain on top of the fuel and not mix. Liquid hydrogen can not be stored in the same tank as other fuels either, as it will result in freezing of the other fuels, due to the low boiling point of hydrogen.[87, 88]

5.2 Fuel cell

A fuel cell performs an electrochemical process, where hydrogen-rich fuel is converted in to electricity, unlike an ICE where the fuel is burnt. The fuel cell generate electricity in an electrochemical reaction, where oxygen, together with hydrogen, produces water and electricity. The technology produces electricity in the form of DC. A fuel cell operates near-silently, as it has no moving parts, compared to a diesel generator.[90]

The technology ranges from portable power sources in consumer electronics, to large power plants. Despite the ongoing development of the fuel cell, the production volume is low, and hence the technology is expensive compared to other commercial solutions. During the forecast period of 2020 to 2025, the market for fuel cell is expected to grow more than 14.97 %, according to Mordor Intelligence. With an increase in annual production volume, the prices are expected to decrease. In addition, maritime application systems may share similar features with the more developed heavy duty road vehicles. This can further accelerate the cost reduction for fuel cells.[91–93]

A fuel cell consists of several individual cells. These cells are compiled on top of each other, forming stacks. This makes the fuel cell easily scalable and can vary greatly in size and power relative to the demand. The lifetime for each stack is dependent on how they are operated. Operating the stacks at very high or low current, starting or shutting the fuel cell wrong and start-up below subfreezing temperature reduce the stack lifetime significantly.[93, 94]

Table 5.2 presents cost and parameters for a proton exchange membrane fuel cell, PEMFC, as this is the most common type of fuel cell. The capacity of the fuel cell depends on the demand of the plant. A total system cost of 21 000 NOK/kW is assumed for this thesis.

Table 5.2: *Costs and parameters used to model the PEMFC.*

Parameter	Amount	Unit	Source
Capacity	100 to 3 000	kW	[95]
Energy efficiency	50	%	[95]
Life expectancy	20 000	h	[93]
Weight	5.5	kg/kW	[95]
CAPEX	21 000	NOK/kW	[93]
OPEX	3 % of CAPEX	NOK/kW	[96]

Half of the CAPEX accounts for components with limited lifetime, such as the fuel cell stacks and wearable components in the Balance of plant, BoP. The other half includes components such as non-wearable BoP, control and monitoring systems, auxiliary equipment, safety systems, piping and regulatory approvals. CAPEX is given for a PEMFC, with platinum as a catalyst, which is an expensive material and accounts for a large part of the capital cost. The OPEX for this fuel cell is anticipated to 3 % of the CAPEX, as the technology is still emerging. Beyond the service and replacement of stacks, there are no wear parts or consumables involved.[93, 95, 96]

5.3 Solar power

Solar power can be utilized by converting sunlight into electricity with photovoltaics, PV, cells. Solar power technology has a great potential as the sun is a renewable power source. Crystalline silicon is the most common material, consisting of almost 90 % of the solar cells sold. This material has the highest efficiency among the materials on the market, thus the most expensive and energy-intensive to produce.[97, 98]

The maximum power output, P_{max}, of a given solar cell can be determined by equation 5.2. Average solar irradiation light intensity is represented as Φ_{in} measured in W/m^2, A is the effective surface area for the solar cells measured in m^2 and η is the efficiency.[99–101]

$$P_{max} = \eta \cdot \Phi_{in} \cdot A \tag{5.2}$$

Today, an average solar cell delivers approximately 160 kWh/m^2 electricity annually. The amount of electricity extracted depends on location, angle of gradient, system solution and efficiency of the solar cells. Solar cells can not continuously convert sunlight into electricity, due to the absence of the sun, thus it is difficult to provide a reliable electricity supply. The energy must either be used immediately, stored or sold through the electricity grid.[97, 102]

In Norway, the solar irradiation is usually between 700 to 1 000 kWh/m^2 annually for a horizontal surface. To compare, Germany has between 1 000 to 1 200 kWh/m^2, which is a global leading country within solar power. The solar irradiation in Norway at a chosen day in the summer and winter, are shown in Figure 5.3. The figure indicates higher solar irradiation during the summer. The most optimal areas for solar power are south in Norway. However, if the angle of gradient is optimized, it can contribute with more energy independent of the season. Solar cells are more efficient in a cold climate, which Norway with its cold climate can take advantage of.[97, 98, 103]

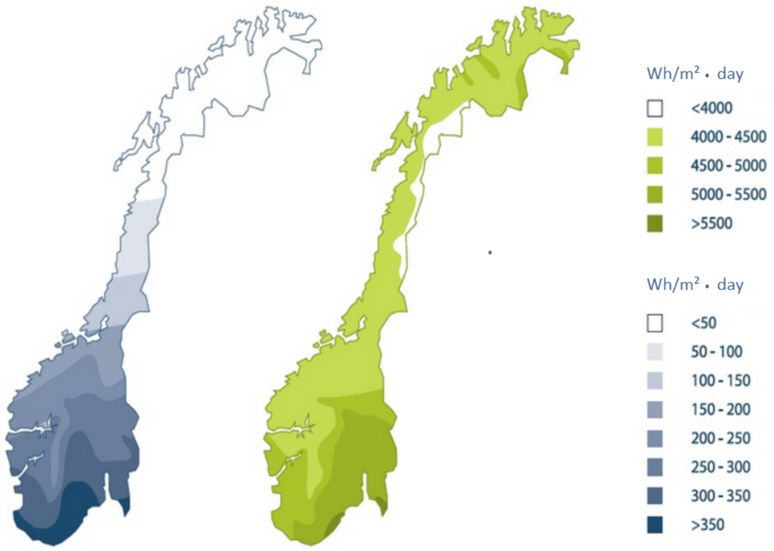


Figure 5.3: *The average solar irradiation in $Wh/m^2 \cdot day$ distributed over Norway. The solar irradiation during winter to the left, and summer to the right.[98]*

The costs associated with solar cells are mainly investments. The life expectancy is 25 years for an 0.10 MW power plant, which is an estimate based on an average of several solar power plants in Norway. The power plant has a LCOE of 0.83 NOK/kWh from 2018, based on a discount rate of 6 % with a CAPEX of 8 750 NOK/kW and an annual OPEX of 50 NOK/kW. Small power plants will have a more expensive cost per kWh installed, and large power plants may have a less expensive cost per kWh installed. Solar power installation is expected to expand further the next two decades, driving the cost down.[104–106]

There are some difficulties considering installing solar cells on an offshore fish farm. The installation will be more complex than installation of conventional solar cells for households or larger power plants, due to tougher ambient conditions offshore. In addition, the fish farms planned or installed offshore will not have dedicated area to install solar cells, and hence only small areas will be suitable for installation. Installation of solar cells onshore and connecting them to the offshore fish farm is a solution. However, the distance must be under 1 km from shore to be efficient and profitable.[106, 107]

Several costs will change when considering an offshore installation of solar cells, compared to onshore. The installed capacity of solar cells possible for offshore installation will be lower. In addition, the CAPEX increases due to the need of more solid mounting, higher quality requirements on the solar cells and the distance from land causing a longer way for the installation personnel to travel.[106]

The higher quality and mounting is required because of the though weather conditions offshore. A higher efficiency per cell, compared to conventional solar cells, will increase output power, and can be considered due to the limited space at the fish farm. A solar cell with increased capacity will contribute to an increase of CAPEX. OPEX will increase accordingly with the distance from shore, as the service personnel must travel further. In addition, life expectancy will decrease as the condition offshore is not optimal for solar cells. On the other hand, costume made solar cells for offshore condition may last up to 20 years, though they are very expensive.[106–108]

Table 5.3 presents efficiency, dimensions, cost and life expectancy for an offshore installation, with a capacity of 20 kW distributed over 100 m^2. The parameters are based on general assumptions by consulting with Getek. In addition, the dimension and capacity for each solar cell are presented, which are representative values for commercial solar cells utilized by the industry. Parameters presented in Table 5.3 have considerably higher costs compared to onshore solar cells for an average conventional solar power plant.[106]

Table 5.3: *Different parameters considering capacity, efficiency, investment cost, maintenance cost and life expectancy for an offshore installation of solar cells.[106]*

Parameter	Amount	Unit	Source
Capacity plant	20	kW	[106]
Capacity	320	W	[108]
Efficiency	19	%	[106]
Life expectancy	10	years	[106]
Dimensions	1.657×0.996	m	[108]
CAPEX	15 000 to 20 000	NOK/kW	[106]
OPEX	200	NOK/kW/year	[106]

There are some environmental impacts in manufacturing and construction of the PV materials and installations. These impacts are however small compared to a coal burning plant. However, to install solar power a large area of land is required to harness the energy. A 1 GW PV facility requires 48.5 km^2 of land, which is a large area compared to 2.42 km^2 of land for a 1 GW coal-fired power plant.[102]

The most mature technology is solar cells installed on rooftops and large scaled parks on the ground. Examples on new technology under development are floating solar cell parks and solar cells integrated as a material in buildings and roads. A test project for a floating solar plant is illustrated in Figure 5.4. The plant is located at Osterøy close to Bergen, and is supposed to supply a fish farm with electricity.[109–111]

Figure 5.4: *A test project for a floating solar plant, located at Osterøy near Bergen, and is supposed to supply a fish farm with electricity.[110]*

Floating solar power could solve the issue concerning space to install power plants. The technology is innovative and has an increased efficiency, due to the reflection of light from the water and lower temperature conditions than onshore. However, it is a new concept with no commercial deployment being undertaken yet, and only a few demonstration projects that are being deployed worldwide. In addition, if the system is installed offshore, it will have an increased corrosion on the components and be prone to more threats involving storms, sea waves and cyclones. Currently, a new pilot project on offshore floating solar cells is under development by Equinor in cooperation with Moss Maritime. In the future, when the technology has evolved, it might be more suited for offshore conditions.[109–113]

5.4 Wind power

Wind turbines utilize the kinetic energy in wind to convert mechanical energy to electricity, and the current flow is usually AC. The system consists of a turbine connected to a generator, and can be placed both onshore and offshore. Wind turbine technology has developed rapidly over the last years, which has led to a higher power production of wind turbines today. Norway can benefit from favorable wind conditions, as shown in the map of average amount of incoming wind in Figure 5.5. The wind supply of the Nation is abundant and inexhaustible, though variable and unpredictable.[114, 115]

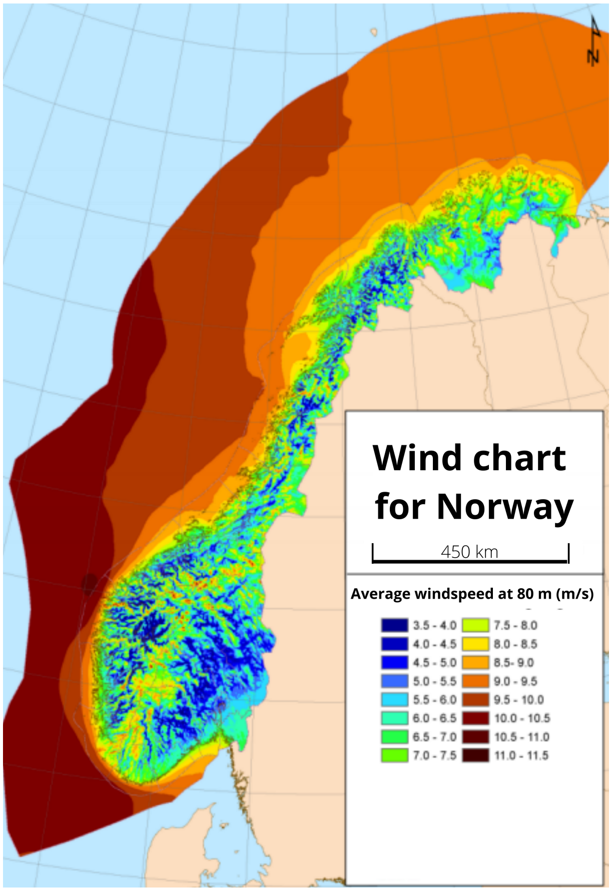


Figure 5.5: *The amount of incoming wind in Norway, which has especially favourable wind conditions. The wind is measured 80 m above the ground.[116]*

5.4.1 Onshore wind power

A typical onshore wind turbine, installed in 2019, produces 14 GWh annually, which is equal to the consumption of 700 households. Table 5.4 shows several parameters such as costs and life expectancy of an onshore wind turbine of 3.45 MW. The calculation of LCOE was based on a 6 % discount rate and 20 years life expectancy. The LCOE is given for the average wind power plant put in operations in 2018, and was reduced by 34 % from 2012 to 2018. A big part of this reduction is due to technological development. According to NVE, it is expected to be further reduced to 0.27 NOK/kWh by 2020. Consequently, onshore wind power is able to compete with other power production technologies, for instance hydro power. Both the LCOE and CAPEX in the table are given for wind turbines over 3 MW.[114, 117]

Table 5.4: *Different parameters considering capacity, efficiency, life expectancy, CAPEX, OPEX and LCOE for an onshore wind turbine.*

Parameter	Amount	Unit	Source
Capacity	3.45	MW	[117]
Efficiency	30 to 40	%	[115]
Life expectancy	20	years	[114]
CAPEX 2017	10 708	NOK/kW	[118]
OPEX 2018	0.10	NOK/kWh	[114]
LCOE 2018	0.34	NOK/kWh	[114]

5.4.2 Offshore wind power

Norway has better wind conditions in coastal areas compared to onshore, as shown in Figure 5.5. In October 2010, NVE started a study of 15 coastal areas for the possibility of offshore wind power. The Norwegian Parliament decided three potential areas in 2019. These three areas, Sandskallen - Sørøya nord, Utsira nord and Sørlige Nordsjø II, are shown in Figure 5.6. Sørlige Nordsjø II and Sandskallen - Sørøya nord are suitable for bottom fixed turbines, while Utsira nord is for floating turbines. The remaining areas from the study are represented as light-squares in the figure.[35]

Figure 5.6: *The three suitable areas for offshore wind power, both floating and bottom fixed, in Norway, shown as dark-squares. The rest of the evaluated areas are shown as light-squares.[35]*

In recent years, the development of offshore wind power has increased in Europe. Commercial offshore wind power plants in operation are mainly bottom fixed installations in shallow waters. Bottom fixed wind turbines can be built at depths up to 60 m, although technological development makes deeper waters possible. In Norway, the potential areas for bottom fixed wind turbines are further from shore and in deeper waters than the average bottom fixed turbines in Europe. This increases the costs in Norway compared to the rest of Europe.[114, 119]

In Norway, large parts of the sea areas are deeper than what is currently suited for bottom fixed technology, thus floating turbines are more practical. Floating technology is not yet mature, in contrast to bottom fixed turbines, resulting in the technology being expensive. However, this is expected to decrease in the future as the technology becomes more commercial. In 2009, Equinor installed a 2.3 MW floating turbine, called Hywind Demo, outside the western coast of Norway. The company experienced ten years of successful operations. This led to the first floating wind power plant in the world in 2017, Hywind Scotland, located on the east coast of Scotland. Hywind Tampen is the newest project of Equinor and will provide electricity for offshore oil and gas platforms in Norway.[114, 119–121]

Table 5.5 shows CAPEX and LCOE of a floating turbine of 5.64 MW in 2017. The costs include turbine capital, development, substructure and foundation, in addition to site access, staging, port, assembly and installation. The turbine usually constitutes 30 % of the total cost. A floating wind turbine will also have costs related to a subsea cable to shore or fish farm, and possibly inverters both on the turbine and farm. The capacity in the table is given for the Hywind Demo turbine.[119, 122, 123]

Table 5.5: *Different parameters considering capacity, efficiency, life expectancy, CAPEX and LCOE for a floating wind turbine.*

Parameter	Amount	Unit	Source
Capacity	2.3	MW	[120]
Efficiency	40 to 50	%	[124]
Life expectancy	30	years	[122]
CAPEX 2017	37 000	NOK/kW	[123]
LCOE 2017	0.810	NOK/kWh	[123]

The OPEX for floating wind turbines is relatively unknown, though is substantially higher compared to onshore. This is mainly due to the custom-built boats for transportation of components and personnel to the wind power plant. In addition, maintenance is only possible in steady weather conditions. Therefore, it can take time before maintenance can be completed. This results in loss of power production, as the turbines will be inoperative for a period of time. New and improved methods for maintenance through remote control, can decrease this loss.[119]

5.5 Wave power

Wave power utilize the kinetic energy in waves and breakers to create mechanical and electrical energy. The energy potential in wave power along the Norwegian coast has an estimated potential equal to the hydro power in Norway. All of the energy captured in a wave, is located between the water surface and top quarter of the wave length. This energy can be extracted in different ways, through a turbine. The potential in wave power has driven a development of a large variety of technologies.[125]

According to NVE, wave power in Norway has a theoretical resource potential of 400 TWh [126]. Conflicts with other industries and the depth of the sea are among the restricting factors on how much of this can be extracted [127]. In addition, the variations of the oscillating waves cause technical and economic challenges in the conversion to electrical power. Among other factors, a wave power facility is exposed to stress caused by extreme wave conditions. Despite intensive research work, nobody has successfully developed a technology that has fulfilled the technical and economical requirements for production in a large scale. Wave power has hence, never reached a commercial market.[128]

Several countries are working on pilot projects based on different types and principals. The main advantage of wave power technologies is their simplicity, and they are in theory reliable. There are no moving parts other than the turbine, however, the performance level is low. New control strategies and turbine concepts are under development, which are notably increasing the power performance.[125, 128]

Waves4Power, a Swedish company, constructed a solution based on buoys anchored with elastic ropes in the seabed, called Wave-EL. A full-scale pilot facility was placed outside Runde in 2016. The buoys move according to the oscillation in the waves around a pipe. The pipe is supplied with a piston which keeps 400 tonnes of water at rest. The kinetic energy converts to electricity in a generator with the help of hydraulics. Special built cables are connected to a substation at the sea bed and transmit the power to the power grid.[128, 129]

In 2017, the facility was the first wave power technology ever to be resynchronized with the Norwegian electricity grid. It delivered 100 kW to an energy and communication corporation in Ørsta. Figure 5.7 shows the installed Wave-EL. The system was fully functional from June until mid-November 2017, when two of the mooring lines were mechanically impacted, cut straight off, by unknown means.[128, 129]

Figure 5.7: *Wave-EL placed outside Runde in Sunnmøre was the first wave power technology ever to be resynchronized with the Norwegian electricity grid. The system was fully functional delivering 100 kW.[129]*

5.6 Storage solutions

As the world is leaning more against renewable energy resources, there is a higher demand for energy storage solutions. Wind, solar and wave energy are all intermittent energy resources, which are not continuously available for electricity conversion. These non-dispatchable sources of electricity can not be switched on or off in order to meet the offshore farms demand. Hence, the renewable energy resources will be more desirable if an effective method of energy storage is available on the site.[130]

Energy storage such as lead-acid batteries, lithium-ion batteries and hydrogen are crucial parts of solving the problem. Both of the battery storage options are secondary batteries, meaning they are rechargeable. With reasonably low manufacturing and operation costs, this technology has become easily accessible on the market. Several rechargeable batteries have a wide power bandwidth, meaning they can handle small and large loads in an effective manner. In addition, batteries deliver DC electricity. [131, 132]

5.6.1 Lead-acid batteries

Lead-acid batteries are a mature and inexpensive technology. The battery is easily recycled with a relative high efficiency of approximately 80 to 85 %. One of the disadvantages of the battery is the lead, as it is categorised as a heavy metal. In addition, the battery has a low energy density, although it offers a reasonable power density.[131]

There are different safety aspects related to the lead-acid battery. One potential problem regarding floating lead-acid is the production of hydrogen as a waste product upon charging. This can create a safety hazard in a diesel generator hybrid solution, if the battery is located close by, as hydrogen is a flammable gas. Table 5.6 summarises the costs and several parameters of the lead-acid battery. The OPEX is given as an annual value. The gravimetric and volumetric energy density is given for a stationary lead-acid battery.[133]

Table 5.6: *Costs and several parameters for lead-acid batteries.*

Parameter	Amount	Unit	Source
Life expectancy	5	years	[134]
Gravimetric energy density	20	Wh/kg	[135]
Volumetric energy density	70	Wh/dm^3	[135]
CAPEX	2 700	NOK/kWh	[136]
OPEX	100	NOK/kW	[136]

5.6.2 Lithium-ion batteries

The demand of lithium-ion battery has over recent decades increased significantly, due to its dramatic progress in both presence and performance. This especially applies to the transport industry. The battery is characterized by being able to transfer lithium-ions between electrodes during charging and discharging.[134]

Compared to lead-acid batteries, there are several advantages with lithium-ion batteries. The energy density of a lithium-ion battery is well-proven to have a significantly higher energy density. In addition, they take up less room, are lighter and require minimal maintenance. Another characteristic of these batteries are their long lifetime.[134, 137]

The lifetime of the battery is determined by several factors. One of these factors include the state of charge, SOC. SOC is defined as the remaining charge of a battery, relative to its nominal capacity. By cycling the battery between 20 to 80 %, rather than 30 to 50 %, the lifetime expectancy of the battery will decrease. However, a large SOC window can be allowed if there are expected to be few cycles during the battery lifetime. This can occur if a battery is used as a peak shaver, rather than a base load. For battery cycles lower than 11 000, a SOC between 20 to 80 % is acceptable.[138]

The number of discharge and recharge cycles the battery experiences during the operation, the cell temperature, cell voltage and c-rate during discharging and charging are other factors determining the lifetime of a battery. For lithium-ion batteries, there are no charge permitted below freezing point because of the reduced diffusion rates on one of the electrodes.[138, 139]

The efficiency of the lithium-ion battery is significantly higher than a lead-acid battery, and saves electrical energy from being wasted as heat during charging and discharging. To draw energy from a battery is however expensive. The cost is about three times higher than getting it off the AC grid. The calculations are based on the cost of the battery, charging it from the grid and budgeting for an eventual replacement.[131]

The costs and parameters to model a specific Siemens battery cabinet are shown in Table 5.7. The battery type is lithium with a cathode combination of nickel-manganese-cobalt, NMC. The CAPEX cost for the batteries include the entire battery system, with cabinets for cooling and control. The OPEX is given for a 10 year span, equivalent to the assumed lifetime of the battery. The efficiency in the table applies to both charging and discharging the battery. In addition, all systems must include a cooler and a control cabinet.[138]

Table 5.7: *Costs and parameters used to model the LiNMC-battery cabinet from Siemens.*

Parameter	Amount	Unit	Source
Nominal capacity	60	kWh	[138]
Efficiency	94 to 97	%	[138]
Life expectancy	10	year	[138]
Gravimetric energy density	150	Wh/kg	[135]
Volumetric energy density	400	Wh/dm^3	[135]
C-rate, max charge	1.9	-	[138]
C-rate, max discharge	4	-	[138]
Weight	800	kg/ battery	[138]
CAPEX	6 000	NOK/kWh	[138]
OPEX	100 000	NOK/battery	[138]

5.6.3 Hydrogen

Hydrogen is another energy storage option, produced by either steam reforming, 95 %, or electrolysis, 5 %. An advantage of hydrogen is that it can be produced from surplus renewable energy, and be stored for an extended period, unlike electricity. This form for energy storage is therefore better suited for long discharge applications, and can be a part of a redundant system. Hydrogen does also have the highest energy per mass compared to other fuels. However, this element requires an advanced storage solution with a high energy density. This is due to its low ambient temperature resulting in a low energy per unit volume.[134, 140, 141]

Hydrogen gas is highly inflammable, and in contact with oxygen, an ignition can cause an explosion. The highly reactive gas is used in a number of industrial areas, but is not as commercialized in the public sector. Handling the energy carrier will always involve a risk. It is therefore necessary to establish safety procedures when using the substance. Although the gas is easily flammable, the fire hazards are only large in confined areas with high concentration, and large amounts of hydrogen gas.[142]

Hydrogen can be stored as either a compressed hydrogen, CH2, or liquid, LH2. The standard is set at 700 bar for storage tanks in passenger cars, while industry or heavy-duty vehicles most commonly use a 350 bar hydrogen tank. The low pressure tanks take up more space, but are far cheaper than the 700 bar tanks.[143]

Depending on the power demand, pressured tanks as low as 250 bars can be utilized. A X-store gas container module, version ADR V2, full carbon design, 250 bar, H_2 is shown in Table 5.8. The CAPEX is a rough estimate, and will decrease close to exponentially in terms of tank pressure, total hydrogen demand and type of container. The CAPEX for a container with a hydrogen net weight of approximately 650 kg will be around 4 MNOK, and the kg price will have dropped to around 6 200 NOK/kg.[144]

Table 5.8: *Cost and parameters for a 250 bar compressed hydrogen container. The container is a X-store 9 m model.*

Parameter	Amount	Unit	Source
Energy content	33.3	kWh/kg	[144]
Hydraulic capacity	29 400	L	[144]
Nominal transport capacity H_2 (15 °C)	6 305	m^3	[144]
Container dimensions	9 087 × 2 438 × 2 743	mm	[144]
Net weight container	13 100	kg	[144]
Gas weight H2	530	kg	[144]
CAPEX	8 450	NOK/kg	[144]
OPEX	2 % of CAPEX	NOK/kg	[145]

The table is given for a 250 bar tank. Hexagon, a global supplier of hydrogen containers, are planing to use 317 bar tanks and 653 kg hydrogen capacity, in their new standard releasing in 2021. The new standard does however plan to use the parameters for the 250 bar model, which the thesis will use further on.[144, 145]

In 2020, hydrogen production from natural gas is the cheapest way to produce hydrogen on a large scale. However, it is important to note that different markets for hydrogen provide room for price differentiation. A hydrogen production mapping report from Renewable Energy Cluster estimate a hydrogen sales price of 60 NOK/kg. The price will decrease for a local production with a sufficient demand.[145, 146]

LH2 is also a storage possibility, and is under development for numerous hydrogen ferries in Norway. The LH2 is kept at -253° C in special cooling tanks, to not evaporate into gas. The LH2 tank is then used in a low-temperature fuel cells, such as a PEMFC.[95, 147]

The LH2 technology is not as commercial as CH2, which causes higher CAPEX and OPEX. By first changing the aggregate state of hydrogen from gas to liquid, then designing and investing in special cooling tanks, lead to additional costs for LH2. In addition, hydrogen must be converted back to gas when it is to be used in a fuel cell. There are several challenges associated with this stage. This includes the damage and danger of several components freezing when the hydrogen changes aggregate state.[144]

LH2 can come in handy when a larger amount of stored energy, over 1 500 kg hydrogen, is needed. Especially in cases where there is limited storage space, LH2 is a good option. The energy density is about eight times that of CH2. However, LH2 is not considered to be neither economically or practically appropriate in the cases outlined in this thesis.[95, 144]

There are several regulations regarding the safety of hydrogen tanks. International Organization for Standardization, ISO, develop international standards for management system, manufacturing process, service, or documentation procedure. The cylinders, container and corner casting must fulfill the requirements for standardization and quality assurance set by the ISO. The tanks must have both an offshore approval and a transport approval by external certification bodies to be placed offshore.[144, 148]

5.7 Hybrid solutions

A hybrid solution is defined as an energy system integrated of several types of energy generating elements. Typically, it will consist of electrical energy generators, electrical energy storage systems and renewable energy resources. The systems can deliver highly efficient solutions, due to the multitude of possible combinations.[149]

Hybrid solutions of intermittent energy resources usually include an appropriate energy storage device to store surplus power during periods with high power production or low power demand. The stored energy will be used in periods with lower power production or high power demand. These systems often include a complementary electricity production generator, such as diesel generators, to secure reliability. The diesel generators will have reduced hours of operation in a hybrid energy system. This results in decreasing diesel consumption and CO_2 emissions, in addition to reduced noise pollution.[149, 150]

A hybrid solution will require an energy management system. This is especially important when utilizing different types of energy elements, and to ensure reliability of supply. The management system will most likely be a part of future aquaculture facilities. The system will monitor and regulate when the different energy elements will be utilized to cover the power demand. It can also optimize the usage of the different elements, such as shore power when electricity prices are low. The system can also regulate which energy element will be used for specific operations or conditions, for example by only using the diesel generator as a backup.[151]

The energy elements can have different current flow. In a hybrid solution, inverters are therefore needed to convert current from AC to DC, or the other way around. A bidirectional inverter can convert current both ways. Table 5.9 shows the efficiency and cost of a bidirectional and DC/AC inverter. The efficiency of the inverters can vary as they are dependent on the output voltage, but the values given in the table are a sufficient basis. The DC/AC inverter is for a 20 kW solar plant.[138]

Table 5.9: *Different parameters considering efficiency and CAPEX of a bidirectional and DC/AC inverter.*

Parameter	Amount	Unit	Source
Bidirectional inverter efficiency	99	%	[138]
Inverter DC/AC efficiency	98	%	[138]
Bidirectional inverter CAPEX	750 000	NOK	[138]
Inverter DC/AC CAPEX	40 000	NOK	[138]

6 Case study

The NDF initiated development licences in 2015, to spur new and innovative technology concepts. There are 19 of 104 concepts which have received licences. Some of the projects will be located in sheltered waters, while others will be placed in more exposed and open sea areas. An overview of all companies with accompanying offshore concepts, which have received development licenses per January 2020, are listed in Table 6.1. A detailed description of these projects is given in Appendix B.[8]

Table 6.1: *The 13 concepts with development licences that can be placed offshore and accompanying companies. Three of these concepts are chosen to be further focused on, and are shown in bold writing.[6]*

Company	Concept name
Ocean Farming AS	**Ocean Farm 1**
Nordlaks Oppdrett AS	Havfarm 1, Havfarm 3
Mowi Norway AS, Hauge Aqua	The Egg
Atlantis Subsea Farming AS	Atlantis
Norway Royal Salmon ASA, Aker Solutions AS	**Arctic Offshore Farming**
Hydra Salmon Company AS, SalMar ASA	Produksjonstank
Måsøval Fiskeoppdrett AS	Aqua Semi
Mariculture AS	Smart Fishfarm
Nova Sea AS	**Spidercage**
Stadion Laks AS	The Stadion Basin
Nekst AS	Havliljen
Lerøy Seafood AS	Pipefarm
Reset	Reset

Three of these concepts are chosen to be further focused on, and are shown in bold writing in Table 6.1. Only offshore concepts were evaluated, as these will play an important role in tackling the challenges of the aquaculture industry. One of the main challenges of offshore fish farms is the rougher and more extreme weather conditions offshore, which the design and operations of the farms must take into account. The chosen concepts are, or will be, placed at different locations in Norway, and are all at different stages of development. In the following chapter, technical information, power demand and area description will be presented for each case. This will constitute the basis for further simulations of the energy solutions. Each chosen facility is stationary, and will not change location in the near future.

6.1 Case 1 - Ocean Farm 1

Ocean Farm 1 is owned by Ocean Farming AS, a subsidiary of the SalMar Group. Global Maritime AS is one of several partners on the project, and is responsible for design and system integration. The project was granted eight development licences, with a MAB of 6 240 tonnes, in 2016.[4, 152, 153]

There are several factors contributing to this concept choice. Ocean Farm 1 is the first offshore fish farm in the world, and the pilot project is in operation outside the coast of Trøndelag. This makes it possible to get actual data and values, and is hence a contributing factor to the concept choice. In addition, the facility requires a substantial demand of power and is currently operated by diesel generators, giving it potential to substitute these with more eco-friendly solutions. The facility with accompanying work vessel is shown in Figure 6.1.[45]

Figure 6.1: *The facility Ocean Farm 1 is an independent unit with rigid steel structure. The total height of the facility is 68 m with a diameter of 110 m. The volume is 250 000 m^3.[153]*

6.1.1 Technical description

Ocean Farm 1 is an independent unit with rigid steel structure and compliant mooring. The facility is semi-submersible with a permeable closing net. The technological solution is based on experience from the Norwegian fish farming industry and offshore oil technology. All handling of the fish can be internally performed at the facility, without the use of external boats and equipment. It is considered escape proof, from former analyses. The facility is also automated, avoiding heavier manual operations. A daily personnel has been set up to monitor and control operations.[6, 45, 153]

Most of the surface area at the facility is walkways. The centred building at the facility has a roof area of 100 m^2. However, a proportion of this area is covered by a tower and antennas. Vessels will frequently visit the facility. A fish feed carrier comes once a week delivering feed, water and MDO.[45]

6.1.2 Power demand

A normal production cycle is between 13 and 15 months for this facility. The average power demand per day in 2019 is presented in Figure 6.2. The facility is operated by three diesel generators of 230 kVA each, equivalent to 198 kW. The generators are not operated at constant optimal load. In hourly resolution, a few peaks over 200 kW occur during the day when feeding the fish. Heating and defrosting of pipes are needed in cold weather. Cage lights are turned off during summer, resulting in a decreased power demand of 50 kW through the day.[45]

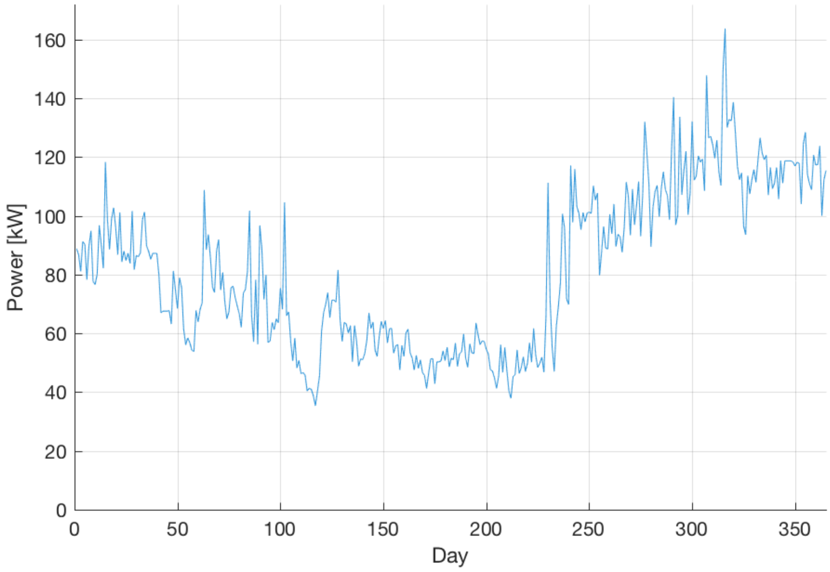


Figure 6.2: *The average power demand per day in 2019 at Ocean Farm 1.[45]*

6.1.3 Area description

The pilot project is currently operating in Frohavet outside the coast of Trøndelag, within the baseline at 100 m depth. The facility has been in operation since 2017. Figure 6.3 shows the location including onshore grids and substations.[6, 35, 153]

Figure 6.3: *A map over the location of Ocean Farm 1, and grids and substations onshore.[54]*

The island group Froan is the closest land to the facility, with an approximate distance of 4 km. It consists of hundreds of islands, islets and reefs, which constitutes an area of 400 km^2. The islands have a total population of 38 people. The island group has a rich bird life and contains a few breeding grounds for seals. The largest island close to Ocean Farm 1 is Risøya.[154, 155]

An island nearby, Frøya, has a well developed 24 kV power grid which supplies the island inhabitants and industries with power. The power grid is run at 11 kV to provide flexibility if there is a need for higher voltages. The electricity grid at Frøya is capable to withstand new loads with peaks up to 300 kW without affecting the security of supply for end users and additional voltage losses. A subsea cable connected to the electricity grid at Frøya transmit the power to Froan. However, the grid here is not sufficiently developed. It does not have the capacity to cover new loads with peaks up to 300 kW, because of a lot of voltage drops. The subsea cable is to be replaced in the future.[156]

The nearest weather station to the pilot location is Sula, approximately 35 km away. Average solar irradiation at Sula for each day over a year is illustrated in Figure 6.4. Highest values occur during summer, between day 140 to 220.[157]

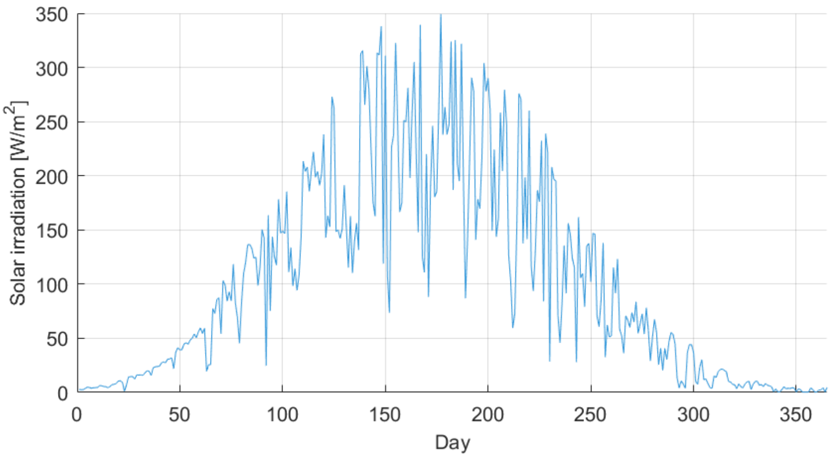


Figure 6.4: *The average solar irradiation for each day over a year at Sula. Highest solar irradiation occur during summer, between day 140 to 220.[157]*

Average wind speed measured each day of 2019 at Sula is illustrated in Figure 6.5. Measurements during some hours were not extracted, and are hence registered as 0 m/s. This applies to all of Norway in 2019. The figure illustrates a large variation in wind speed at Sula. The highest average value during an hour is 26.1 m/s, and the overall average is 6.24 m/s.[158]

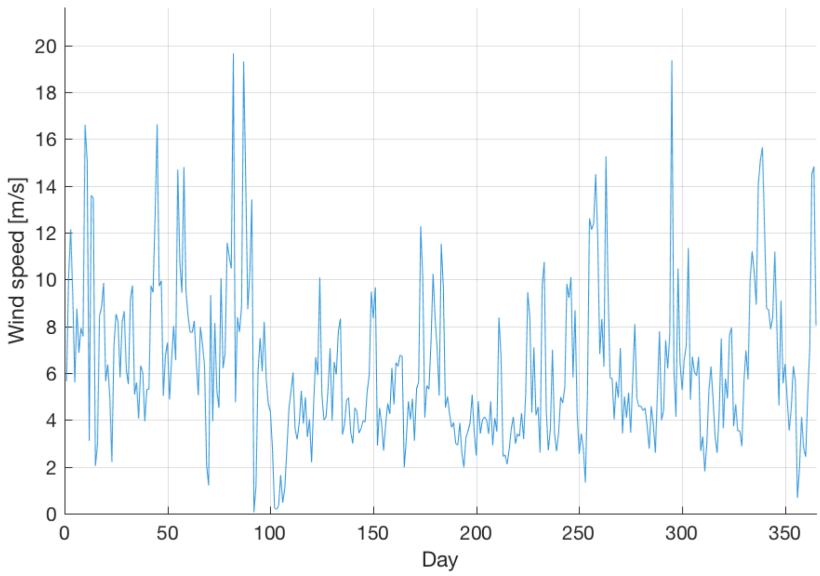


Figure 6.5: *Measured wind speed each day of 2019 at Sula.[158]*

There is a wind power plant on Hitra, an island nearby the location of Ocean Farm 1, which has recently expanded. The surplus wind power from the plant is possibly going to be utilized in hydrogen production. Local hydrogen production has a potential to be utilized in a fish farm as an energy carrier for a hydrogen generator or fuel cell.[146]

6.2 Case 2 - a full offshore version of Arctic Offshore Farming

Case 2 is a full offshore version of Arctic Offshore Farming, OAOF, with design and functions updated for fully independent open seas operation. The Arctic Offshore Farming, AOF, project is owned by Norway Royal Salmon ASA, where Aker Solutions AS has developed the concept and design. The project combines knowledge about the fish farming industry from Norway Royal Salmon, and the experience about design and operation of floating offshore structures from Aker Solutions. The project was granted eight development licences, with a MAB of 5 990 tonnes, in 2019.[41, 152, 159]

The concept choice for the OAOF was determined by several factors, including the facility being fully offshore. In addition, the exact location for the OAOF is yet to be decided, making it possible to analyse several areas. The present farm design is planned to operate with several diesel generators, and is hence another determining factor. It is possible to make design changes from the current AOF, as the farm is a future facility. The design changes might include more eco-friendly solutions compared to the usage of diesel generators. The AOF facility is shown in Figure 6.6.[41]

Figure 6.6: *The facility AOF is a semi-submersible construction with rigid steel structure. The height of the facility is 21 m with an outer diameter of 79 m. Number of fish per cage are 600 000.[160]*

6.2.1 Technical description

Technical description will be given for the current AOF design, although the concept focused on is a further development of AOF for open sea. AOF is a semi-submersible construction with rigid steel structure and permeable closing net. The fish farm facility consists of two cages, mooring and a common feed barge. The cage is constructed of a semi-submersible floating steel structure with a closing net.[6, 160]

The cage design consists of an upper and lower ring pontoon connected by 16 columns, which constitute to the steel floater. The pontoons and columns include space for ballast, ballast pumps, compressors, control systems and other equipment. The facility is constructed with minimized surface area in order to be stable and effective in waves. The surface area is around 400 to 500 m^2, and will mostly be occupied by walkways and railings. The fish feed carrier will frequently visit the facility for loading of feed and ensilage every 14th day. During periods of rough weather or other undesirable incidents, the vessels can be delayed up to one week.[41, 160]

The steel floater can be ballasted between two drafts, service and operation, by filling and emptying the ring pontoons for water. In service draft, the steel floater floats on lower ring pontoon and is de-ballasted, as shown in Figure 6.7a. Maintenance and inspection can be done at this draft. In operation draft, the steel floater floats on upper ring pontoon and is ballasted, as shown in Figure 6.7b. The fish will be less exposed to sea lice at this draft, and wave forces on the closing net and fish are reduced.[160]

(a) *The facility is de-ballasted during service.*

(b) *The facility is ballasted during operation.*

Figure 6.7: *The steel floater can be ballasted between two drafts, service and operation.[160]*

There is an umbilical connected between the cages and feed barge. In addition, a dead fish hose goes from each cage to transport dead fish. The cages are equipped with four symmetrical air pockets, which are attached to the lower ring pontoon. With these air pockets, it is unnecessary to de-ballast the steel floater for the fish to adjust their swim bladder, and the fish will always have access to air.[41, 160]

6.2.2 Power demand

The power demand of the OAOF is based on an unknown location in open sea, in contrast to the current AOF design. The OAOF have a planned production cycle of 12 months. Transfer of smolt takes place in the first month, followed by eight months of normal operation. Slaughtering happens in the tenth month, and the facility is in fallowing the two remaining months. The total planned power demand of each month during the cycle is shown in Figure 6.8. For this figure, the cycle starts in in June with two months of fallowing in April and May.[41]

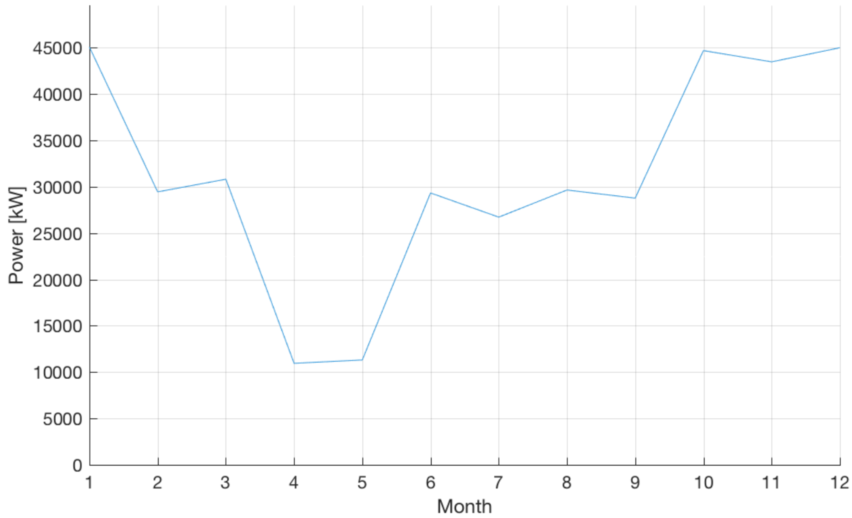


Figure 6.8: *Total planned power demand per month at the OAOF.[41]*

The total power demand includes ballasting of the steel floater and loading of feed and ensilage for the first ten months. It also includes closing net winch operations during transfer of smolt and slaughtering, and changing of the net cage when in fallowing. Systems for navigation, communication, sensors and automation demands power through the whole cycle. The facility will utilize a waterborne feeding system. A compressor is used for filling air pockets and operating dead fish collection. Subsea lights are used independent of the season, as the facility will be submerged, and are only turned off when in fallowing.[41]

6.2.3 Area description

The exact location of the OAOF is currently not determined. The NDF has recommended 11 areas for offshore aquaculture in Norway, as mentioned in chapter 2.4. All of these areas can be relevant for the OAOF. Three of them are close to the location of the current AOF, Fellesholmen outside of Kvaløya in Troms, and will thus be focused on further. Figure 6.9 illustrates these as all-covered areas. All of the areas are outside the baseline. There are no nearby islands to either of the areas. Area 21 and 23 is at 200 to 300 m depth. The potential area for bottom fixed wind turbines, Sandskallen-Sørøya nord, is approximately 35 km away from the middle of area 23. Area 7 is at 250 to 400 m depth, and is approximately 100 km from shore.[35, 159]

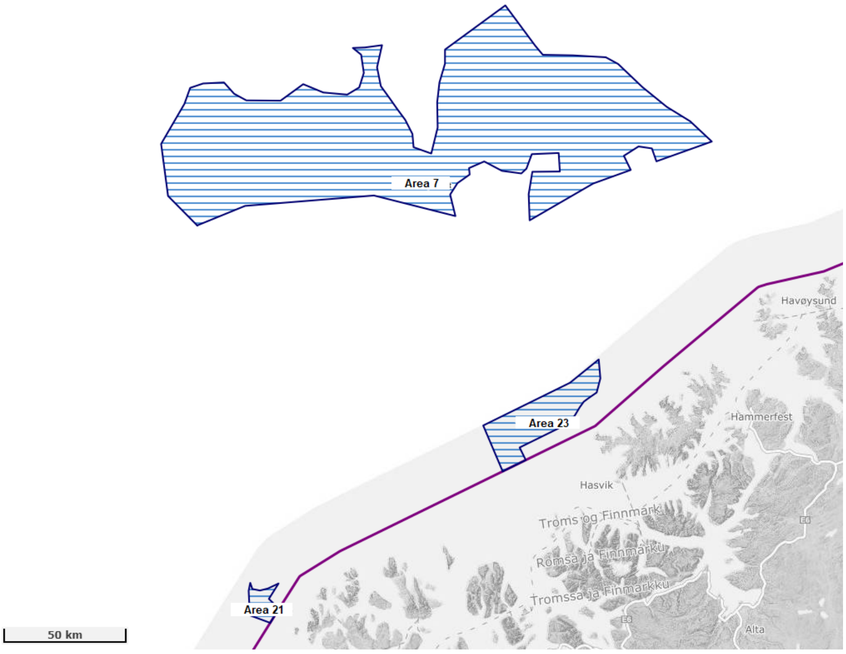


Figure 6.9: *Areas recommended for offshore aquaculture by the NDF close to Kvaløya in Troms.[35]*

The closest electricity grid to area 21 is the 22 kV grid at Rebbenesøya, as shown in Figure 6.10. The grid is sufficiently developed and capable to provide power to new loads, equal to 700 kVA. Meanwhile, voltage losses in the transmissions lines happens, and is the biggest limitary factor for a new connection at Rebbenesøya. [69]

Figure 6.10: *The closest electricity grid to area 21 is the 22 kV grid at Rebbenesøya.[116]*

The closest electricity grid to area 23 is the electricity grid at Sørøya, as shown in Figure 6.11. Sørøya has well developed distribution grid at 22 kV, and a regional grid at 72 kV. The grid is sufficiently developed and capable to provide power to new loads with peaks up to 300 kW, without affecting the security of supply.[161]

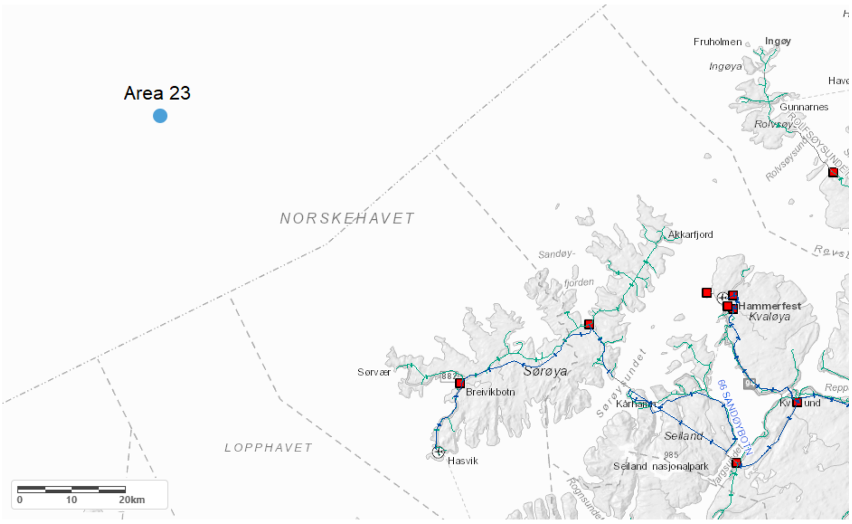


Figure 6.11: *The closest electricity grid to area 23 is located at Sørøya.[116]*

The average solar irradiation for each day over a year at Rebbenesbotn, the closest island with available data to area number 21, is shown in Figure 6.12. Highest values occur during spring and early summer, between day 120 to 220. There are no solar irradiation during the first and last month of the year, due to polar nights which occurs in northern Norway every year.On the contrary, the midnight sun may contribute to a higher average of solar irradiation in northern Norway during summer.[157, 162, 163]

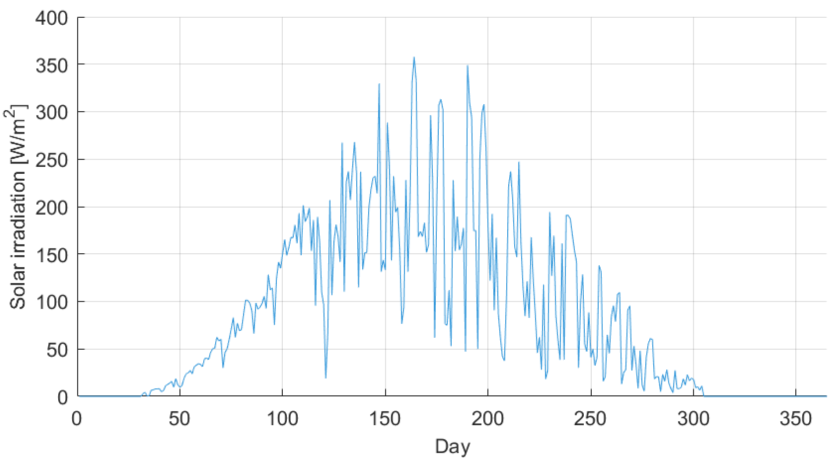


Figure 6.12: *The average solar irradiation for each day over a year at Rebbenesbotn. Highest solar irradiation occur during summer, between day 120 to 220.[157]*

The nearest weather station to area number 21 is Måsvik, approximately 25 km away. Average wind speed measured each day of 2019 on Måsvik is illustrated in Figure 6.13. The wind speed varies throughout the year, with an average of 5.8 m/s. The highest average value during an hour is 24.1 m/s.[158]

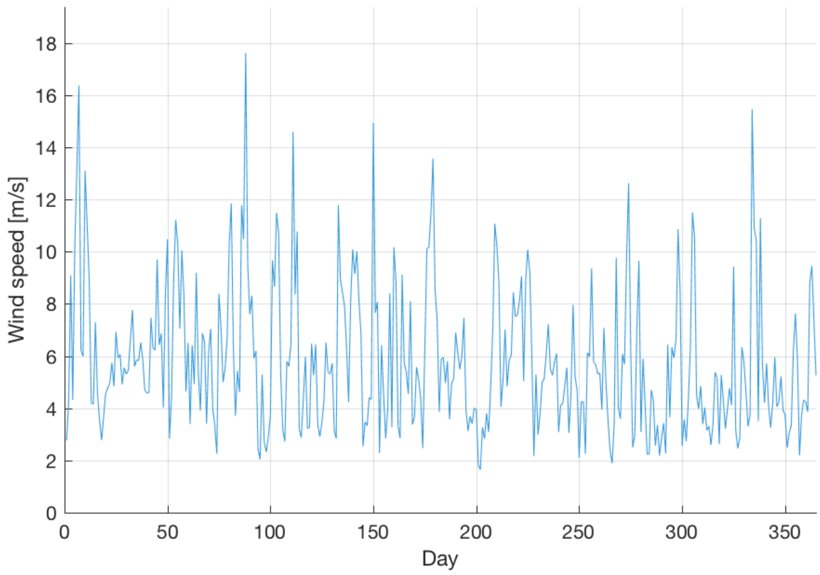


Figure 6.13: *Measured wind speed each day of 2019 at Måsvik.[158]*

6.3 Case 3 - Spidercage

Spidercage is developed by Viewpoint AS, and will be commercialized through its subsidiary, Viewpoint Spidercage AS. Their affiliates include among others Nova Sea AS, which is the farmer and end customer of the first facility. Viewpoint Spidercage AS will, through the knowledge of offshore and marine technology, develop a heave compensated fish farming system. The project was granted four development licenses, with a MAB of 3 120 tonnes, in 2019.[152, 164]

The concept was chosen based on various factors. Firstly, it is an innovative project concerning eco-friendly energy solutions. The facility intends to be energy neutral by using energy capture of wave energy and utilizing innovative wind power technology. Since new and immature technologies are expensive, other renewable alternatives can be more cost efficient. The first facility is currently being built, though it is unsure if all of the energy solutions will be implemented. The facility is shown in Figure 6.14.[165]

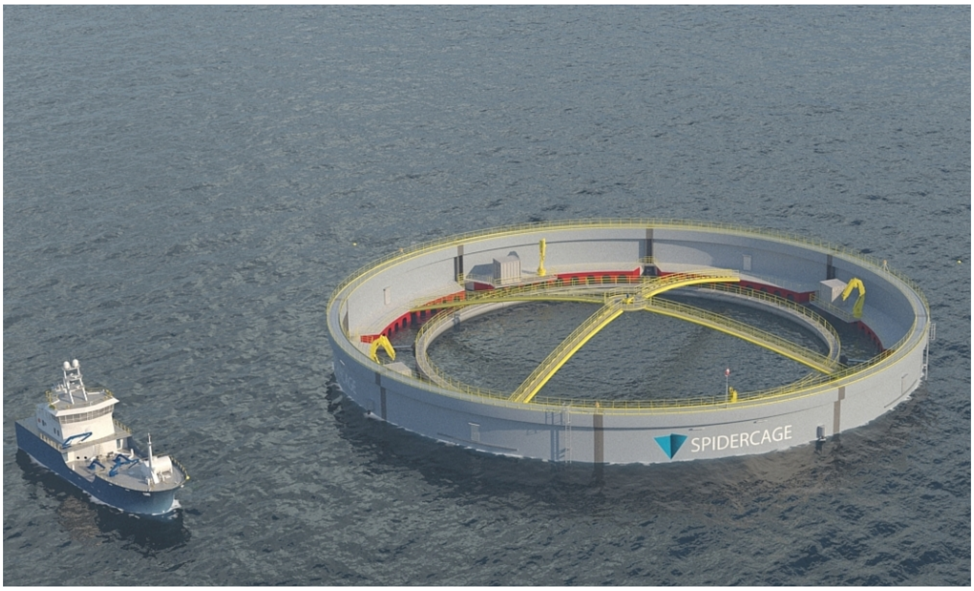


Figure 6.14: *The facility Spidercage is a semi-closed facility for exposed areas. The external diameter of the facility is 100 m and the inner diameter of the cage is 70 m. The volume is 100 000 m^3.[6]*

6.3.1 Technical description

Spidercage is a semi-closed facility. The facility will be remotely controlled from shore with daily supervision by smaller vessels. All equipment needed for operation is available on board the facility. It will be placed far from other facilities, reducing the risk of disease infection. The system can endure waves up to 16 m high. There is little surface area at the facility, as it is mostly occupied by walkways and railings.[164]

Spidercage will utilize heave compensation technology, which is based on experience from the oil and gas industry. The heave compensated solution consist of a floating external structure in steel, which will resist the waves, and an inner cage. The cage is firmly stretched in the seabed with a solder or suction anchor. The heave compensation prevents the cage from moving, thus avoiding the fish from getting damage and ensuring calm working conditions for personnel. It will also provide energy capture, making the facility energy neutral. The external structure includes feeding silos, which can store food up to 10 days.[164, 165]

6.3.2 Power demand and projected energy solutions

The average power demand per day for Spidercage is 130 kW during autumn and winter and 110 kW during spring and summer, as shown in Figure 6.15. The given power demand values are based on assumptions, as the concept is not in operation today. The maximum consumption is set to be 250 kW, with annual energy consumption of 1 GWh.[164]

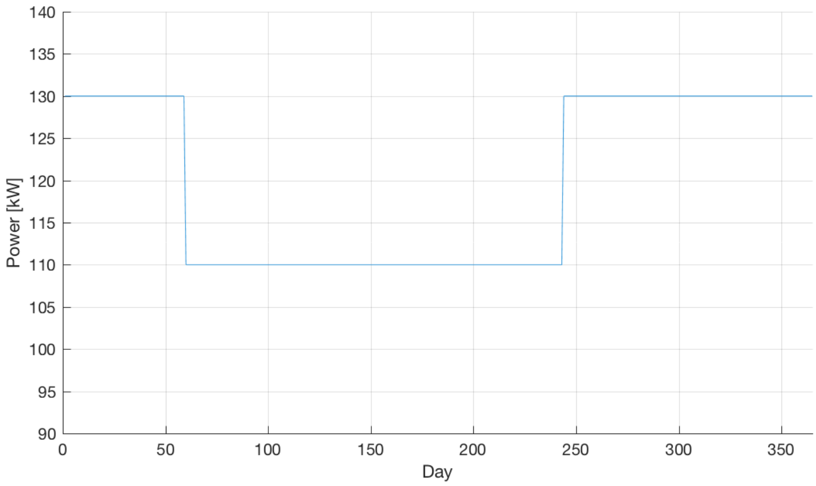


Figure 6.15: *The average power demand of Spidercage during each hour of the year.[164]*

The facility is planning to capture energy from the heave compensation through wave energy. In a fish farm anchored to the seabed, the buoyancy element will be above the minimum tension point at a significant wave height or breaker. This represents a large buoyancy excess and considerable potential of kinetic energy, which can be exploited. Energy can be captured in hydraulic piston cylinder, by limiting the buoyancy excess, and further stored in a battery. The principle is based on a wave pump, shown in Figure 6.16, which is a concept of wave power.[164, 165]

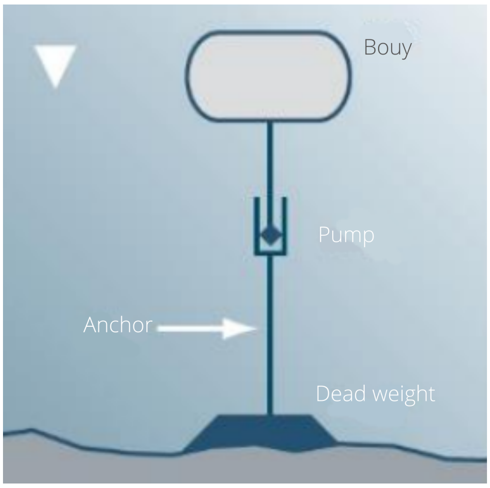


Figure 6.16: *The wave pump concept with a bouy pump, anchor and dead weight.[164]*

The facility is also planning to utilize wind energy through kite generators. The concept is shown in Figure 6.17. The cost estimate for implementing this technology is unknown, though is estimated to be around 10 MNOK including the wave energy concept. Further, a diesel generator is planned as a backup.[164, 165]

Figure 6.17: *The projected kite generator concept for Spidercage.[165]*

The concept plans to use wave energy in combination with wind and storage solutions, rather than the diesel generator and thereby reducing CO_2 emissions. Viewpoint has yet to decide if all the energy solutions will be implemented on the first facility. Table 6.2 shows capacity of the projected energy solutions.[164, 165]

Table 6.2: *Capacity of the projected energy solutions of Spidercage.*

Energy solution	Capacity	Source
Wave power	250 kW	[164]
Kite generator	30 kW	[164]
Battery	1 500 kWh	[164]
Diesel generator	250 kVA	[164]

6.3.3 Area description

Spidercage is currently being built, and will be placed outside of Blikvær in Rødøy municipal in Nordland, within the baseline at 100 m depth. Figure 6.18 shows the location with closest onshore grid. The island group Blikvær is the closest land to the facility, approximately 2 km away. The nearest island of these to Spidercage is Nilsøya.[35, 54, 165]

Figure 6.18: *A map over the location of Spidercage and onshore grid.[54]*

The closest electricity grid to the location of Spidercage is the 11 kV distribution grid at Gjessøya. The grid has the capacity to cover new users of the grid with a peak power demand of 250 kW by developing new infrastructure. The maximum capacity can be increased to approximately 1 MW if the 11 kV lines are upgraded to 22 kV. There is no electric powered infrastructure at the islands of Blikvær.[166]

Figure 6.19 illustrates the average solar irradiation for each day over a year at Gjessøya, the island closest to the planned location of Spidercage with available data. Highest values occur during spring and early summer, between day 120 to 220. There are no solar irradiation during the first and last month of the year, due to polar nights which occurs in northern Norway every year.On the contrary, the midnight sun may contribute to a higher average of solar irradiation in northern Norway during summer.[157, 162, 163]

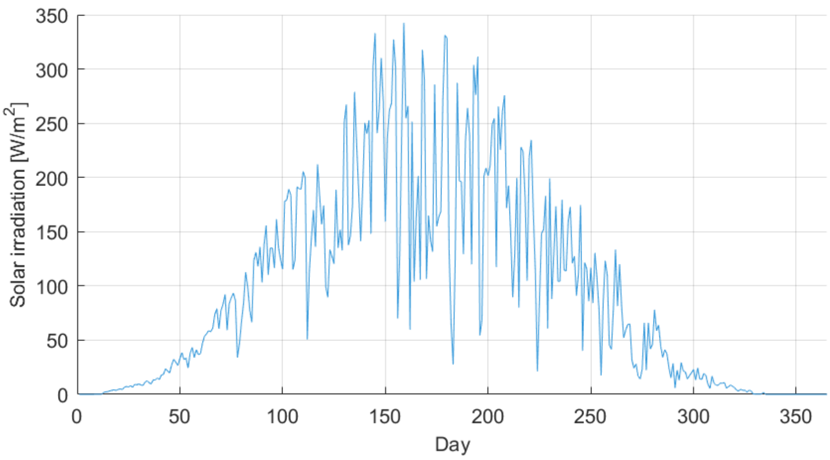


Figure 6.19: *The average solar irradiation for each day over a year at Gjessøya. Highest solar irradiation is during summer season, between day 120 to 220.[157]*

The nearest weather station to the location is Myken, approximately 15 km away. Average wind speed measured each day of 2019 at Myken is illustrated in Figure 6.20. The measured values vary, and have an average wind speed of 7.6 m/s. The highest average value during an hour is 26.5 m/s.[158]

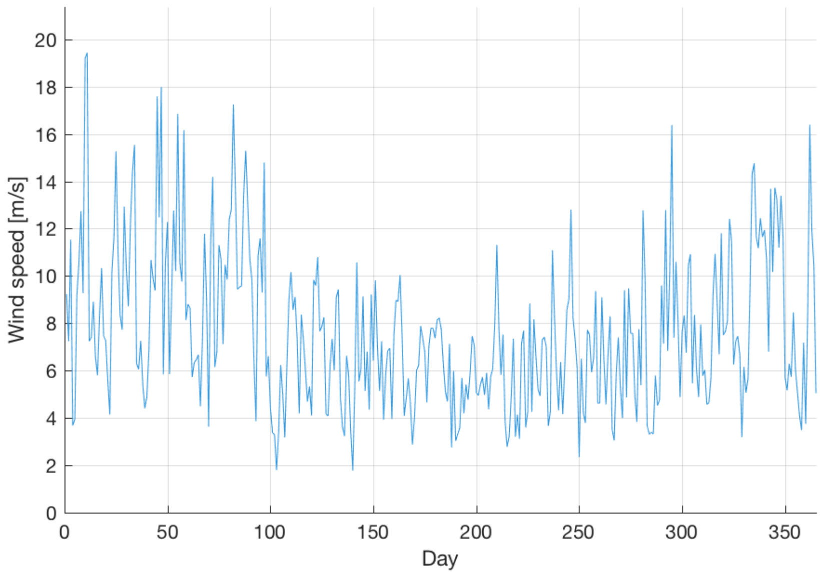


Figure 6.20: *Measured wind speed each day of 2019 at Myken.[158]*

7 Simulations and cost calculations

To analyze different energy solutions for the three cases, specified calculations and simulations are performed for each case. In this section the method utilized to find the most suitable combination of energy resource and storage options are described. The calculations and assumptions are based on the specified conditions at each location. The method for simulation and calculation of the different energy solutions will be the same for each case.

The thesis addresses six different hybrid solutions. They all have a certain number of batteries and generators. In addition, another energy solution considered is shore power alone, which is the only solution without storage opportunities. Solutions related to fuel cell or hybrid shore power have a similar layout. This also applies to solar and wind solutions. The battery and diesel generator solution will have a different layout, hence a separate script. All solutions are simulated in Matlab. Wave power and hydrogen generator will not be simulated for any of the cases.

The simulations and calculations are limited by the growth phase, shown as the system boundary in Figure 7.1, and are based on the received power demand for each case. Infrastructure required to supply the power demanding equipment are assumed installed and available at the fish farms. In addition, all simulations are based on data over a time period of 12 months.

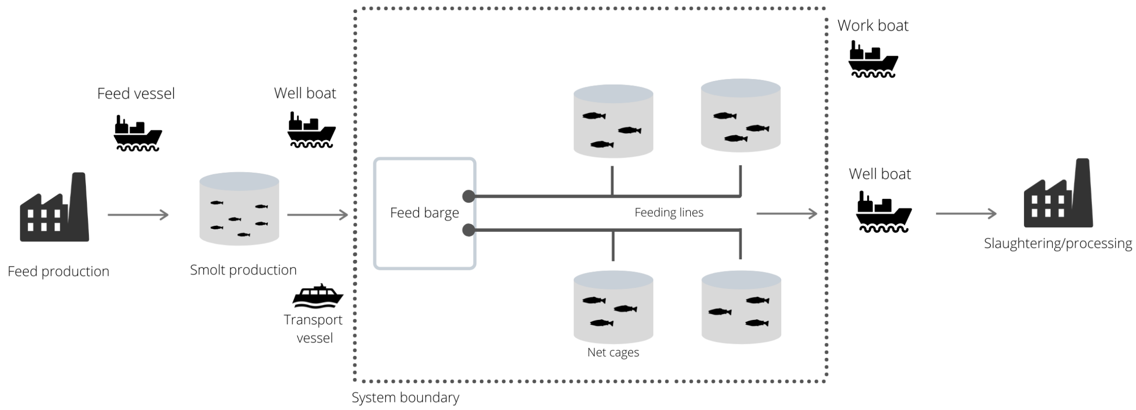
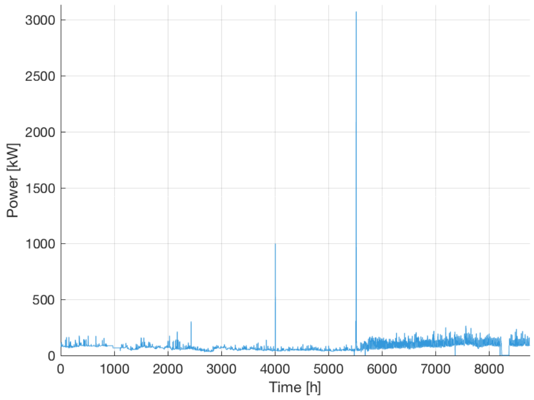


Figure 7.1: *The production cycle with a system boundary. The simulations and calculations are limited by the growth phase.*

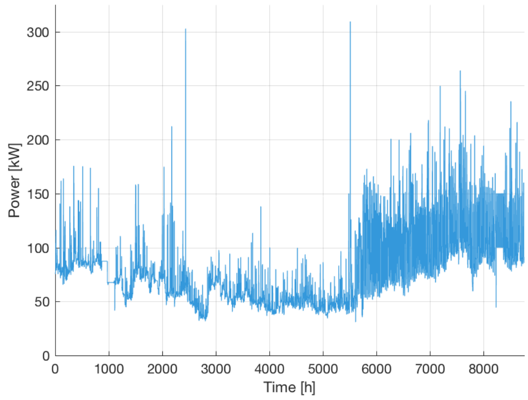
7.1 Power demand

To simulate different energy solutions for the cases, the power demand of each facility was required. This was received from each company in the form of different time resolutions and formats. For Ocean Farm 1, the values were measured each hour of 2019. This was possible since the facility is in operation, as opposed to the two remaining cases. For the OAOF, an assumed list of loads was sent, with power demand values of each month and a typical summer and winter day. Average and assumed values of the different seasons were sent for Spidercage.

There are some unusual troughs and peaks throughout the measured values of Ocean Farm 1, as shown in Figure 7.2a. The bottom point has a power demand of about 0 kW. This has occurred due to work on the main switchboard. During these days, there was hence no light or heat on board. The two largest peaks have occurred due to work during installation and repair, which does not apply for normal operation. These extrema were disregarded from the trends, and were altered to mean values of 100 kW at night and 150 kW at day. A more realistic trend was thereby achieved, as shown in Figure 7.2b, and was used in further simulations and calculations of case 1. Daytime was defined between 11:00 AM to 07:00 PM, and the rest was defined as nighttime.[45]



(a) *The power demand with unusual peaks and troughs.*



(b) *The power demand after alteration of the extrema.*

Figure 7.2: *The power demand of Ocean Farm 1 before and after alteration of the troughs and peaks to get a more realistic trend, given in an hourly resolution.[45]*

The total power demand for the OAOF was calculated from assumed values, given in monthly demand. This is shown in Figure 6.8. To get an hourly resolution, the power demand for each month was divided by the hours per month. Hence, each hour in a month has the same power demand. For this model, the cycle is assumed to start production in June with two months of fallowing in April and May. In the months, November to February, winterization is applied, causing a higher energy consumption. The power demand on OAOF, in hourly resolution, will be used in further simulations and calculations of case 2.

Power demand trends received from Spidercage, are assumed average values. These values have a constant trend for both spring and summer, in addition to another trend for the rest of the year, as shown in Figure 6.15. The power demand for spring and summer, was set to 110 kW each hour, and 130 kW each hour for the rest of the year. This will not reflect upon the actual power demand, however it gives an impression of the overall trend at Spidercage. This power demand will be used in further simulations and calculations of case 3.

7.2 Diesel generator

Diesel generators are utilized as a backup system for all the different hybrid solutions. Ocean Farm 1 have three generators of the same capacity as listed in Table 5.1. This corresponds to a capacity of 594 kW and a total weight of 3 090 kg. The same model will be used in simulations and cost analysis for the remaining cases. The number of diesel generators are however dependent on the power demand at each farm. For both the OAOF and Spidercage it is assumed to be adequate with only two generators to cover their power demand. The same number of diesel generators, needed for each case, are utilized as a backup system in each of the solutions presented in the thesis. This is to ensure reliability of supply.

The total diesel generator output, given in kWh, for each hybrid solution, was extracted from the Matlab script. In order to find the amount of diesel fuel consumed per kWh produced, the SFC was found. To calculate the SFC, Figure 5.2 was used. If the hourly demand is under 198 kWh, equal to the load of one generator, the ratio between demand and load would be interpolated in the SFC graph. For power demand between 198 and 396 kWh or 396 and 594 kWh, two or three generators would be used respectively. The number of generators and SFC are illustrated in the flowchart in Figure 7.3.

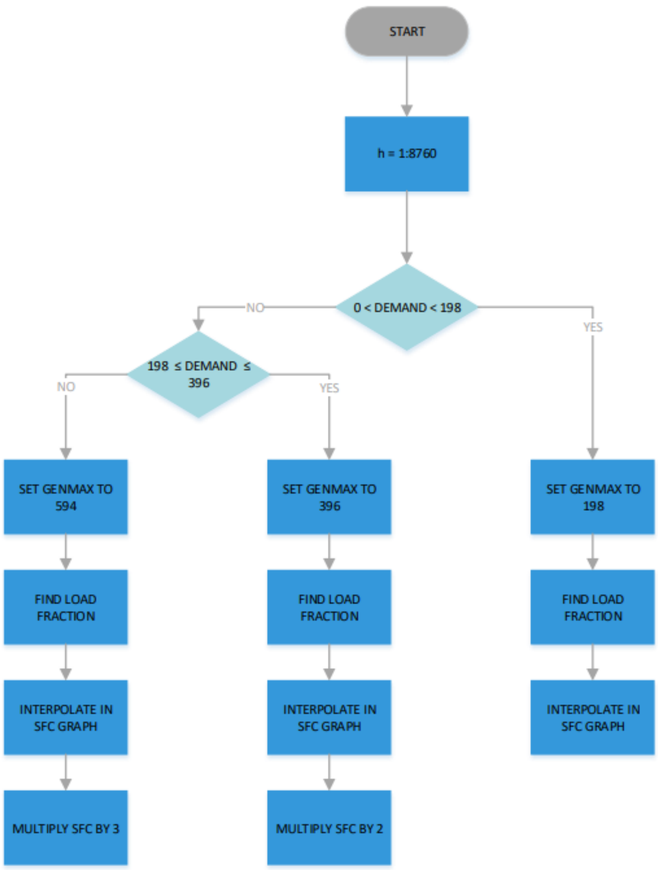


Figure 7.3: *Flowchart showing the method used to find the SFC for all solutions with diesel generators, except the battery and diesel generator solution.*

Furthermore, to find the fuel cost and CO_2 emissions from the generators for each solution, the calculated SFC and Table 5.1 was used. All the energy solutions were compared to a scenario where diesel generator is the only energy resource utilized. This will give an impression of how much diesel consumption, fuel costs and CO_2 emissions are reduced by. The annual OPEX for one generator from Table 5.1 is assumed constant in this thesis, independent if it is optimized or not.

7.3 Battery

For each hybrid solution, a certain amount of lithium-ion battery cabinets was chosen. A battery cabinet has a nominal capacity of 60 kWh. The maximum number of batteries were set to nine cabinets, corresponding to a 540 kWh capacity. Further calculations regarding the cost and LCOE, were done with respect to a battery life expectancy of 10 years. In order to maintain such a high lifetime, the SOC maximum for the battery was set to 80 % and the minimum was set to 20 % of the total battery capacity for each of the solutions, in accordance with chapter 5.6.2. This was based on calculations of the battery cycles for each solution.

The battery size was dimensioned as required for the different hybrid solutions. For each solution, an efficiency of 97 % was accounted for in the Matlab script, when charging and discharging the battery, as Table 5.7 shows. A c-rate of 1.9 during charging, will charge a battery in 0.526 hours. The largest battery capacity the thesis addresses is equivalent to 540 kWh. Hence, not allowing the battery to charge more than 1 030 kW per hour. When discharged, the energy equals 2 000 kW, as the c-rate is 4.

An hourly resolution takes an average of the power demand over an hour. An hour consists of several measurements, both high and low. The battery will not withstand peaks of more than 1 030 kW. In the Matlab script, this will not be an issue, as the power demand is in hourly resolution and will hence not reach 1 030 kW. In reality, it is possible that an energy resource would produce more, but due to the hourly resolution, the battery will never charge more than 540 kWh in one full hour. This corresponds to 540 kW, which in turn is lower than 1 030 kW. Therefore, the c-rate will not be a limitation to the battery cycles.

The cost of the battery depends on how many cabinets the different hybrid solutions require. To determine the CAPEX for each hybrid solution, the amount of batteries were multiplied with the nominal capacity and the CAPEX from Table 5.7. OPEX calculation was done in the same manner as for CAPEX.

7.4 Shore power

Different network companies were contacted in order to map the capacity in the nearby grid for the different sites, and to look at the possibility to utilize shore power. The mapping of the electricity grid included a suitable connection point onshore, necessary development of infrastructure, and was based on peak values of the power demand for each fish farm. Potential voltage drop in the exciting onshore grid was taken into account by receiving this data directly from the network companies.

Table 7.1 gives a description of the network companies contacted for each case, and in which area they have concession. For case 2, two different network companies were contacted in order to evaluate both area 21 and area 23. For case 1 and 3, this was not of interest, as their location are already determined. The table does also include area 7 for case 2, as it potentially can have the same connection point as area 23.

Table 7.1: *Overview of contacted network companies for the different cases, and where the network company has area concession.[116]*

Case	Location	Network company	Area concession
1	Frohavet	Tensio TS	Southern parts of Trøndelag county.
2	Area 21	Troms Kraft Nett AS	Southern parts of Troms and Finnmark.
2	Area 23/7	Hammerfest Energi Nett AS	Middle parts of Troms and Finnmark and the area around Hammerfest.
3	Blikvær	Norlandsnett AS	Middle parts of Norway, around Tærna muncipal.

The distance from the localities to the suitable connection points were measured by utilizing map data and measurement tool from NVE. The measurements were taken in an overhead line, not taking the depth of the sea, variations on the sea bed, island and reefs into consideration. A cable length of 2 km was added to the overhead cable length, in order to take these factors into account. The additional length was determined by studying the depth of the sea, utilizing sea drafts given by NVE. Other soundings on the sea bed such as mud and sand, were not accounted for.

The further calculations for case 1 was based on a connection point at Svellingen at Frøya, approximately 23 km from Ocean Farm 1. Svellingen has sufficient capacity in the existing grid of 11 kV to cover the power demand of Ocean Farm 1. Figure 7.4 illustrates the distance from the connection point at Svellingen to Ocean Farm 1. At Svellingen, a new compact substation has to be developed in order to provide the demanded power.[156]

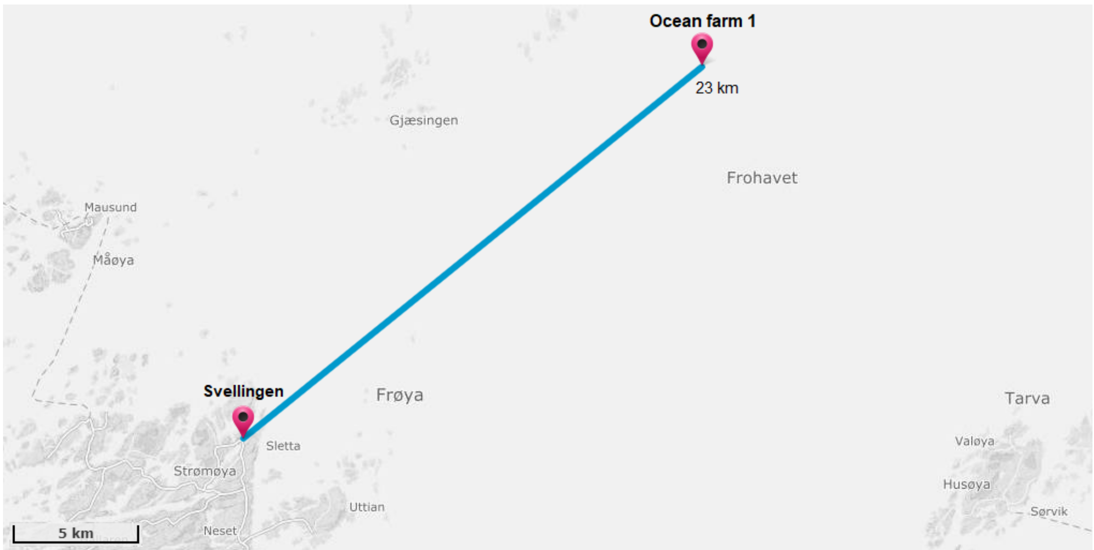


Figure 7.4: *Svellingen at Frøya, approximately 23 km from Ocean Farm 1, have sufficient capacity in the existing grid of 11 kV to cover the power demand of Ocean Farm 1. The blue line represents the length of the subsea cable. The length does not include the depth of the sea or possible obstacles on the sea bed.*

Rebbenesøya, approximately 15 km from area 21, has sufficient capacity in the existing 22 kV grid to cover the power demand of the OAOF. The most suited connection point will be at Engvika. Engvika is an extreme point in the grid at Rebbenesøya and will not influence other customers on the grid. The length of the subsea cable ranges from 15 to 30 km, depending on where in area 21 the farm will be placed, as illustrated in Figure 7.5. Further calculations for the OAOF in area 21 were based on the closest point, 15 km, to Engvika. A circuit breaker in Engvika has to be developed in order to provide the demanded power.[69]

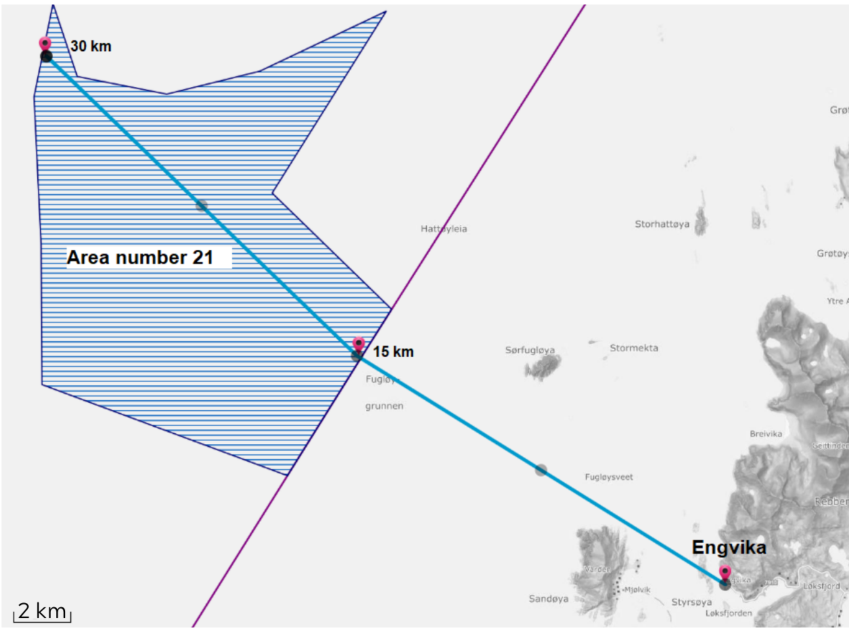


Figure 7.5: *There is sufficient capacity in the grid at Engvika at Rebbenesøya. The blue line represents the length from the connection point to the area, which ranges from 15 to 30 km. The length does not include the depth of the sea or possible obstacles on the sea bed.[116]*

For area 23, there is sufficient capacity in the existing 24 kV grid at Sørøya. The best connection point will be at Sørvær. The length of the subsea cable ranges from 22 to 52 km, and is dependent on where in area 23 the farm will be placed. This is illustrated in Figure 7.6. Further calculations for the OAOF in area 23 were based on the closest point, 22 km, to Sørvær. A compact substation has to be established at Sørvær in order to provide the demanded power. Area 7 can potentially have the same connection point as area 23, but was not considered in further calculations, due to the great distance from shore.[161]

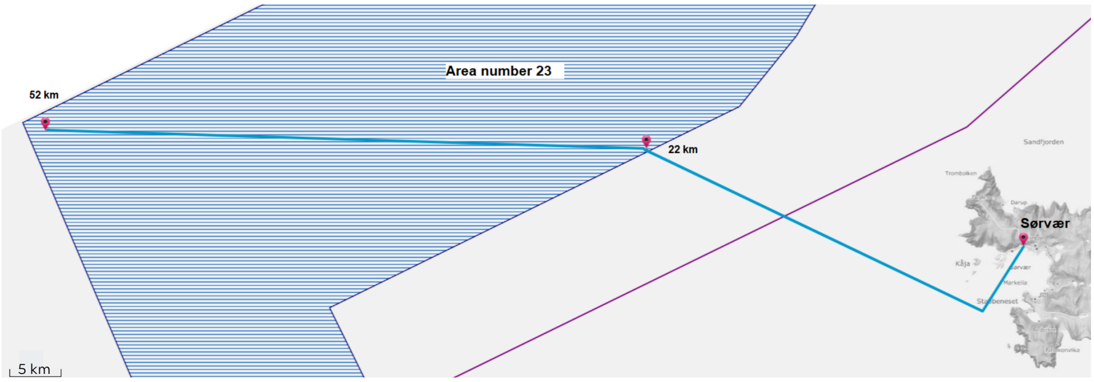


Figure 7.6: *There is sufficient capacity in the existing grid at Sørvær, located on Sørøya. The blue line represents the length from the connection point to the area, which ranges from 22 to 52 km. The length does not include the depth of the sea or possible obstacles on the sea bed.[116]*

Gjessøya in Rødøy municipal, approximately 8 km from Blikvær, has sufficient capacity in the existing 11 kV power grid to cover the power demand of Spidercage. Figure 7.7 illustrates the distance from Gjessøya to Blikvær, which further calculations were based on. At Blikvær, a new compact substation has to be established with further subsea connections to Spidercage. The subsea cable connection from Blikvær to the facility was not accounted for in further calculations, as it was assumed that this would constitute a small and insignificant part of the total investment.[166]

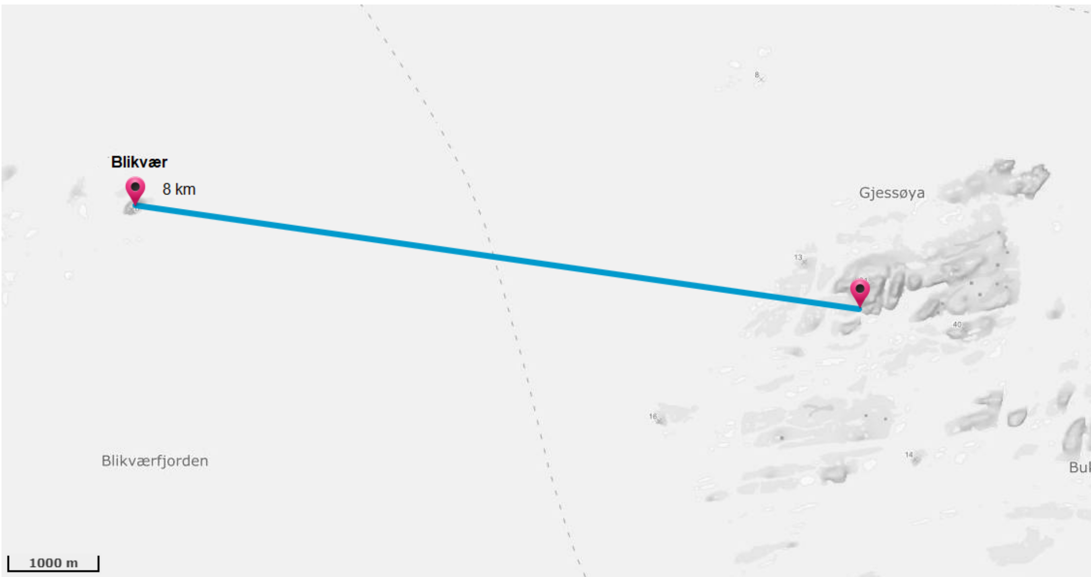


Figure 7.7: *The blue line represents the distance from Blikvær to Gjessøya. The distance is approximately 8 km in overhead line. The distance does not include the depth of the sea, variations on the seabed or crossing of islands.[116]*

Research was done in order to find a suitable cable in pursuant with the requirements for installation and power demand, according to chapter 4.4. It was chosen to only focus on one type of cable, for all three cases, as there are few high voltage subsea cables on the market. The cost of the cable was investigated by contacting Nexans and other firms with expertise within shore power technology.

The information gathered from the mapping was used to perform a cost analysis based on the cable length, the suitable connection point and development of necessary infrastructure. It was assumed that each facility has to invest in an offshore substation and a subsea cable with a rated voltage of 22 kV. Calculations were based on the cost of different equipment, as presented in Table 4.1. A CAPEX of 2 MNOK was used for the onshore substation, and a CAPEX of 0.8 MNOK was used for the offshore substation. The total CAPEX of the cable was calculated by multiplying the length of the cable with the cost. A CAPEX equal to 750 NOK/m was utilized. This was added to the cost of laying of the cable per meter, and the overhead cost of the subsea cable.

In addition, tables with additional equipment and installation cost, as presented in Appendix A, was utilized to calculate the total CAPEX for implementation of shore power. It was assumed that the cable and additional equipment are dimensioned correctly for each fish farm, and that they can operate properly.

To calculate the annual OPEX, the costs given in Table 4.2 was used. The OPEX for the cable was found by taking the total length of the subsea cable into account. An OPEX of 900 NOK per substation was assumed, which includes cost of work and transportation of personnel. The cost of electricity for each site over a year was based on the power demand. The network tariff was divided into summer and winter months, and based on monthly peak values from the power demand. Summer was set from April to October, and winter was set for the rest of the year.

The electricity cost and network tariff were summed with the overhead cost to find the total OPEX. It was assumed that a control of the cathodic protective gear in the cable happens in the first year of operation, which includes costs of personnel. There were no malfunctions assumed during operation, and hence the diesel generators will not cover any of the power demand on the facilities.

Another option explored was connecting several fish farms to the same onshore power supply, and see how this would affect the total costs. Figure 7.8 illustrates the concept of four facilities with the same power demand. It was assumed that all the facilities were connected to the same offshore substation. The subsea cable from the substation to shore will have the same length and connection point as for the solutions for shore power with one facility.

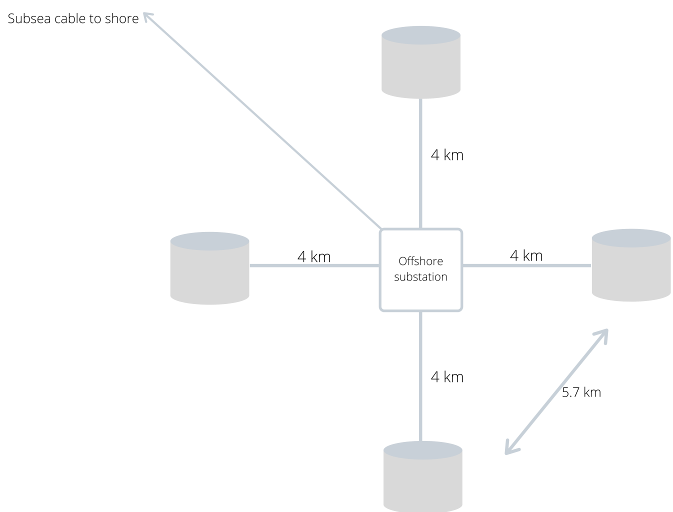


Figure 7.8: *A solution of four fish farms in a circle around the offshore substation. The substation is connected by a subsea cable to the grid at shore, and distributes the power to the four facilities.*

Each facility has a distance of 5.7 km between each other, and is connected to the substation, 4 km away, with a subsea cable. An additional length of 1 km was added to the cable to compensate for sea depth. The additional length was less than for the subsea cable to shore, due to a shorter distance between the facilities and the substation. For case 1 and 2, the substation was assumed to be placed at the bottom of the sea. For case 3, the substation is placed on Blikvær.

The CAPEX and OPEX was calculated for each facility. The total cost for the subsea cable from the substation to shore, and the substation, was assumed to be split equally between the facilities. The CAPEX for the cable from the substation to each site was added to the total CAPEX. It was assumed that each facility consumes the same amount of energy, and was based on the power demand for each case. The network tariff, overhead network tariff and electricity costs were calculated in the same manner as for shore power to one facility.

7.5 Shore power hybrid solution

In areas where the grid is not sufficiently developed or does not have the demanded capacity, a solution of shore power in combination with other energy resources can be utilized. The maximum capacity in the grid was assumed to be 100 kW. Power demand over 100 kW is to be covered by other energy resources.

Subsea cables of voltage levels lower than 22 kV were assumed adequate. This was based on calculations of the voltage loss for different cables, by equation 4.1. The transferred power was set to 100 kW. The voltage loss was calculated for both 1 kV and 12 kV Cu-cables, with a cross sectional area equal to 25 mm^2. The reactance and resistance values are given in Appendix C, in pursuance with the voltage levels, conductor material and cross sectional area. The power factor was set to 0.8. Further calculations were based on a 12 kV cable, as it resulted in a voltage loss of 0.75 %.

For Ocean Farm 1, a shore power connection from Risøya to the facility was assumed. The OAOF was not considered for the hybrid shore power solution. The reason for this was the lack of other alternative connection points in the areas, hence the length and voltage level of the subsea cable could not be changed. A lower voltage level cable was therefore not suitable. In addition, Spidercage was not considered for this solution. It was assumed that the batteries would never charge due to the power demand not going below 100 kW.

A cost analysis was performed based on the same criteria as for shore power alone. It was assumed that a substation onshore, and additional shore power equipment and installation costs were required. The cost for the offshore substation varies with the chosen additional energy system. In addition, it was assumed a cable CAPEX equal to 350 NOK/m, because of lower voltage levels.

7.6 Fuel cell

The thesis only addresses a fuel cell solution for Ocean Farm 1, as there is currently planned hydrogen production in Trøndelag close to this farm. In order to use a fuel cell on the fish farm, a hydrogen storage tank must be available on board at all times. The size of the hydrogen storage has to correspond with the vessel frequency at the farm. As the vessels to Ocean Farm 1 only arrive once a week, the maximum stored hydrogen at a given fuel cell capacity was to be calculated. The net hydrogen demand per week was determined based on values from Table 5.8.

A buffer was added to the maximum calculated required hydrogen storage per week, to choose a suitable tank. A 9 m container with 317 bar and 653 kg was used. CAPEX for such a solution depends on the size and number of containers, and is displayed in Table 5.8. OPEX will account for around 3 % of CAPEX. In addition, the hydrogen fuel cost was calculated by multiplying the hydrogen price with the input of hydrogen consumption of Ocean Farm 1 and the inverse of the energy content. Hydrogen consumption at the farm thorough the year, was calculated from the Matlab script. This was proceeded in the same manner as for the generator output. Costs for manning, transportation of hydrogen tanks and loading of hydrogen tanks to vessels were not included in the calculations.

When choosing a fuel cell capacity, the average consumption of Ocean Farm 1 was first calculated to 81 kW. A constant average capacity will not be suited for this case, as the power demand at Ocean Farm 1 has a much higher demand in the winter months compared to the summer months. In order to minimise the generator usage, a fuel cell with a higher capacity was chosen. Fuel cells of different capacities were inserted into the script, and the size of the hydrogen containers and cost were taken into account when deciding upon a fuel cell capacity. A 125 kW was found to be suited for this specific farm. The CAPEX and OPEX for a 125 kW fuel cell was calculated based on the values from Table 5.2.

7.7 Solar power

Solar irradiation affects the potential power extracted from the solar cells, as equation 5.2 indicates. PVsyst was utilized to extract the average solar irradiation in an hourly resolution over a year. The extracted data was based on horizontal global irradiation measurements from Metonorm 7.2. The location for each case is offshore, and to get the most reliable solar irradiation data, an island or land near the location was chosen. The solar measurements for the OAOF extracted from Rebbenesbotn near area 21, were used in calculations for all the areas. The coordinates were inserted in the database when opening PVsyst. Furthermore, a simulation of a chosen solar cell at each site was preformed trough the project design function in PVsyst. The solar cell model was chosen randomly, since the solar irradiation were the only data of interest.

Produced solar power at Ocean Farm 1 was calculated based on exploitable rooftop area at the feed barge. Due to the tower and several antennas occupying a large part of the roof, the solar cell area was sat to 80 m^2. For OAOF, an area of 113 m^2 was assumed to be installed on top of the 16 columns. Spidercage has limited spare area for installation of solar cells, because most of the area is occupied by walkways and railings. Therefore, an area of 60 m^2 was assumed to be installed at the platform. Installing solar cells on the nearest islands or land, will not be efficient or profitable as the distance is more than 1 km from each of the fish farms. Floating solar power was not considered possible for any of the facilities, as they all are located in too exposed areas.

The solar cells used in simulations and calculations were based on values from Table 5.3 and 5.9. The power output for every hour over a whole year at each site, was calculated with equation 5.2 in Matlab. The CAPEX considering installation for each case was based on total installed capacity multiplied with the cost of 20 000 NOK/kW installed. Further, OPEX was multiplied with the installed capacity to find the total annual OPEX for an installation at each facility.

The potential area for installation of solar cells at the fish farm is small, and hence gives a low power output. In order for the solar cells to cover more or all of the power demand, an analysis of different areas was conducted. The increased area chosen for each case was dependent on their power demand. The power output graphs for the different areas and the power demand curve were based on a daily average over a whole year.

7.8 Wind power

The calculations of produced wind power were distinguished between onshore, bottom fixed and floating turbines, depending on what was fitting for each site. The onshore wind turbine model used in all the calculations was Vestas V136-3.45, and the bottom fixed model was Vestas V112 Offshore. The floating wind turbine was the Siemens turbine from Hywind Demo. The power curve for each turbine is shown in Figure 7.9.

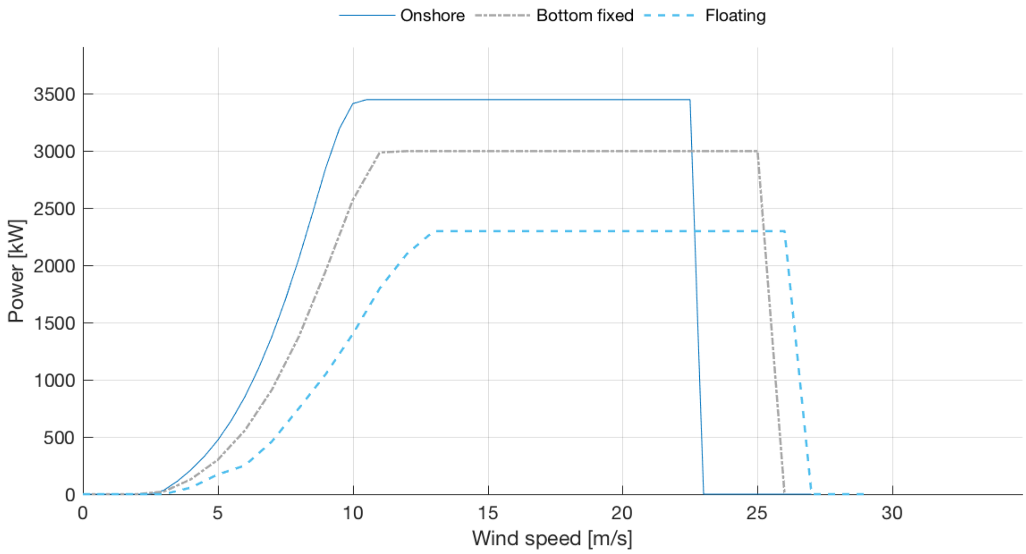


Figure 7.9: *The power curve of the onshore turbine V136-3.45, the bottom fixed turbine V112 Offshore and the floating turbine, Hywind Demo, from Siemens.[117, 167, 168]*

The produced power from each wind turbine was calculated in the same manner for all of the cases. This was done by interpolating the average wind speed measured each hour of 2019, into the power curve of the respective wind turbine in Matlab. This was done in order to find the right power output at different wind speeds. The turbines have different rated wind speed values, which are often between 11 and 25 m/s. All the wind speed measurements were taken onshore for each case.

The location of Ocean Farm 1 is not suitable for bottom fixed turbines, as the sea depth is greater than 60 m. Therefore, only onshore and floating turbines were taken into consideration in the simulations. An onshore wind turbine can be placed at Risøya, 4 km away, while a floating turbine can be placed closer to the facility at sea. This also applies for Spidercage, where an onshore wind turbine can be placed at Nilsøya, 2 km away.

The three possible locations for the OAOF are all in deep waters and thus not suitable for bottom fixed turbines. There is, however, a potential area for bottom fixed turbines 35 km away from area number 23. As the distance to the suited area is greater than the distance to shore, bottom fixed turbines will not be cost efficient and hence not included in the calculations.

There are no islands around the three areas, and the nearest land is at shore. Onshore wind turbines will therefore not be included, as the cost of the subsea cable will be the same as for onshore power supply. As a result, only floating wind turbines are fitting for all the three areas, and can be placed at sea close to the facility. Wind measurements were taken close to area 21, but used in calculations for all the areas.

To calculate the investment cost of the onshore wind turbine, the CAPEX from Table 5.4 was multiplied with the capacity of the turbine. The OPEX from the same table, given in NOK/kWh, was multiplied with the produced power of the turbine over a year. The produced power was calculated in the Matlab script.

The cost must also include a subsea cable from the island where the turbine is placed to the farm. Cost of the cable and laying are given in Table 4.1, and was multiplied with the length of the cable. For each case, the length varies, and 1 km was added due to depth and variations on the seabed. The additional length of the cable was less than for shore power, due to a shorter distance from the turbine to the farm. The overhead cost of the cable, given in the same table, was added to the cost. The cost for maintenance of the cable was included in the OPEX, as given in Table 4.2.

The CAPEX given in Table 5.5 was multiplied with the capacity of the floating wind turbine, to find the investment cost. As the OPEX for floating turbines are relatively unknown, a ratio between the LCOE for onshore and floating turbines was calculated to 2.38. This ratio was multiplied with the OPEX for onshore turbines, given in Table 5.4, to get an estimate of the OPEX per kWh for floating turbines. The OPEX was then calculated by multiplying this value with produced power over a year. The cost also had to include a subsea cable from the turbine to the fish farm, laying and overhead as for the onshore turbine, in addition to maintenance on the cable. The length of the cable was set to be 1 km in all the cases, mainly due to depth and variations on the seabed.

7.9 Hybrid solutions

In order to supply the fish farm in the most eco-friendly manner, different hybrid solutions were considered. Each solution will have its own management system, which was constructed in Matlab. All hybrid solutions are represented by flowcharts and schematic diagrams. Each of the schematic diagrams include a diesel generator, an offshore transformer and a collective bus bar. The total power demand of the facilities is represented by P_{load}. The Matlab script for all the hybrid solutions are illustrated as the management system in the schematic diagrams. A few differences such as an onshore transformer, DC/AC inverters and bidirectional inverters occur. The costs of the bidirectional and DC/AC inverter are given in Table 5.9.

The battery cabinets were set to be fully charged at the beginning for each of the solutions. The efficiency for both the battery cabinets and generators were accounted for in the simulations. Possible loss in the cable, for shore power hybrid, and efficiency for the transformer and inverters were not taken into consideration.

The total cost of the hybrid solutions must include a transformer and inverter. A transformer of 315 kVA was needed at the site of the fish farm, and the cost is given in Table 4.1. The transformer is not dimensioned for any of the energy resources, but will be used as a basis for the cost analysis.

7.9.1 Diesel generator in combination with batteries

In the battery and diesel generator hybrid solution, Figure 5.2 was used to find the most optimal load the generator could operate on. In this scenario, the generator was set to run at an 80 % load at all times. This was the most optimized load regarding the diesel generator. The batteries were used as energy storage.

Whenever the batteries reached their SOCMIN, the generator would start running at optimal load for a whole hour. The generator would firstly cover the power demand at the farm, and further use the remaining power to charge the batteries in a while loop. If the batteries were to be charged more than their SOCMAX, the generator would not run on optimal load for an hour. The generator would in this case run at an optimal load for a fraction of an hour, in order to not overcharge the battery. This is shown in a flowchart in Figure 7.10.

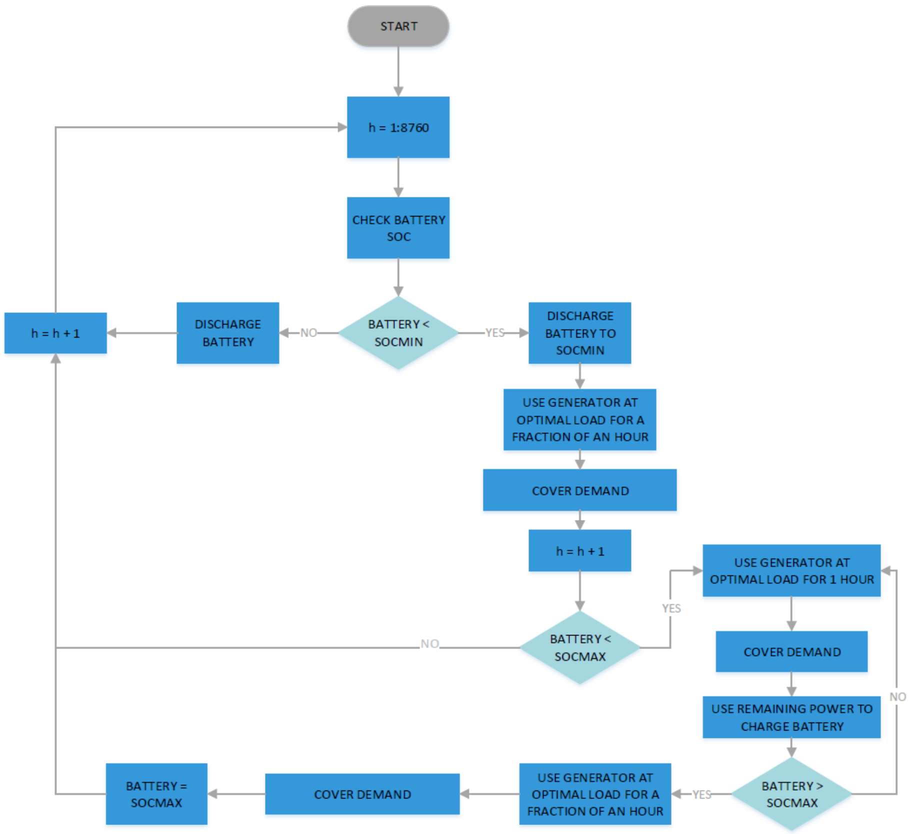


Figure 7.10: *Simplified flowchart for the battery and diesel generator hybrid solution.*

In order to get the generator to run on 80 % of its load, even when the power demand is low, the total time the generator runs at an 80 % load was calculated. This solution will therefore not remain constant over one hour with a low load, such as the other hybrid solution, but rather use the generator for a shorter period of time, at a higher and more optimal load. This will give a lower full load hour for the generator. A hybrid solution combining the battery with the diesel generator is shown in Figure 7.11. The solution also includes a bidirectional inverter between the battery and diesel generator, in addition to a transformer.

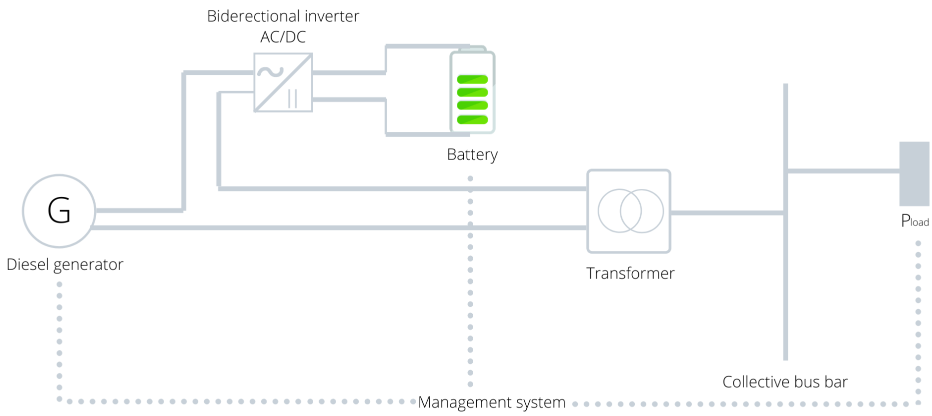


Figure 7.11: *Schematic diagram of the battery and diesel generator hybrid solution in combination with a bidirectional inverter and transformer.*

7.9.2 Shore power or hydrogen in combination with batteries

The hybrid solutions for either shore power or fuel cell, in combination with diesel generators and batteries, were simulated likewise in Matlab. A constant capacity was set as the maximum power input for both the fuel cell and the grid. The fuel cell or shore power will primarily cover the demand on the farms. If the demand is higher than the power input, a battery or diesel generator would kick in. If the power input is higher than the demand, the excess power would charge the battery. Both the fuel cell and power from the grid are continuous, and will hence only be used when needed. A simplified flowchart of the hybrid solutions is illustrated in Figure 7.12.

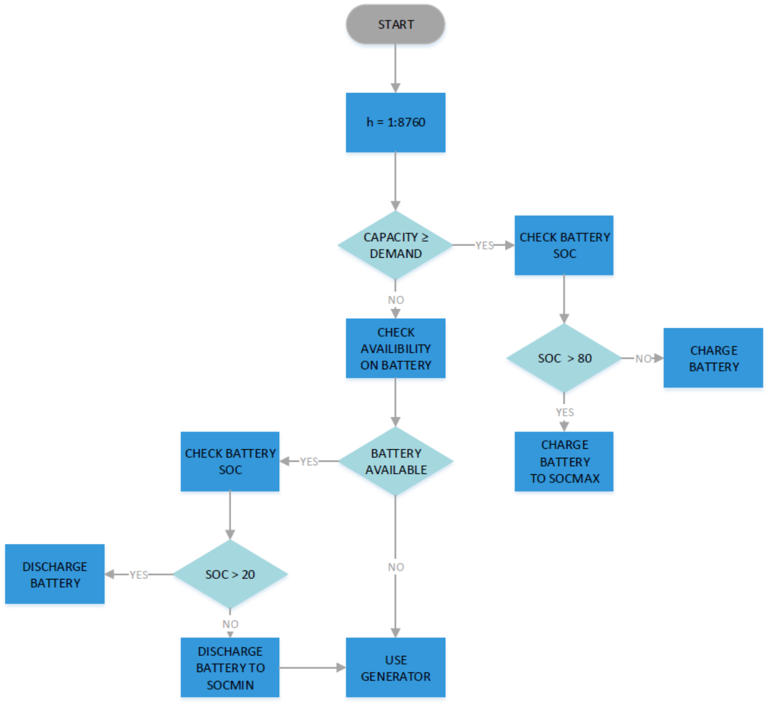


Figure 7.12: *Simplified flowchart for both fuel cell and shore power in combination with batteries and diesel generators.*

A hybrid solution combining a shore power connection and battery cabinets is illustrated in Figure 7.13. For a hybrid solution of this kind, a cable from the onshore grid, through a compact substation, is connected to both the battery for charging and to the load at the fish farm. A bidirectional inverter is connected in between the cable and the battery.

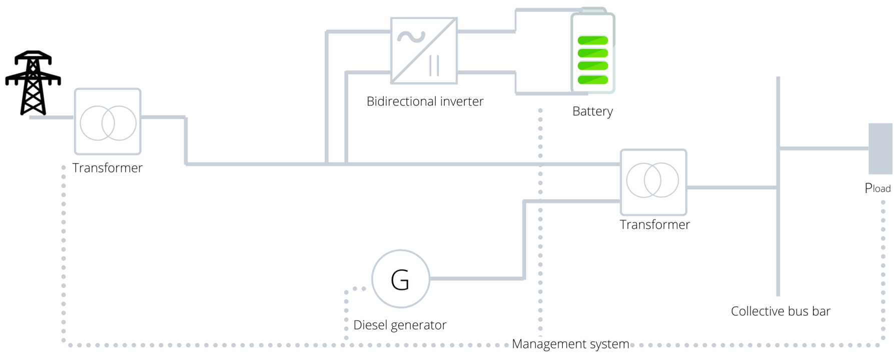


Figure 7.13: *Schematic diagram of shore power in combination with battery cabinets, diesel generators, bidirectional inverter and a transformer.*

It was assumed that the voltage level in both the cable and in the battery was higher than the system voltage on board the feed barge. The voltage level in the generator was also higher. Therefore, a transformer was needed to decrease the voltage to the applied voltage at the feed barge.

A hybrid solution for the fuel cell is shown in Figure 7.14. To combine the fuel cell and batteries to the rest of the system, a DC/AC inverter was needed. In the cost analysis a bidirectional inverter was rather used, as the DC/AC inverter in Table 5.9 only applies to a solar cell solution. A transformer was applied to connect the fuel cell, battery and diesel generator to the load.

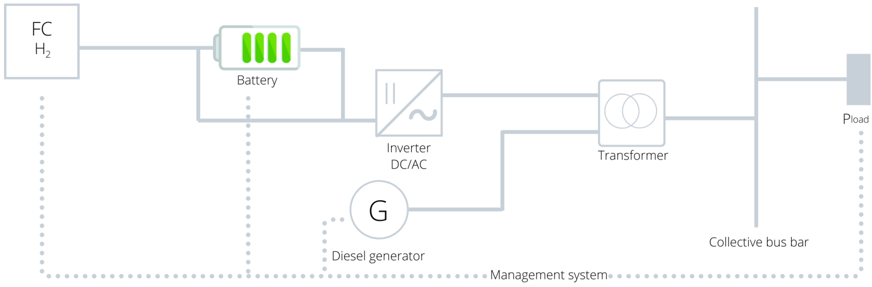


Figure 7.14: *Schematic diagram of fuel cell in combination with battery cabinets, diesel generators, DC/AC inverter and a transformer.*

7.9.3 Solar cells or wind turbines in combination with batteries

The method considering the hybrid solutions for solar and wind power in combination with battery cabinets and diesel generators were similar. Each site has a different power output, considering solar and wind power. The power output for a whole year at each site was inserted into the Matlab script in order to find the contribution from solar or wind power to the power demand at each farm.

When the energy resource delivered more power than needed to the farm, the batteries would be charged. Similarly, when it delivered less power than needed, the batteries would discharge to cover the power demand. When neither the energy resource nor batteries could deliver enough power to meet the demand, diesel generators were utilized to cover the remaining demand. This is illustrated in the flowchart shown in Figure 7.15. The amount of battery cabinets varied for each hybrid solution and case.

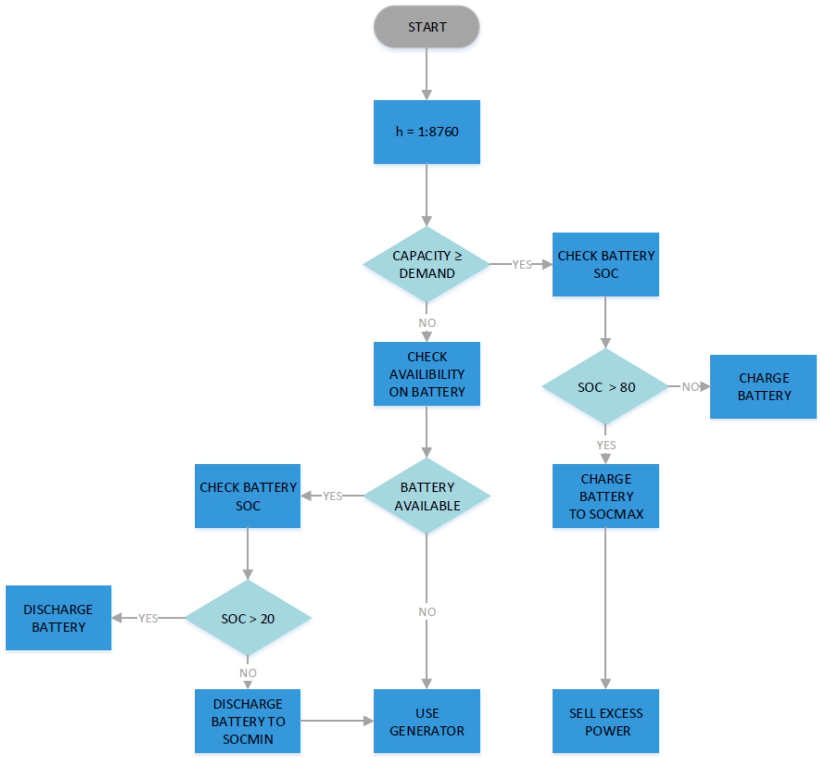


Figure 7.15: *Simplified flowchart for both solar and wind power in combination with batteries and diesel generators.*

Figure 7.16 shows solar cells in combination with batteries and diesel generators. The current produced in the solar cells can be used to charge the battery directly, as they both run on DC current. An inverter is needed after the battery, to convert the DC current into AC.

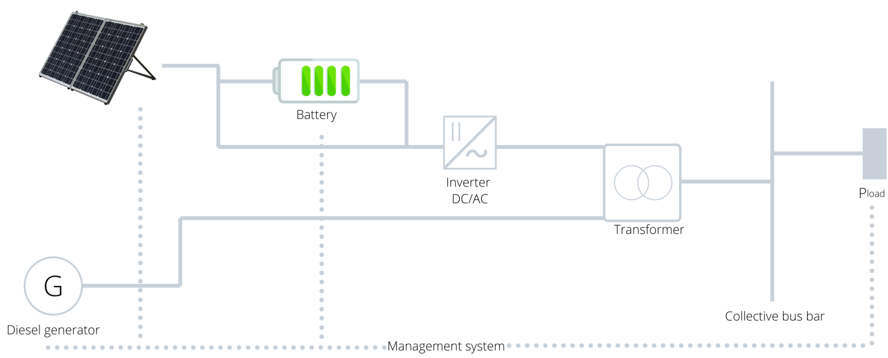


Figure 7.16: *Schematic diagram of solar power in combination with battery cabinets, diesel generators, DC/AC inverter and a transformer.*

Figure 7.17 illustrates wind turbines, both onshore and floating, in combination with battery cabinets and diesel generators. A transformer at the site of the turbine was not included, as it was assumed that the turbine and subsea cable would have the same voltage. Since the wind turbine will most likely have an alternator, a bidirectional inverter is needed to convert the AC current to DC before charging the batteries. The same inverter will convert the current back to AC before reaching the transformer.

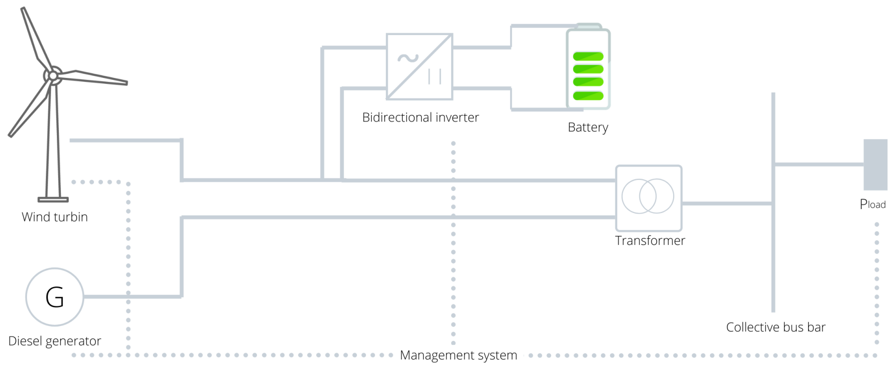


Figure 7.17: *Schematic diagram of wind power in combination with battery cabinets, diesel generators, bidirectional inverter and a transformer.*

7.10 LCOE calculations

The LCOE for each energy element of the solutions was calculated for every case. Equation 5.1 was utilized in the calculations, and the discount rate was set to 4 %. Additional equipment, such as inverters, transformers and hydrogen tanks, were not included in the calculations, as they do not produce energy. The total CAPEX of each technology was set to be paid before the first year. The annual OPEX, fuel costs and total energy production were inserted from the first year until the number of years reaches the life expectancy of each technology.

Both the diesel generator and fuel cell have life expectancy given in hours. As the calculations of LCOE require this in years, the life expectancy in hours were divided by the annual operation hours. The annual operation hours for the diesel generators variate for each solution, and are shown in Table 7.2, including the resulting life expectancy for each solution. This applies if the only factor affecting the life expectancy of the diesel generators are their operation hours at the facility. The lifetimes will be used further in the calculations of diesel generator LCOE for each hybrid solution. The fuel cell was assumed to have a life expectancy of 10 years.

Table 7.2: *The annual operation hours for the diesel generators used in all of the hybrid solutions, with corresponding life expectancy given in years.*

Energy solution	**Annual operation hours**		**Life expectancy**
	[h]	[%]	[year]
Diesel generator	4 000	100	13
Battery and diesel generator hybrid	2 240	56	22
Shore power hybrid	600	15	83
Fuel cell hybrid	600	15	83
Solar power hybrid	3 800	95	13
Wind turbines hybrid	600	15	83

The CAPEX and OPEX of one diesel generator are set to be constant for each case, regardless of how much the generators are used in the different solutions. These costs will only change regarding to the number of diesel generators needed at the facilities. The LCOE of the diesel generators in the different solutions will hence only be dependent on the fuel cost and produced energy by the generators.

As all the simulations are based on one year of operation, the values of OPEX, fuel cost and energy production were assumed to be constant for each year throughout the whole life expectancy. In the calculations regarding batteries, shore power, solar cells and wind turbines, the fuel costs were set to zero. The LCOE of diesel generators and battery cabinets were calculated separately for each energy solution, as the amount of cabinets, fuel consumption and produced energy variate. LCOE for the backup diesel generators used in the shore power solutions were not calculated, as it was assumed they would not produce any energy.

8 Energy solutions and costs

In this chapter, the results of the simulations and cost calculations will be presented for every energy solution for each case. An energy solution graph, cost plots and diesel consumption for each solution will be presented. The calculations for all the solutions are preformed over a whole year. However, the results presented in graphs will only illustrate an extraction of a time period, in order to show the results more clearly. A 100 % diesel generator solution was examined in each case. This solution was included as a baseline for costs and emissions, if all the electricity came from a diesel generator. The most cost efficient solution will be based on the LCOE plot, which includes both CAPEX and OPEX for each solution. The highest renewable fraction for the lowest cost can be one way to define the most suitable solution.

8.1 Case 1

In the following section, the results for all energy and hybrid solutions regarding case 1, Ocean Farm 1, will be presented.

8.1.1 Battery and diesel generator hybrid solution

Figure 8.1 shows the solution of batteries in combination with diesel generators, for a period between hour 7 300 to 7 500. The results are based on a solution of nine battery cabinets. The batteries cover 57.4 % of the power demand, and the diesel generator covers the rest of the demand at the farm. The percentage used to cover the power demand by the batteries on the farm, equals the diesel generator percentage used to charge the batteries. The diesel generators only run at 316 kWh at any given time, but are presented at lower power values in the plot, in order to show how the generators cover parts of the power demand. In reality, as the diesel generators only run at an optimal load, the peaks are higher, but occur for smaller periods of time. The full load hours for the generator for this solution is calculated to be 2 253 h.

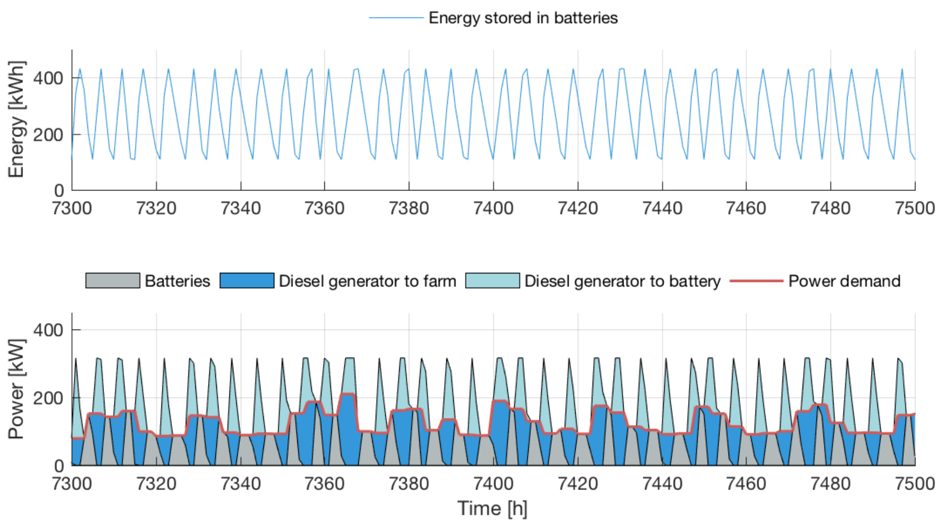


Figure 8.1: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the diesel generator and batteries complement the power demand. Diesel generator to farm illustrates the power from the diesel generator directly used to cover the power demand. Diesel generator to battery illustrates the power from the diesel generator used to directly charge the battery.*

8.1.2 Shore power solution

Table 8.1 shows the CAPEX and annual OPEX for onshore power supply for Ocean Farm 1. The cable investment cost constitutes 80.0 % of the total CAPEX, which is within the historical figures from Enova. The costs are based on a 22 kV subsea cable with a total length of 25 km, and include development of necessary infrastructure and an additional unspecified cost. The cost for the compact substation includes both the substation onshore and offshore.

Table 8.1: *CAPEX and annually OPEX for onshore power supply for Ocean Farm 1.*

Post	**CAPEX** [NOK]	**OPEX** [NOK]
Subsea cable	26 450 000	50 000
Compact substation	2 800 000	1 800
Installation and additional equipment	814 500	-
Unspecified cost	3 006 540	-
Electricity and network tariff	-	462 150
Total	**33 070 950**	**513 950**

If four facilities with the same power demand are placed around a shared offshore substation, the total CAPEX for each facility results in 10.3 MNOK and the total OPEX for each facility results in 0.490 MNOK annually. The results are based on a subsea cable length of 25 km and subsea cables of 5 km to each of the four facilities.

8.1.3 Shore power hybrid solution

For a hybrid solution combining shore power with batteries, the batteries are used in limited periods throughout the year. Figure 8.2 illustrates the power stored in the batteries, and usage of the different energy resources for the hybrid solution from hour 6 000 to 6 200. The hybrid solution is based on four battery cabinets, a maximum grid capacity at 100 kW and a subsea cable of 12 kV. The grid will account for 89.4 % of the consumption. The battery covers 2.74 % and the generator will account for the rest.

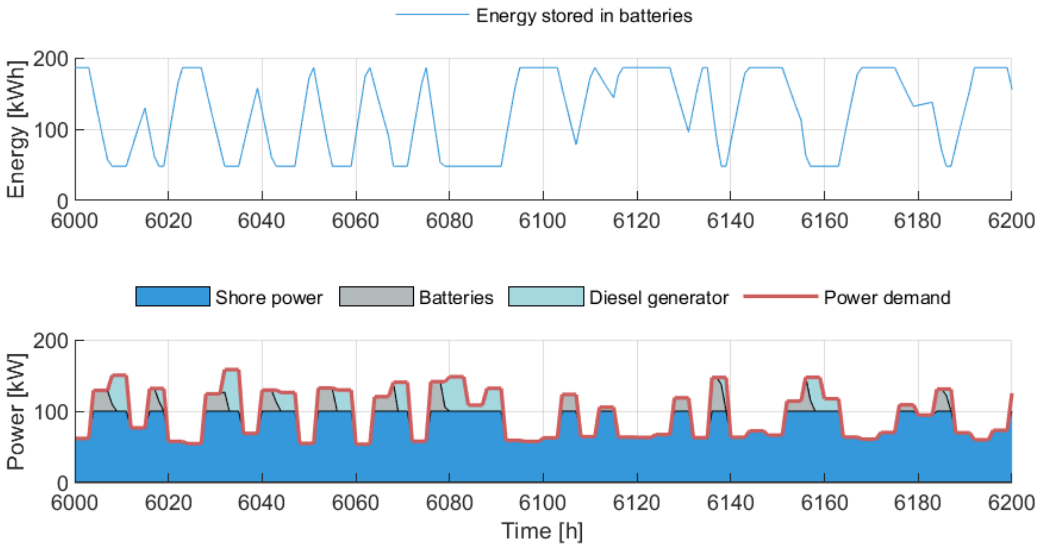


Figure 8.2: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the shore power, batteries and diesel generators complement the power demand. The maximum grid capacity is 100 kW.*

8.1.4 Fuel cell hybrid solution

For the fuel cell hybrid solution, it has to be invested in four hydrogen containers, in order to get the vessel logistics to add up. The solution is to replace two empty containers with full ones, every time a supply ship arrives once a week. The fuel cell will account for 94.7 % of the consumption. The two battery cabinets will cover 1.41 % and the diesel generators will account for the rest. This is illustrated in Figure 8.3 for the time period between hour 7 000 and 7 400.

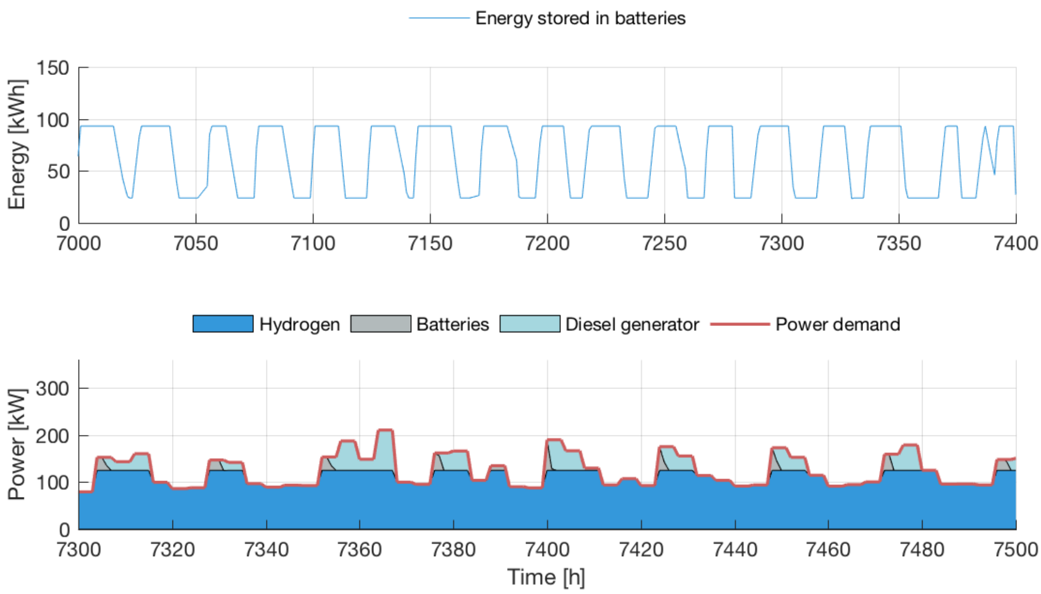


Figure 8.3: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the fuel cell, batteries and diesel generators complement the power demand.*

8.1.5 Solar cells hybrid solution

Results considering the hybrid solution of solar cells, batteries and diesel generators are illustrated in Figure 8.4. The time period is set from hour 3 500 to 4 100, which corresponds to a period with high solar irradiation. The installed capacity is 15.5 kW, and solar power will thus only cover a small part of the power demand. As a consequence, they will never charge the battery. Therefore, the cost considering batteries is neglected for this hybrid solution. The diesel generators cover 98.0 % of the power demand, and solar power only accounts for 2.00 %.

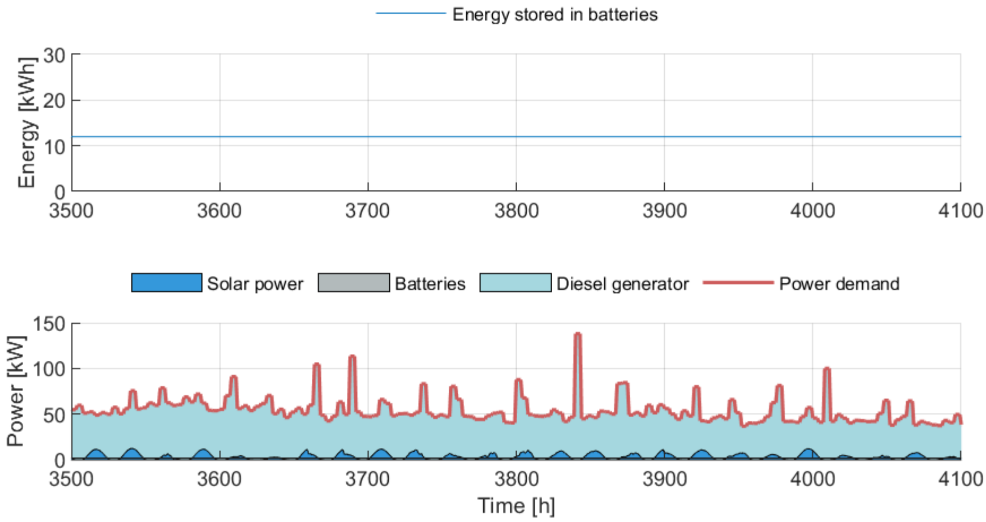


Figure 8.4: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the solar cells, batteries and diesel generators complement the power demand.*

The potential power output when increasing the area for the solar cells, in comparison with the power demand, is shown in Figure 8.5. The area installed at the farm, 80 m^2, is compared to two larger areas of 320 m^2 and 800 m^2. 800 m^2 will cover all of the power demand during a few summer days, and only parts of the demand for the rest of the year. The power output covers only parts of the power demand for 80 m^2 and 320 m^2.

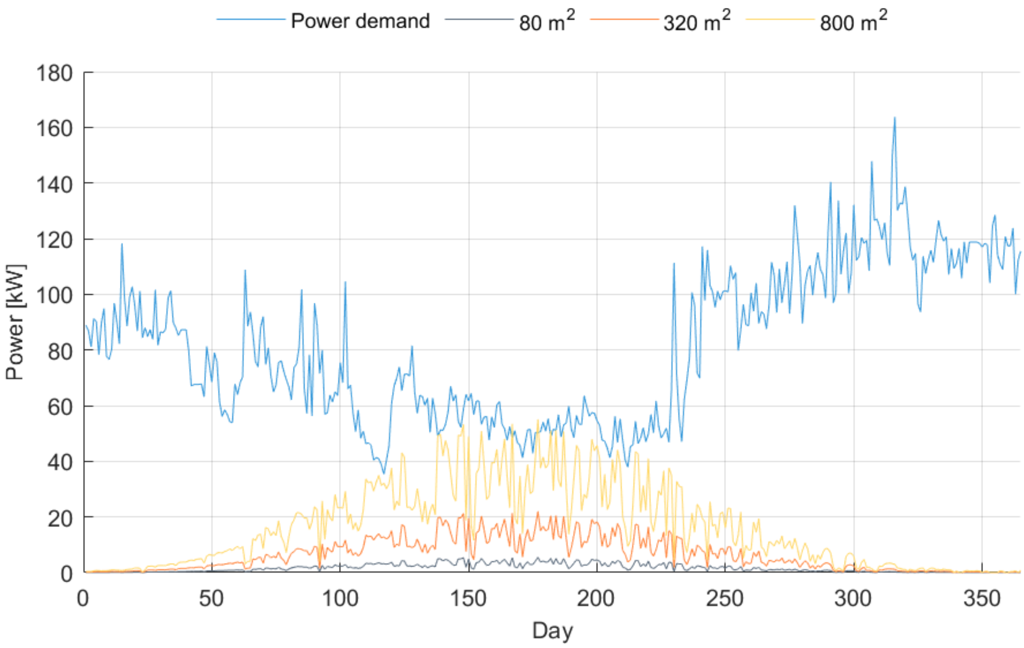


Figure 8.5: *The potential power output when increasing the area for the solar cells, in comparison with the power demand. The area installed at the farm, 80 m^2, is compared to two larger areas of 320 m^2 and 800 m^2.*

8.1.6 Wind turbine hybrid solutions

One of the hybrid solutions simulated is an onshore wind turbine of 3.45 MW in combination with battery cabinets and diesel generators. A section of the power demand is shown in Figure 8.6 from hour 7 000 to 7 400, and shows which energy resource covers the demand. The onshore turbine will cover 79.9 % of the power demand, and the nine battery cabinets will account for 8.08 %. The diesel generators will cover 12.0 % of the demand. The surplus wind power during the year is 9.91 GWh, equal to 93.2 % of the total wind power production. A comparison of a 600 kW turbine and the 3.45 MW turbine is given in Appendix D, and shows that surplus wind power would decrease with the usage of a smaller turbine.

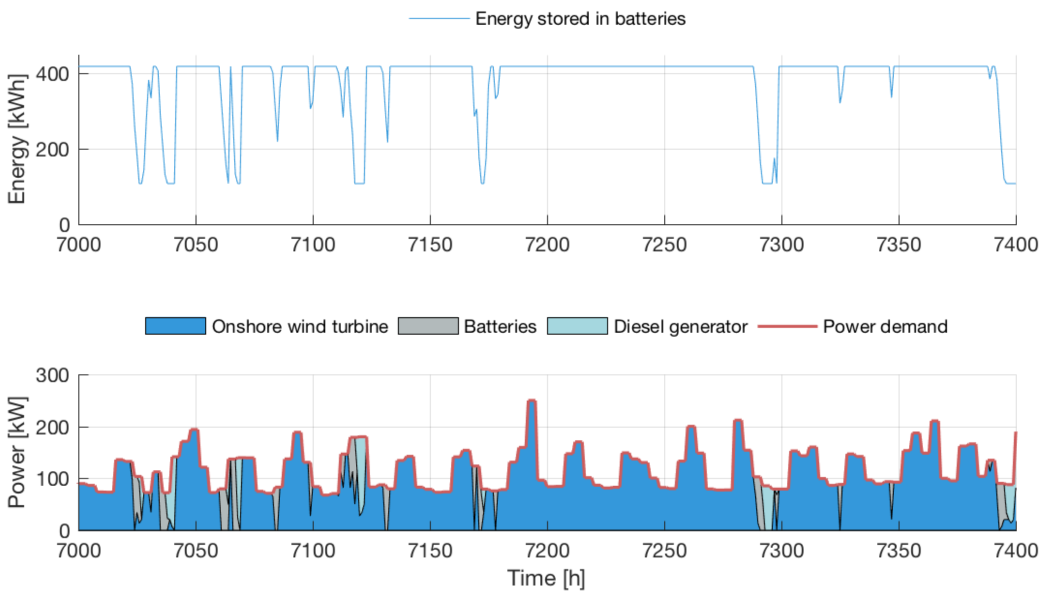


Figure 8.6: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the onshore wind turbine, batteries and diesel generators complement the power demand.*

Another hybrid solution is a floating turbine of 2.3 MW in combination with battery cabinets and diesel generators. A section of the power demand is shown in Figure 8.7 from hour 7 000 and 7 400, and shows which energy resource covers the demand. The floating wind turbine will cover 71.7 % of the power demand, and the nine battery cabinets will account for 8.21 %. The diesel generators will cover 20.1 % of the demand. The surplus wind power is 4.33 GWh, equal to 87.0 % of the total wind power production.

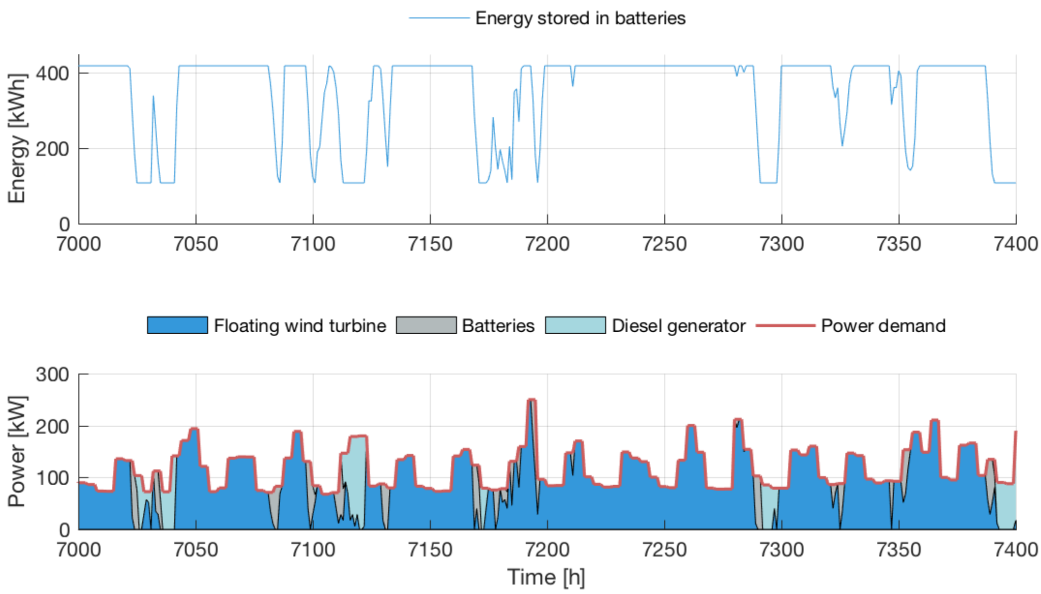


Figure 8.7: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the floating wind turbine, batteries and diesel generators complement the power demand.*

8.1.7 Costs and diesel generator emissions

The total CAPEX of each energy solution is illustrated in Figure 8.8, in addition to a scenario where diesel generators are the only energy resource utilized. Each bar represents an energy solution, and their total investment cost. The bar is divided into several sections, accounting for the cost of each element of the solution. The floating turbine hybrid solution has the highest CAPEX, and the diesel generator solution has the lowest. The costs of the DC/AC inverter and transformer are low compared to other technologies, and are hence not visible in the figure.

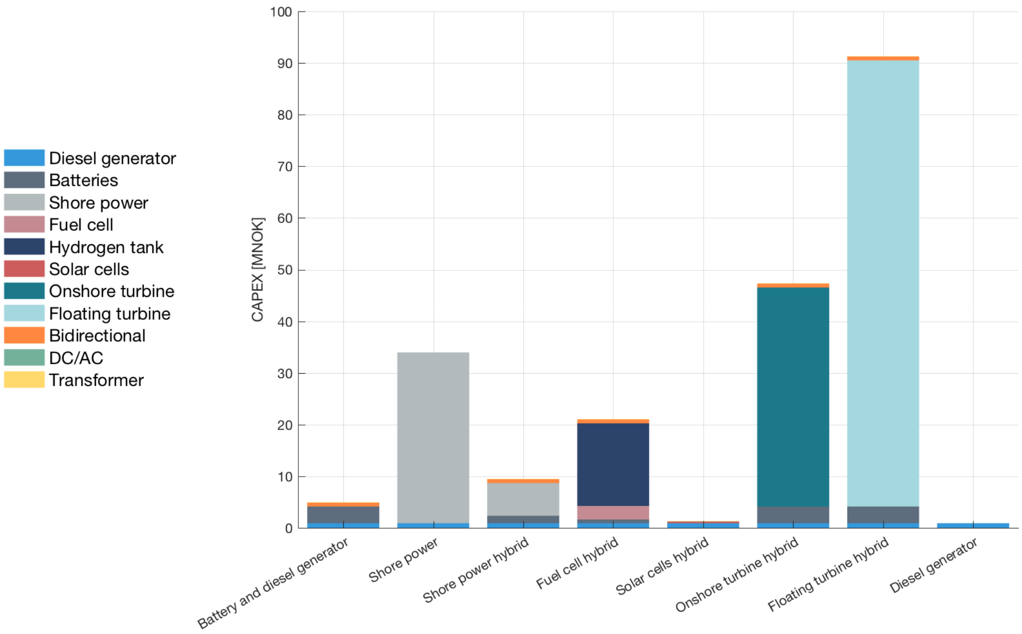


Figure 8.8: *The total CAPEX of each energy solution for Ocean Farm 1 given in MNOK.*

Figure 8.9 illustrates the total OPEX of each energy solution, including fuel costs of diesel and hydrogen. The OPEX is calculated based on a year of operation. The fuel cell hybrid solution has the highest OPEX, and shore power has the lowest.

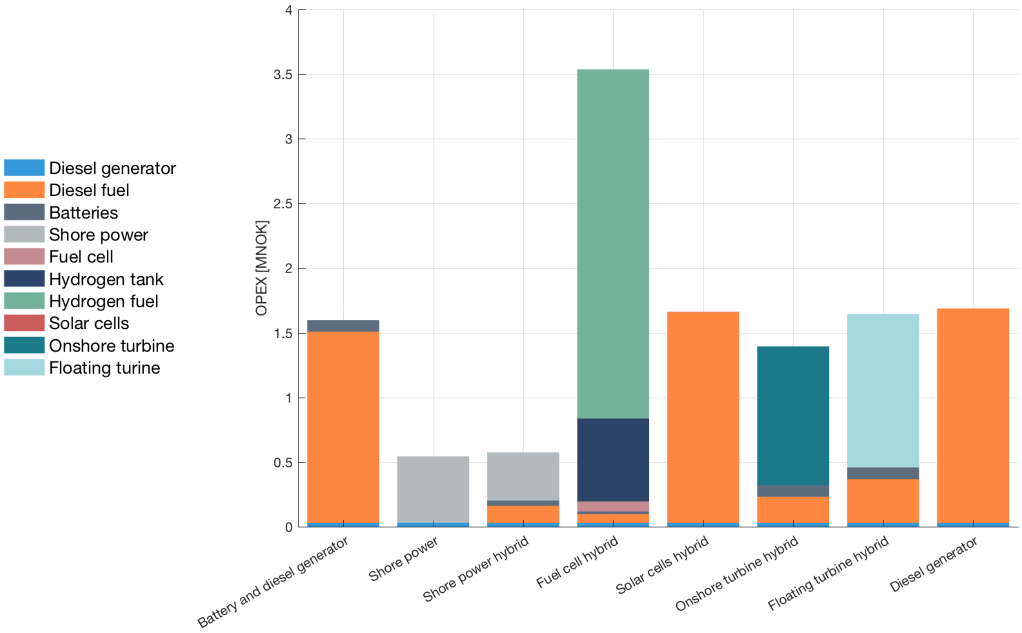


Figure 8.9: *The annual OPEX of each energy solution for Ocean Farm 1 given in MNOK, including the fuel costs of diesel and hydrogen.*

The total LCOE of each energy solution is illustrated in Figure 8.10. The LCOE is calculated based on total costs and energy production over the life expectancy of each technology, and does not include additional equipment. The fuel cell hybrid solution has the highest LCOE, and the diesel generator solution has the lowest. A more detailed description of the CAPEX, OPEX and LCOE results are given in Appendix E.1.

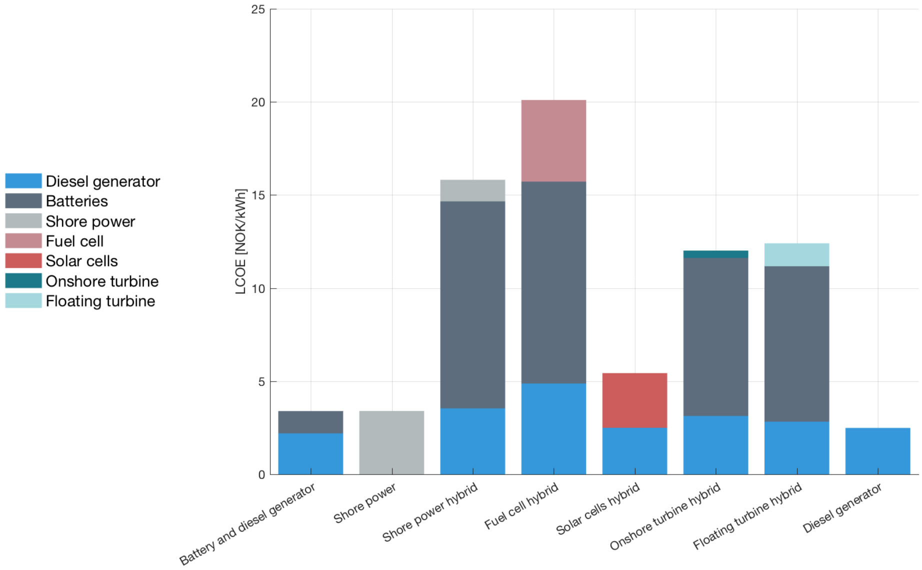


Figure 8.10: *The total LCOE of each energy solution for Ocean Farm 1 given in NOK/kWh.*

All the solutions will have three diesel generators installed as a backup system. The usage of diesel generators for each energy solution is presented in Table 8.2. In addition, the table lists the CO_2 emissions and fuel costs for each energy solution. The table also includes a 100 % diesel generator solution. Usage of diesel generators during maintenance or ambient conditions is not accounted for in this thesis. Therefore, the emissions and fuel costs are considered 0 for the diesel generator when utilizing shore power alone.

Table 8.2: *The usage of diesel generators, in addition to CO_2 emissions and fuel cost, for different energy solutions.*

Energy solution	Diesel generator [%]	CO_2 [tonnes/year]	Fuel cost [MNOK/year]
Diesel generator	100	580	1.65
Battery and diesel generator	100	517	1.47
Shore power	0	0	0
Shore power hybrid	7.90	46.3	0.132
Fuel cell hybrid	3.87	23.6	0.070
Solar cells hybrid	98.0	570	1.62
Onshore turbine hybrid	12.0	70.5	0.201
Floating turbine hybrid	20.1	118	0.337

8.2 Case 2

In the following section, the results for all energy and hybrid solutions regarding case 2 will be presented. The presented results for the OAOF are based on calculations done for area 21, as similar conditions are assumed for the three areas. Shore power is the only energy solution which is calculated for both area 21 and 23. This is however not a solution for area 7.

8.2.1 Battery and diesel generator hybrid solution

Figure 8.11 shows the solution of batteries in combination with diesel generators, for a period between hour 7 300 to 7 500. The results are based on a solution of nine battery cabinets. The batteries cover 62.8 % of the power demand, and the diesel generator covers the rest of the demand at the farm. The percentage used to cover the power demand by the batteries on the farm, equals the diesel generator percentage used to charge the batteries. The diesel generators only run at 316 kWh at any given time, but are presented at lower power values in the plot, in order to show how the generators cover parts of the power demand. In reality, as the diesel generators only run at an optimal load, the peaks are higher, but occur for smaller periods of time. The full load hours for the generator for this solution is calculated to be 2 380 h.

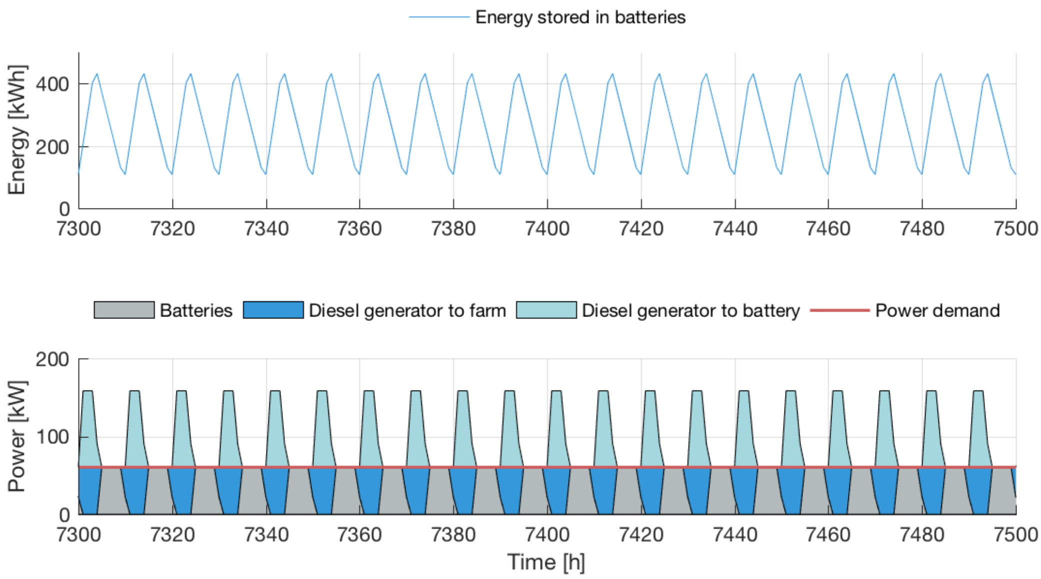


Figure 8.11: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the diesel generator and batteries complement the power demand. Diesel generator to farm illustrates the power from the diesel generator directly used to cover the power demand. Diesel generator to battery illustrates the power from the diesel generator used to directly charge the battery.*

8.2.2 Shore power solution

Table 8.3 shows the CAPEX and OPEX for onshore power supply for the OAOF for both area 21 and 23. For area 21, the cable investment cost constitutes 82.0 % of the total CAPEX. For area 23 it constitutes 80.0 %. Both are within the historical figures from Enova. The cable costs are based on a 22 kV subsea cable length of 17 km for area 21, and a total length of 24 km for area 23. The cost for the compact substation includes both the substation onshore and offshore for area 23. For area 21 the substation is the offshore substation, as the connection point onshore will be a circuit breaker.

Table 8.3: *CAPEX and annual OPEX for onshore power supply for area 21 and 23.*

Post	Area 21		Area 23	
	CAPEX [NOK]	OPEX [NOK]	CAPEX [NOK]	OPEX [NOK]
Subsea cable	18 050 000	34 000	25 400 000	48 000
Compact substation	800 000	900	2 800 000	1 800
Circuit-breaker	300 000	-	-	-
Installation and additional equipment	814 500	-	814 500	-
Unspecified cost	1 996 450	-	2 901 450	-
Electricity and network tariff	-	217 501	-	217 501
Total	**21 960 950**	**252 401**	**31 915 950**	**267 301**

If four facilities with the same power demand are placed around a shared offshore substation in area 21, the total CAPEX for each facility results in 8.63 MNOK. The total OPEX for each facility will result in 0.240 MNOK annually. The results are based on a subsea cable length of 17 km from shore to the substation, and a subsea cable of 5 km to each of the four facilities for area 21. For area 23, the total CAPEX for each facility results in 10.1 MNOK, and the total OPEX results in 0.240 MNOK annually. The results, for area 23, are based on a subsea cable length of 24 km from shore to the substation, and subsea cables of 5 km to each of the four facilities.

8.2.3 Solar cells hybrid solution

Results considering the hybrid solution of solar cells, batteries and diesel generators are illustrated in Figure 8.12. The time period is set from hour 3 500 to 3 900, which corresponds to a period with high solar irradiation. The installed capacity is 21.9 kW. The solar power only covers a small part of the power demand. In this case, solar cells charge the battery only once when the fish farm is in fallowing. The total charged value is 0.664 kW, which is very low. Therefore, the cost considering batteries is neglected for this hybrid solution. The diesel generators cover 95.7 % of the power demand, and solar power only account for 4.30 %.

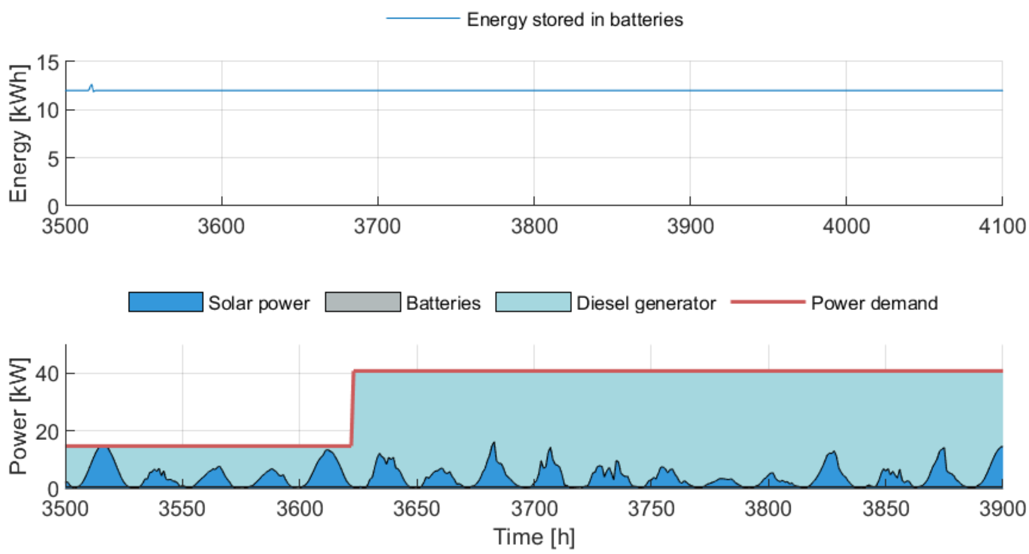


Figure 8.12: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the solar cells, batteries and diesel generators complement the power demand.*

The potential power output when increasing the area for the solar cells, in comparison with the power demand, is shown in Figure 8.13. The area installed at the farm, 113 m^2, is compared to two larger areas of 340 m^2 and 800 m^2. 800 m^2 will cover all of the power demand during fallowing and summer. The power output for 340 m^2 covers only parts of the power demand when in fallowing. An area of 113 m^2 covers some parts of the demand for the whole year.

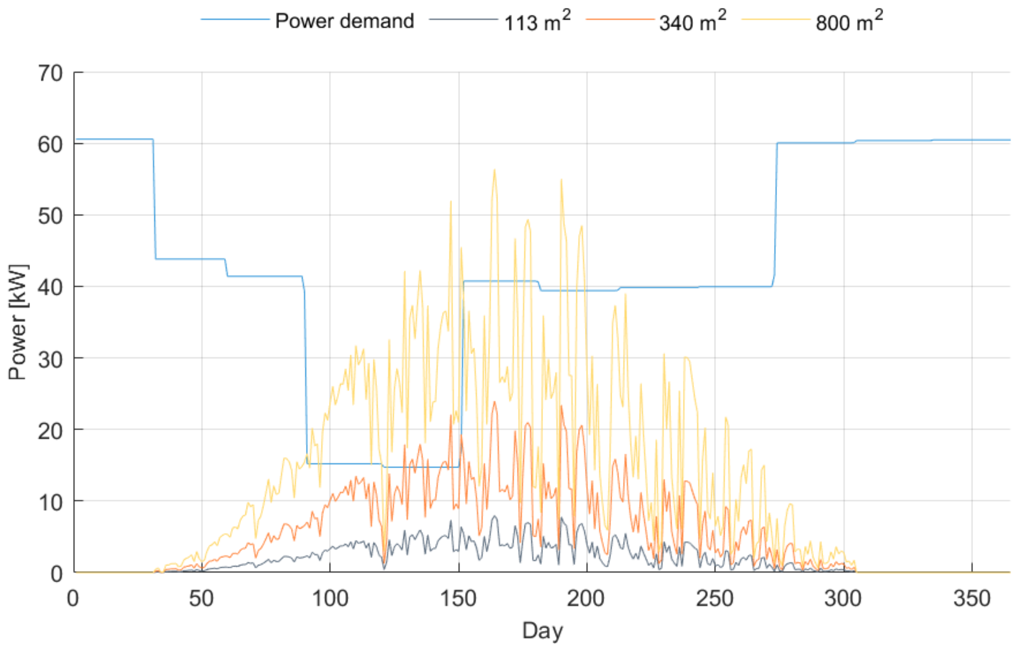


Figure 8.13: *The potential power output when increasing the area for the solar cells, in comparison with the power demand. The area installed at the farm, 113 m^2, is compared to two larger areas of 340 m^2 and 800 m^2.*

8.2.4 Floating turbine hybrid solution

A hybrid solution is a floating turbine of 2.3 MW in combination with battery cabinets and diesel generators. A section of the power demand is shown in Figure 8.14 from hour 7 000 to 7 400, and shows which energy resource covers the demand. The floating wind turbine will cover 70.4 % of the power demand, and the nine battery cabinets will account for 15.3 %. The diesel generator will cover 14.3 % of the demand. The surplus wind power is 3.91 GWh, equal to 90.5 % of the total wind power production.

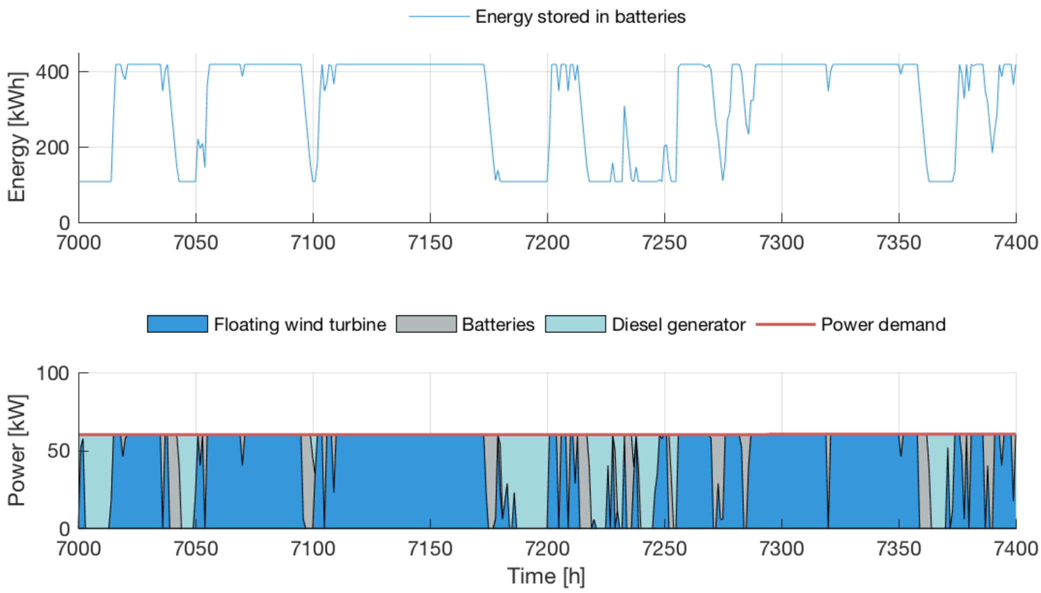


Figure 8.14: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the floating wind turbine, batteries and diesel generators complement the power demand.*

8.2.5 Costs and diesel generator emissions

The total CAPEX of each energy solution is illustrated in Figure 8.15, in addition to a scenario where diesel generators are the only energy resource utilized. Each bar represents an energy solution, and their total investment cost. The bar is divided into several sections, accounting for the cost of each element of the solution. The floating turbine hybrid solution has the highest CAPEX, and the diesel generator solution has the lowest. The costs of the DC/AC inverter and transformer are low compared to other technologies, and are hence not visible in the figure.

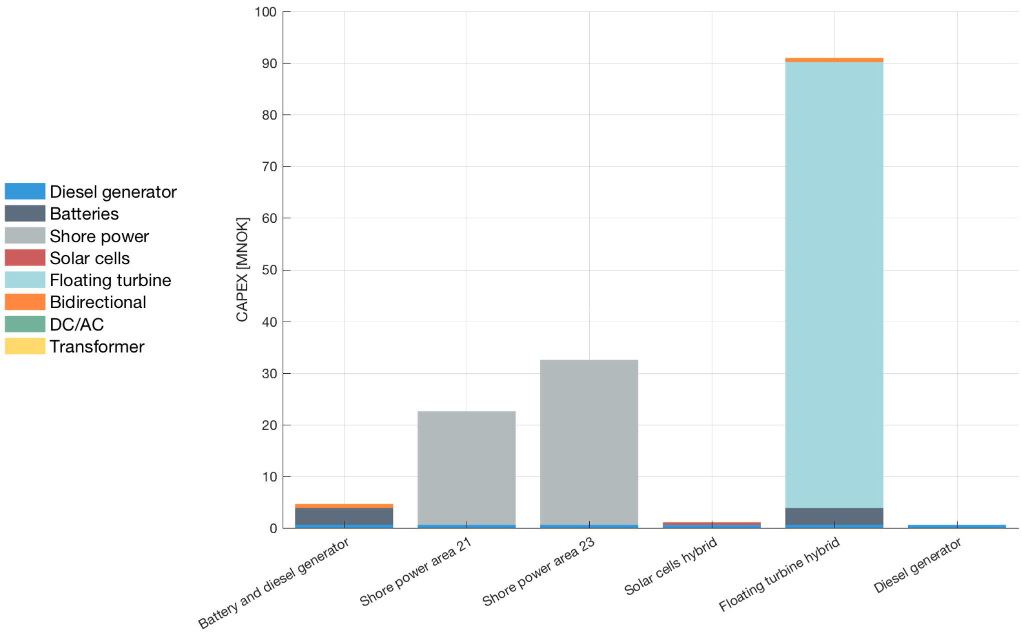


Figure 8.15: *The total CAPEX of each energy solution for the OAOF given in MNOK.*

Figure 8.16 illustrates the total OPEX of each energy solution, including fuel costs of diesel. The OPEX is calculated based on a year of operation. The floating turbine hybrid solution has the highest OPEX, and shore power for area 21 has the lowest.

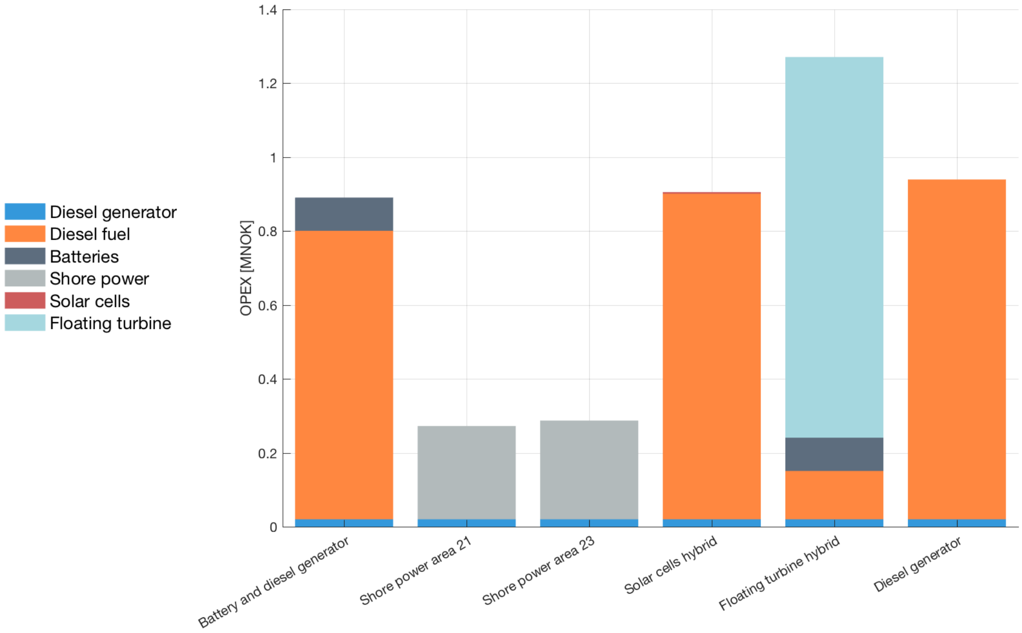


Figure 8.16: *The annual OPEX of each energy solution for the OAOF given in MNOK, including the fuel costs of diesel.*

The total LCOE of each energy solution is illustrated in Figure 8.17. The LCOE is calculated based on total costs and energy production over the life expectancy of each technology, and does not include additional equipment. The floating wind turbine hybrid solution has the highest LCOE, and the diesel generator solution has the lowest. A more detailed description of the CAPEX, OPEX and LCOE results are given in Appendix E.2.

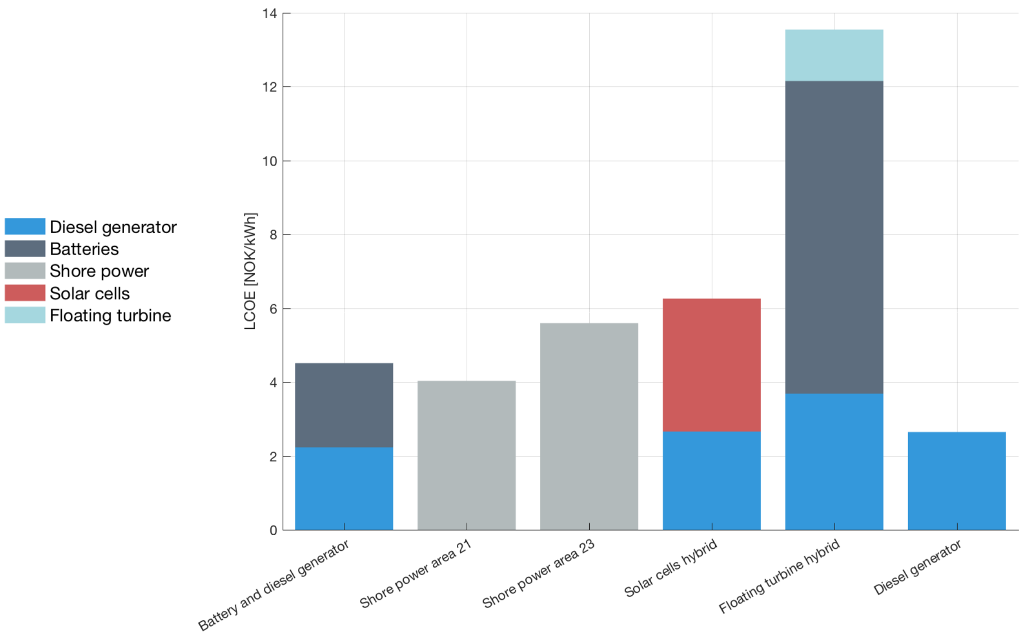


Figure 8.17: *The total LCOE of each energy solution for the OAOF given in NOK/kWh.*

All the solutions will have two generators installed as a backup system. The usage of diesel generators for each energy solution is presented in Table 8.4. In addition, the table lists the CO_2 emissions and fuel costs for each energy solution. The table also includes a 100 % diesel generator solution. Usage of diesel generators during maintenance or ambient conditions is not accounted for in this thesis. Therefore, the emissions and fuel costs are considered 0 for the diesel generator when utilizing shore power alone.

Table 8.4: *The usage of diesel generators, in addition to CO_2 emissions and fuel cost, for different energy solutions.*

Energy solution	**Diesel generator** [%]	CO_2 [tonnes/year]	**Fuel cost** [MNOK/year]
Diesel generator	100	321	0.919
Battery and diesel generator	100	273	0.780
Shore power area 21 and 23	0	0	0
Solar cells hybrid	95.7	301	0.881
Floating turbine hybrid	14.2	45.7	0.130

8.3 Case 3

In the following section, the results for all energy and hybrid solutions regarding case 3 will be presented. The CAPEX and OPEX for the projected energy solution of Spidercage will be presented for a comparison.

8.3.1 Battery and diesel generator hybrid solution

Figure 8.18 shows the solution of batteries in combination with diesel generators, for a period between hour 7 300 to 7 500. The results are based on a solution of three battery cabinets. The batteries cover 54.0 % of the power demand, and the diesel generator covers the rest of the demand at the farm. The percentage used to cover the power demand by the batteries on the farm, equals the diesel generator percentage used to charge the batteries. The diesel generators only run at 316 kWh at any given time, but are presented at lower power values in the plot, in order to show how the generators cover parts of the power demand. In reality, as the diesel generators only run at an optimal load, the peaks are higher, but occur for smaller periods of time. The full load hours for the generator for this solution is calculated to be 3 315 h.

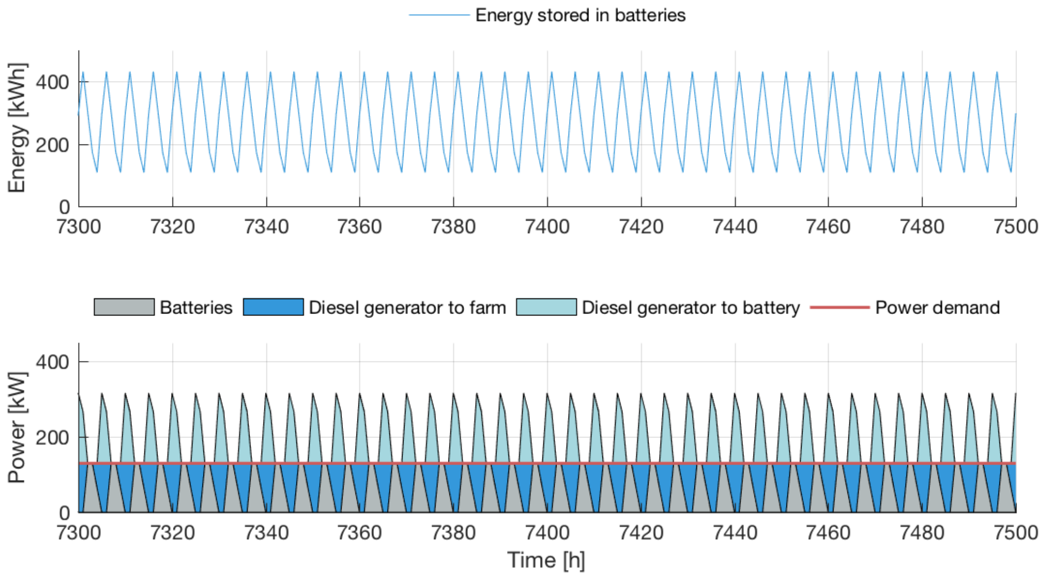


Figure 8.18: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the diesel generator and batteries complement the power demand. Diesel generator to farm illustrates the power from the diesel generator directly used to cover the power demand. Diesel generator to battery illustrates the power from the diesel generator used to directly charge the battery.*

8.3.2 Shore power solution

Table 8.5 shows the CAPEX and OPEX for on shore power supply for Spidercage. The cable cost constitutes 68.0 % of the total investment cost, which is within the historical figures from Enova. The results are based on a 22 kV subsea cable with a total length of 10 km. The cost for the compact substation includes both the substation onshore and offshore.

Table 8.5: *CAPEX and annual OPEX for on shore power supply for Spidercage.*

Post	CAPEX [NOK]	OPEX [NOK]
Subsea cable	10 700 000	20 000
Compact substation	2 800 000	1 800
Installation and additional equipment	814 500	-
Unspecified cost	1 431 450	-
Electricity and network tariff	-	549 642
Total	**15 745 950**	**571 442**

If four facilities with the same power demand are placed around a shared substation at Blikvær, the total CAPEX for each facility results in 7.19 MNOK. The total OPEX for each facility will result in 0.57 MNOK annually. The results are based on a subsea cable length of 10 km from shore to the substation at Blikvær, and an additional length of 5 km from the substation to each facility.

8.3.3 Solar cells hybrid solution

Results considering the hybrid solution of solar cells, batteries and diesel generator are illustrated in Figure 8.19. The time period is set from hour 3400 to 4000, which corresponds to a period with high solar irradiation. The installed capacity is 11.6 kW, and the solar power only covers a small part of the power demand. As a consequence, they will never charge the battery. Therefore, the cost considering batteries is neglected for this hybrid solution. The diesel generators cover the 99.0 % power demand, and solar power only accounts for 1.00 %.

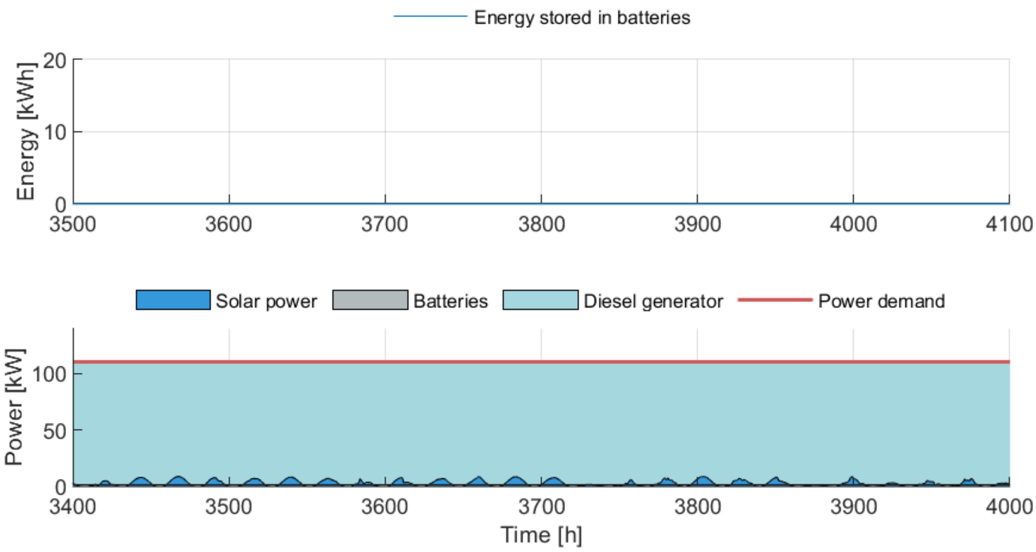


Figure 8.19: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the solar cells, batteries and diesel generators complement the power demand.*

The potential power output when increasing the area for the solar cells, in comparison with the power demand, is shown in Figure 8.20. The area installed at the farm, 60 m^2, is compared to two larger areas of 700 m^2 and 1 700 m^2. 1 700 m^2 will cover all of the power demand during some days in fallowing, and partly during rest of the year. The power output covers only parts of the power demand for 60 m^2 and 700 m^2

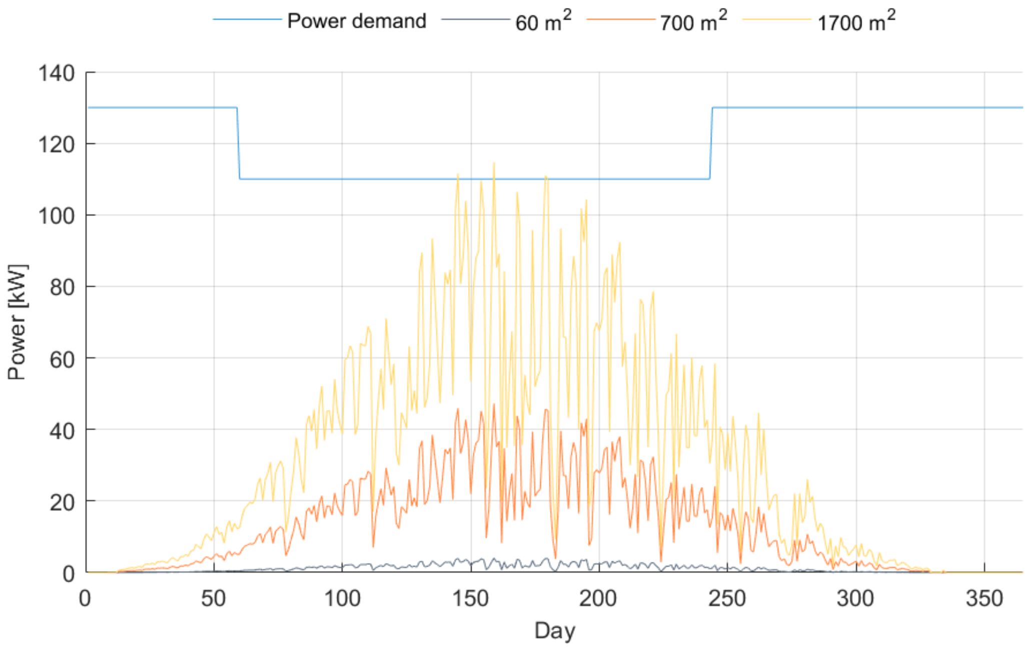


Figure 8.20: *The potential power output when increasing the area for the solar cells, in comparison with the power demand. The area installed at the farm, 60 m^2, is compared to two larger areas of 700 m^2 and 1 700 m^2.*

8.3.4 Wind turbine hybrid solutions

One of the hybrid solutions is an onshore wind turbine with capacity of 3.45 MW in combination with battery cabinets and diesel generators. A section of the power demand is shown in Figure 8.21 from hour 6 000 to 6 400, and illustrates which energy resource that covers the demand during this period of time. The onshore turbine covers 88.5 % of the total power demand, and the nine battery cabinets will account for 5.92 %. The diesel generator will cover 5.56 % of the demand. The surplus wind power produced over the year is 13.6 GWh, which constitutes 92.6 % of the total produced wind power.

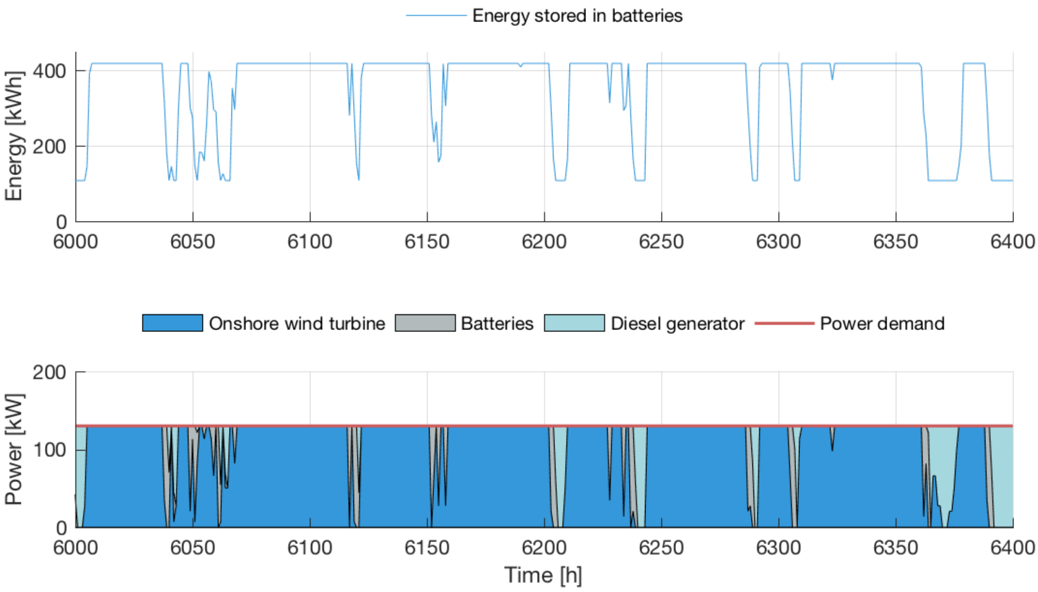


Figure 8.21: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the onshore wind turbine, batteries and diesel generators complement the power demand.*

Another hybrid solution is a floating wind turbine with capacity of 2.3 MW in combination with battery cabinets and diesel generators. A section of the power demand is shown in Figure 8.22 from hour 6 000 to 6 400, and illustrates which energy resource that covers the demand during this period of time. The floating turbine covers 82.0 % of the total power demand, and the nine battery cabinets will account for 6.26 %. The diesel generator will cover 11.7 % of the demand. The surplus wind power produced over the year is 6.10 GWh, which constitutes 85.7 % of the total produced wind power.

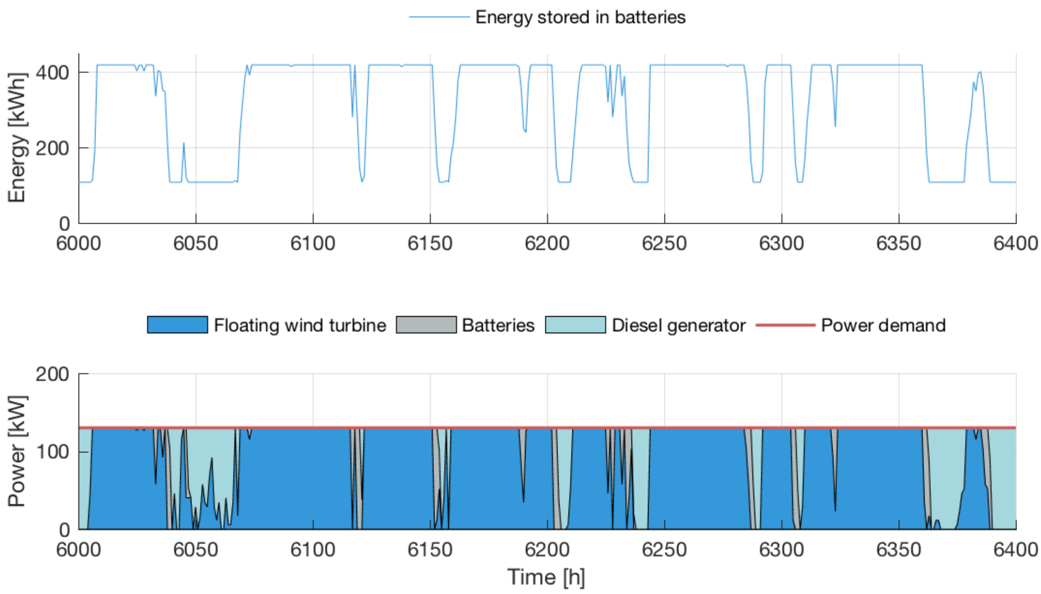


Figure 8.22: *The graph consists of two plots, where the top plot shows how the batteries charge and discharge every hour. The bottom plot shows how the floating wind turbine, batteries and diesel generators complement the power demand.*

8.3.5 Costs and diesel generator emissions

The total CAPEX of each energy solution is illustrated in Figure 8.23, in addition to a scenario where diesel generators are the only energy resource utilized. The figure also includes the planned energy solutions of Spidercage, with wave energy, kite generator, battery cabinets and diesel generators. Two diesel generators and 25 battery cabinets are assumed, in accordance with Table 6.2. Each bar represents an energy solution, and their total investment cost. The bar is divided into several sections, accounting for the cost of each element of the solution. The floating turbine hybrid solution has the highest CAPEX, and the diesel generator solution has the lowest. The costs of the DC/AC inverter and transformer are low compared to other technologies, and are hence not visible in the figure.

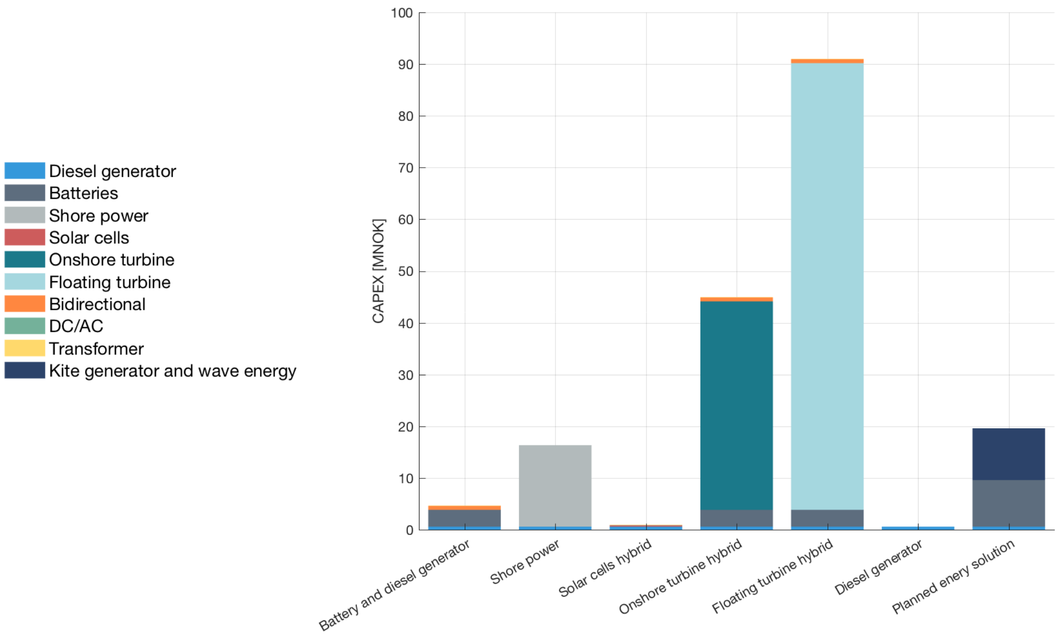


Figure 8.23: *The total CAPEX of each energy solution for Spidercage given in MNOK.*

Figure 8.24 illustrates the total OPEX of each energy solution, including fuel costs of diesel and the planned energy solution of Spidercage. The OPEX is calculated based on a year of operation, and is assumed to be 4 % of the CAPEX for the kite generator and wave energy. The battery and diesel generator hybrid solution has the highest OPEX, and shore power the lowest.

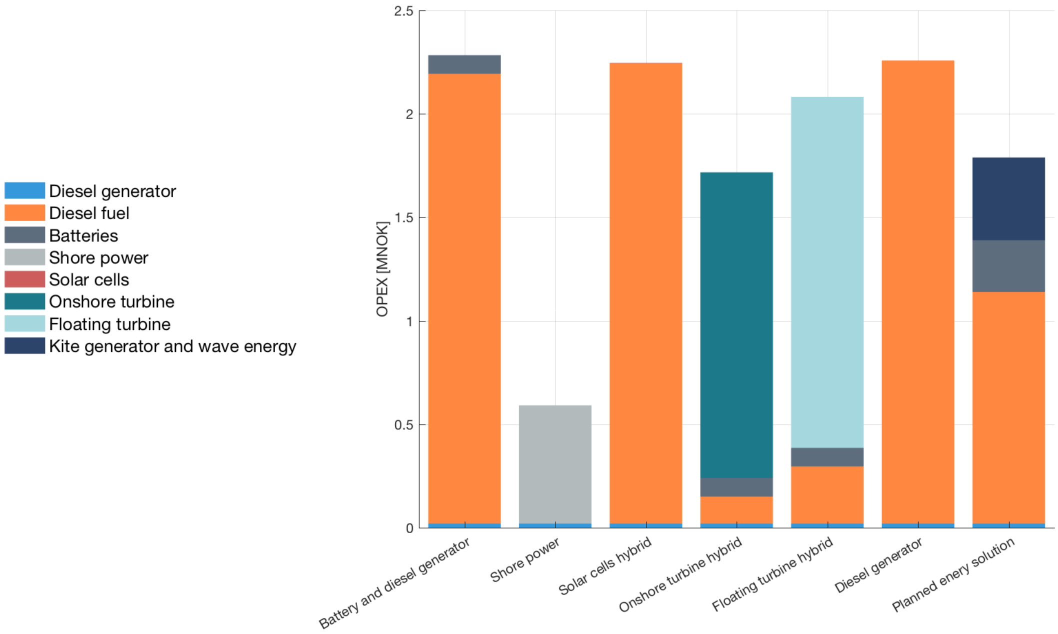


Figure 8.24: *The annual OPEX of each energy solution for Spidercage given in MNOK, including the fuel costs of diesel.*

The total LCOE of each energy solution is illustrated in Figure 8.25. The LCOE is calculated based on total costs and energy production over the life expectancy of each technology, and does not include additional equipment. The planned energy solution of Spidercage is not included in the LCOE calculations. The onshore wind turbine hybrid solution has the highest LCOE, and shore power solution has the lowest. A more detailed description of the CAPEX, OPEX and LCOE results are given in Appendix E.3.

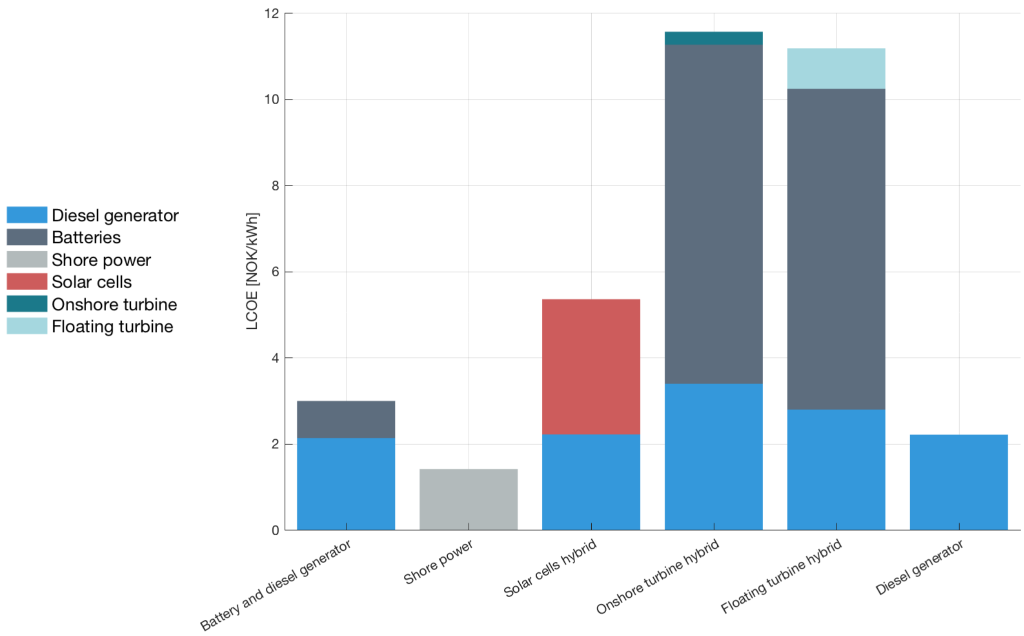


Figure 8.25: *The total LCOE of each energy solution for Spidercage given in NOK/kWh.*

All the solutions will have two generators installed as a backup system. The usage of diesel generators for each energy solution is presented in Table 8.6. In addition, the table lists the CO_2 emissions and fuel costs for each hybrid solution. The table also includes a 100 % diesel generator solution. The planned energy solution of Spidercage is not included in these calculations. Usage of diesel generators during maintenance or ambient conditions is not accounted for in this thesis. Therefore, the emissions and fuel costs are considered 0 for the diesel generator when utilizing shore power alone.

Table 8.6: *The usage of diesel generators, in addition to CO_2 emissions and fuel cost, for different energy solutions.*

Energy solution	**Diesel generator** [%]	CO_2 [tonnes/year]	**Fuel cost** [MNOK/year]
Diesel generator	100	782	2.23
Battery and diesel generator	100	760	2.17
Shore power	0	0	0
Solar cells hybrid	99.0	777	2.22
Onshore turbine hybrid	5.55	45.6	0.130
Floating turbine hybrid	11.7	96.5	0.276

9 Discussion

In this chapter, all the energy solutions for each case will be discussed in accordance with relevant theory. The discussion will emphasize on how cost efficient and eco-friendly each solution is, in addition to whether the solutions are realistic for the three cases. Lastly, further work is included in order to carry forward the solutions presented in this thesis.

Eco-friendly solutions can be expensive. It is rare for major corporations and businesses to choose a green solution, because of the high cost, if there are no profits related. With a higher media interest in renewable energy, however, it can result in pushing more companies to choose more eco-friendly solutions in order to gain a good reputation for marketing reasons. In order for fish farmers to prefer more eco-friendly solutions, the Government might have to step in and take an active role in the transition to reduce GHG. They can require offshore facilities to reduce CO_2 emissions by a certain percentage. In addition, it may be possible to grant subsidies to facilities that want to use more eco-friendly solutions.

Exploring offshore areas for fish farming are necessary due to the lack of available locations near land. With greater available area, fish farms will have larger production capacity, in addition to reduce some environmental challenges facing the industry. On the other hand, challenges can occur when moving the fish farms offshore. Rougher weather conditions can lead to increased mechanical strain on the farm and fish, which further can lead to more maintenance. The rougher weather can also affect the vessel frequency to the farms. The energy solution implemented on the offshore farm must hence be able to operate without supply of fuel for longer periods of time, compared to traditional fish farms. This can however be solved by including a redundant system to the solution, such as stored additional diesel fuel.

9.1 Uncertainties regarding simulations and calculations

Solar cells placed on the facility and offshore wind turbines can include an uncertainty, as the measurements are extracted onshore. In addition, the measurements are not taken from the exact locations of the onshore wind turbines, and can hence lead to an uncertainty. For case 2, measurements and calculations are only done for area 21, with the exception of shore power which is calculated for both area 21 and 23. Solutions for area 7 and 23 will hence include an additional uncertainty.

Another uncertainty can be the efficiencies of the inverters, both DC/AC and bidirectional, as they have not been taken into account in any of the simulations. This could have affected the results and output power for all energy solutions, though not to a large degree, as the efficiencies are relatively high. The costs of each technology can also include uncertainties, due to several different sources of information and assumptions based on experience from the industry. In addition, fuel and electricity costs may change over time. Other uncertainties arise due to assumptions and simplifications.

The life expectancy for each technology is not taken into account when neither calculating the CAPEX nor annual OPEX. These results will hence not reflect upon how long each technology will last before a replacement is required. The LCOE was therefore calculated, as it takes life expectancy and produced energy into account. How long a technology lasts can be a crucial factor when deciding upon the most optimal technology. The LCOE depends on how much energy each technology produces, and does not take equipment such as hydrogen tanks, transformers and inverters into account. The LCOE will therefore not reflect upon the total costs of each solution, but rather give a basis to compare the various solutions on an economical foundation.

9.2 Case evaluation

The three cases were chosen at the start of the project, with little knowledge on how the collaboration would go and how willing the different companies were to share information. Ocean Farm 1 was an optimal choice, as realistic power demand values were received, making it an ideal case. This was not possible for the remaining cases, as none of them are in operation. Aker Solutions was hesitant to share information in the beginning due to competition within the industry, even though they were very enthusiastic about the thesis. The testing of different locations for the OAOF gave the thesis a wider aspect. Spidercage was an innovative extremity, due to their choice of energy solutions, which differs from the traditional diesel generators.

Other concepts which have received development licences could have been chosen, and might have resulted in more realistic results. However, this is unlikely, as there are few other facilities in operation besides Ocean Farm 1. All three cases were overall relevant choices for the thesis, and the established collaborations were adequate, as all information required was received.

Technical and design changes the different energy solutions may lead to, for the fish farms, are not taken into account. The energy solutions presented in the thesis are rather a basis on what is possible regarding electrification of offshore fish farms. All the cases have received development licenses with their selected energy solutions, and may not be able to change the energy solution for their current farms. On the other hand, this can be a possibility for future facilities. However, the energy solutions can not compromise the welfare of the fish, as the fish farming companies are obligated to follow regulations and laws, as explained in chapter 2.4.

The power demand of both the OAOF and Spidercage are assumed, which led to some unrealistic results with uncertainties. The power demand curves show a constant consumption over a month or season. The power demand will hence not fluctuate as it would when put in operation, leading to results with uncertainties. On the other hand, this may be a reasonable basis for simulations, but will not reflect upon a realistic operation.

Fallowing is set to be during spring and summer for the OAOF, as seen in Figure 6.8. This may not be the case when the facility is put in operation, as these are the periods with highest sea water temperature and hence highest growth rate of the fish. Most harvesting takes place in the last quarter of the year, and the facility will thus be in fallowing during the winter. The power demand may therefore be somewhat unrealistic, though is used as a basis for all the simulations and calculations for case 2.

The OPEX of the kite generator and wave energy in Spidercage was assumed to be 4 % of CAPEX. This is about twice the cost compared the other technologies presented, due to both of the technologies being new and immature. As the technologies will be implemented offshore, it can be assumed that the OPEX will increase further, because of mechanical impact due to rough weather conditions. The CAPEX is estimated, and may increase or decrease as the project develops further.

The planned energy solution at Spidercage is assumed to have a lower CAPEX than both the onshore and floating turbine hybrid solutions, and a higher CAPEX compared to the rest of the solutions. However, the OPEX for the projected solution is one of the lowest compared to the other energy solutions, as seen in Figure 8.24. It may therefore be worthwhile to operate with the original projected solution, but this will require more development within the technologies.

In the cost calculations of the planned energy solution of Spidercage, two diesel generators of each 198 kW were assumed in order to compensate for their planned diesel generator of 250 kW. These two diesel generators were chosen as the costs given in Table 5.1 only applies to this model. The investment cost for a 250 kW diesel generator could be lower than what is presented in the cost results. On the other hand, two 198 kW generators can be a good estimate for the projected solution.

The battery capacity of the planned energy solution of Spidercage is 1 500 kWh, as presented in Table 6.2, which will correspond to 25 of the lithium-ion battery cabinets used in this thesis. The facility may therefore have more available space for storage solutions, than what is accounted for in the presented solutions. Therefore, a higher number of battery cabinets could have been chosen. This was, however, not considered to be cost efficient, due to the high LCOE of batteries, as seen in Figure 8.25.

As the planned energy solution for Spidercage contains technologies that are new, immature and underdeveloped, it may be a risky investment. There are currently no successful wave power technologies that have fulfilled the technical and economical requirements for production in a large scale. The lifetime of the wave energy concept can therefore be expected to be short, and the investment might not pay off. On the other hand, if the project is successful, it can be a great breakthrough in wave power technology. As the facility will be placed offshore, high resource potential can be assumed due to more waves. However, it could lead to more mechanical impact on the facility, which is not optimal.

9.3 Diesel generator and emissions

All the hybrid solutions have a calculated value of CO_2 emissions. However, these calculations only take the emissions from burning diesel fuel into consideration. There will be additional emissions when producing the different energy resources. These CO_2 emissions, released in the production, have not been accounted for in this thesis. Therefore, the results may include an uncertainty, if the technologies emit a large amount of GHG during production.

Maintenance and fuel cost will variate depending on what load the diesel generator is running at, which affects the SFC. The optimal load is relative to the rated power. This has not been taken into account for the hybrid solutions, besides the battery and diesel generator solution. For the hybrid solutions, the diesel generator may run at lower loads, in addition to be turned on and off more often. This can potentially increase the OPEX considering the diesel generators for the hybrid solutions. However, the OPEX is assumed to be constant for all the hybrid solutions in this thesis, independent of the diesel generator output, which can lead to uncertainties in the calculations, as maintenance could increase or decrease.

Furthermore, the life expectancy of the diesel generator may be reduced for these hybrid solutions if the diesel generators are not operating at optimal load. Problems related to the diesel generator may be solved if they are dimensioned to always run at optimal load for each hybrid solution, such as the battery and diesel generator solution. For the hybrid solutions, which have a lower usage of diesel generator, a lower rated capacity can be better suited in order to run at an optimal load more often. On the other hand, the life expectancy could increase with reduced operation hours per year, as shown in Table 7.2. The table applies if the only factor affecting the life expectancy of the diesel generators are their operation hours. In reality, this will however not be the case, as there are other contributing factors.

If one or several smaller diesel generators are installed, it is still a need for some large diesel generators to ensure reliability of supply. Therefore, an additional installation of smaller diesel generators will increase the total costs for the solutions. On the other hand, an additional cost for several small diesel generators might be profitable over time as they are operated at more optimal load. This will, as a consequence, reduce the fuel costs and emissions, and increase the life expectancy. Moreover, only using a few large diesel generators at low loads in certain periods, may decrease the SFC and life expectancy, and thus increase fuel costs and emissions. However, smaller generators are less efficient than larger ones, which also needs to be accounted for.

The diesel fuel in a hybrid solution may contribute to an uncertainty in the total costs, as the price of MDO may fluctuate. The price decreased from 10.27 NOK/L in January to 9.90 NOK/L in April 2020. The results are based on the price of MDO, equal to 9.90 NOK/L, which includes a CO_2 tax of 1.45 NOK/L. This tax may, however, change in the future as Norway is dedicated to reduce emissions of GHG, with at least 50 % by 2030, compared to the reference year 1990, in accordance with the Paris Agreement.

The price of MDO can therefore increase, which will make the solutions with diesel generators more expensive. The government may increase the taxes considering energy solutions with high emissions, in order to pressure the industry to choose a future-oriented renewable solution. This may affect the choice when considering an installation of new innovative energy solutions, which is going to last for several years. They may currently be more expensive to install and operate, although, in a future perspective, be more profitable than an installation of a less expensive energy solution, like a diesel generator.

The LCOE of the diesel generators decrease with increased operation hours. This is despite the solutions with lower operation hours having a higher assumed life expectancy. Table 7.2 shows that the diesel generators used in combination with wind turbines, shore power hybrid and fuel cell have a life expectancy of 83 years, while the generators used with solar cells have a life expectancy of 13 years. Figure 8.10 shows that the diesel generators with solar cells have a lower LCOE, despite the life expectancy being shorter than for the other solutions. The main reason for this, can be the amount of produced energy by the generators, which is much higher in the solar cells hybrid solution than for the fuel cell solution.

In addition, the CAPEX and OPEX of the diesel generator are assumed the same in every solution, as the number of diesel generators required are alike due to reliability of supply. With a smaller amount of produced energy by the diesel generators in some of the solutions, the investment of several 230 kVA sets may not be cost efficient. In addition, a life expectancy of 83 years for the diesel generators may not be realistic. As the diesel generators in these solutions are not utilized much, OPEX may increase, and this can result in a lower life expectancy than assumed.

An option could have been to find the exact number of diesel generators the different solutions actually require to meet the demand, rather than accounting for all the generators needed for reliability of supply. The LCOE could then be calculated for this number of diesel generators. This may have given a more realistic result considering the hybrid solutions which utilize the diesel generator only a small portion. This was not done in this thesis, as all the diesel generators will have to be installed in order to ensure reliability of supply, and was therefore included in the LCOE calculations.

Diesel generator usage for the different hybrid solutions variate. The solar power hybrid solution is the overall least eco-friendly, as it is the solution with the highest CO_2 emissions for each case. Solar power uses the diesel generators with a coverage of 95.7 to 99.0 % of the power demand for all three cases. The solution is only covering the power demand with a small part of renewable power, and will only reduce the CO_2 emissions between 0.639 to 6.23 %. On the other hand, it could start a transition to more renewable operations for fish farms offshore.

It is assumed that a shore power solution is emission free. This may not be the actual case, as the diesel generators are kept as a backup. This may lead to CO_2 emissions, if an error in the system occurs or during maintenance. On the other hand, this is rare and there is minimal maintenance work for the electrical equipment. It might therefore be grounds to assume that shore power is a completely eco-friendly solution.

For Ocean Farm 1, the most eco-friendly solution considering usage of diesel generator is the fuel cell hybrid solution, as Table 8.2 indicates. The CO_2 emissions are reduced by 95.9 %, compared to the currently 100 % usage of diesel generators. For the OAOF, the hybrid solution with the lowest emissions is the floating turbine hybrid solution. The CO_2 emissions are reduced by 85.8 %, compared to the currently planned 100 % usage of diesel generators.

For Spidercage, the onshore turbine hybrid solution is the most eco-friendly. The CO_2 emissions are reduced by 94.2 %, compared to the 100 % usage of diesel generators. Spidercage has planned usage of kite generators, wave power, batteries and diesel generators. Emissions considering this innovative hybrid solution is unknown, and hence the result can not be compared to the currently planned solution. The planned solution might be more sufficient considering CO_2 emissions than the most eco-friendly solution presented in the thesis.

To reduce CO_2 emissions from the diesel generators, hydrogen can be utilized as an additional fuel in the ICE. This would save the investment cost of installing new renewable energy resources. By using this method, the usage of fossil fuels would not be substituted, though it would be reduced. If hydrogen is to be used with diesel fuel, it would have to be stored separately. Hydrogen tanks can be expensive and demand a lot of space, which is not beneficial.

Aside from this disadvantage, the use of hydrogen as additional fuel is more desirable than the use as single fuel. The main problems by utilizing hydrogen as a single fuel are premature ignition and low density of hydrogen. It would also require modifications to the ICE, or replacing the ICE with a spark ignition engine. A larger amount of hydrogen fuel would also be required, which can lead to more expenses regarding storage.

9.4 Battery

The two main battery solutions presented in this thesis is the lead-acid and lithium-ion batteries. According to Table 5.6 and 5.7, the CAPEX for a lead-acid battery would only constitute 45 % of the lithium-ion battery. On the other hand, the gravimetric and volumetric energy density are also important factors to take into account when choosing a cell chemistry.

The power demand on the platform must be met, without exceeding the volumetric or weight related restrictions, as the offshore farms have a limited area for battery storage. Lead-acid batteries account for 13.3 and 17.5 % of lithium-ion, for respectively gravimetric and volumetric energy density. To be able to store the same amount of energy into each type of battery, the size of lead-acid would have been 5.7 times larger and weigh about 7.5 times more. This would cause a significantly higher weight and required space for storage. This may further lead to an increase in total cost, in terms of transportation, installation and maintenance of a lead-acid battery storage. Therefore, the lithium-ion batteries were more suitable for this thesis.

The SOC window for each of the hybrid solutions was set between 20 and 80 %. The SOC window can however be smaller, but due to the power demand being given in an hourly resolution, the battery will only charge or discharge ones every hour. In reality, however, usage of the battery will occur more frequently, and the number of battery cycles will increase. This can further result in a decrease of the battery life expectancy or lower the SOC window to between 30 and 50 %. A lower life expectancy will result in a higher LCOE. This can also be the case if the SOC window is lowered, and the energy stored per battery cabinet can be decreased.

The battery cabinets have a high LCOE, as seen in Figure 8.10 and the corresponding figures for case 2 and 3. The high LCOE can be due to the short life expectancy of the batteries. The costs may decrease in the future, as lithium-ion batteries are constantly under research and development. A desire for a higher battery capacity, better efficiency and longer life expectancy with lower cost, offers a great potential for this technology. However, with an increasing interest in electrification of vehicles, a lot of the workload is invested into this, rather than other industrial battery solutions. This could potentially decelerate the industrial battery development, and further take longer to make battery investments profitable.

The chosen lithium-ion battery has a charging c-rate of 1.9. A c-rate for charging of under 1 would not have given any peaks exceeding 540 kW, thereby being better suited for c-rate calculations relative to the hourly resolution for the power demand on the farms. However, the specific lithium-ion battery model was chosen as it was well suited in combination with other energy resources for offshore fish farms. In addition, a c-rate of 1 is almost half of the chosen battery, and it would therefore use twice as much time to charge a battery, making it less fitting for the fish farms. Due to the c-rate exceeding 1 while charging, the c-rate calculations were not to be included, as mentioned in chapter 7.3.

9.5 Battery and diesel generator hybrid solution

A solution with diesel generators in combination with batteries was evaluated as it could reduce the diesel generators emissions, by optimizing the generator to always run at constant load when used to charge the batteries. In addition, it would not require any investments in renewable energy resources, and it would reduce the operational hours on the diesel generator.

For the battery and diesel generator solutions for each case, nine battery cabinets were chosen. As the diesel generator will both cover the power demand at the farms and charge the batteries, the number of batteries will determine how much of the diesel fuel that will charge the batteries. In Table 8.2, and the corresponding tables for case 2 and 3, the diesel consumption for the battery and diesel generator solution is calculated to be equal to the diesel consumption of a 100 % diesel generator solution. This is due to the diesel generator output being dependent on the capacity of the energy storage.

With a lower energy storage capacity, the diesel generator output will be lower. With larger battery capacity, there will be more diesel generator power. Hence, the tables may give a wrong impression of how efficient the battery and diesel generator solution is compared to 100 % diesel generator solution. This can however be seen when comparing the CO_2 emissions or fuel costs for each of the tables.

Even when the battery and diesel generator solution is optimizing the diesel generator, by only using it at 80 % load, it still has more CO_2 emissions compared to some of the other solutions presented in the tables. The solution does not reduce the CO_2 emissions enough in order to achieve the climate goal of Norway, by reducing the GHG emissions with 50 % by 2030. This may therefore be considered as more of a short-term solution.

The ratio between the maximum point, 229 g/kWh, and minimum point, 190 g/kWh, in Figure 5.2, is low. The ratio between the most and least optimal load percentage is therefore low. In addition, this ratio is very similar to the ratio between diesel input for the diesel generator solution and the battery and diesel generator solution. With these low ratios, it can be expected to not be too large of a difference when using the 100 % diesel solution at any given load percentage and a diesel generator at a constant optimal load of 80 %.

There can be some uncertainties regarding the SFC graph, which may affect the results when comparing the 100 % diesel generator solution to the battery and diesel generator solution. This can occur due to the SFC graph not being completely accurate for the specific 198 kW diesel generator used in the thesis. The SFC graph is plotted based on three given points for 50, 75 and 100 % load. As the rest of the graph is based on SFC graph trends for other diesel generators, it is not certain whether the graph would reflect accordingly to a 198 kW diesel generator.

In addition, the gradual slope from 40 to 50 % load, may seem a bit unrealistic, compared to some of the other steeper slopes in the SFC graph. This may be the reason for the small difference in SFC, and thereby fuel cost for the battery and diesel generator solution compared to the 100 % diesel generator solution. If more realistic values for the SFC graph were used for the chosen diesel generator, the calculations could have shown a larger difference between the 100 % diesel generator solution and the battery and diesel generator solution.

The power demand trends for farms located in sheltered waters may be different than the offshore facilities. The difference between the basis demand and peaks is often higher for traditional farms, compared to offshore farms. This may allow a possible battery and diesel generator solution to be better suited for traditional fish farms. However, a shore power solution, if possible, may be more profitable and eco-friendly for a traditional fish farm.

On the other hand, a solution with both diesel generator and battery will reduce the CO_2 emissions by at least 2.8 % for each of the different cases. As it can be expected that CO_2 taxes will increase over the next few years, it is conceivable that a reduction of at least 2.8 % of CO_2 emissions could be profitable in the future. However, investing in batteries will result in a higher CAPEX than for diesel generator alone. It can be possible to look at battery costs with an increasing number of batteries up against the variation in diesel emissions. In addition, it can be interesting to compare declining costs for batteries against rising CO_2 charges in the years to come, to find an optimal solution with regard to a battery and diesel generator solution.

The total LCOE for the solution is overall low for each of the cases, compared to the other hybrid solutions. For each of the hybrid solutions, the battery constitutes a large portion of the total LCOE. The battery LCOE is however rather low, even with the use of nine batteries for each of the cases. This can be due to the batteries being used more effectively in this solution, as the batteries charge and discharge more frequently, as seen in Figure 8.1. This cause the batteries to store more energy during a life expectancy of 10 years. However, with a large number of charging cycles in this solution, the battery life expectancy can be assumed to decrease somewhat.

The full load hours for the diesel generator have decreased with 17 % at least, and 44 % at most, compared to the 100 % diesel generator, for each case. This can reduce the diesel fuel consumption for each case. In addition, when running the generator at an optimal load for less full load hours than the 100 % diesel generator solution, it could lead to a lower LCOE. The optimization of the diesel generator could have been done to some of the other hybrid solutions as well. On the other hand, this would lead to a lot of damage to the diesel generator, when the hybrid solutions have such a low usage of the diesel generator of this size.

It can, however, be difficult to optimize the generator in reality. More than one load per hour can occur at the fish farm, which the power demand in hourly resolution does not take into account. The optimization will hence depend on the batteries to meet the ongoing power demand during the rest of the hour, after the diesel generator has been run at optimal load for a short time.

Whenever the diesel generator is used at optimal load for a fraction of an hour, it should instead run for a longer period of time, to avoid damage by turning it on and off. This power could potentially be used to supply the aquaculture service vessels with energy when operating at the facility. This will decrease some of the vessel emissions. However, this will only be a temporary solution as the diesel generator would still emit a large amount of CO_2. The power can also be used to charge batteries on board the vessels, if they are electrified.

9.6 Shore power solution

Onshore power supply was evaluated as it is a solution widely used today. The technology is well developed, and the required equipment are available. At the same time, 50 % of all farms are electrified per today using this technology. On the other hand, onshore power supply might not be suitable for an offshore fish farm, due to the CAPEX of the required equipment.

The solutions regarding shore power are affected by the Energy Act. There is a possibility to electrify all the localities with shore power, as the Energy Act states that the network companies are obligated to deliver power. On the other hand, if the localities are to be placed outside the baseline, the Offshore Energy Act will be applied. This may influence the possibilities for shore power connection in the future. The Offshore Energy Act does not have any clarification or regulations considering energy supply to offshore fish farms. If such a regulation is to be made, it might affect the availability of shore power and it could be harder to implement the technology to an offshore facility.

All of the cases can be electrified using shore power without triggering new grid investments on the mainland grid. This is independent of location and power demand. The connection point for each site has been given directly from the network companies, and places without grid has not been investigated. However, for the fish farms which do not have a determined location, other connection points might be more suitable, which can trigger new grid investments.

New infrastructure has to be developed in order to establish a connection at the different sites. This mainly includes a subsea cable and substations, both onshore and offshore. The results show that CAPEX for shore power, at each site, will be one of the highest investment costs compared to the other energy solutions evaluated in this thesis. However, in operation, the OPEX is the lowest, independent of the case and power demand. Operating an onshore power supply system does not cost much, which can be beneficial in the long run. This is mainly due to a low electricity price compared to fuel cost.

The CAPEX will increase with an increasing distance from shore, mainly due to the investment of the cable. The investment of the cable will constitute approximately 80 % of the total CAPEX for case 1 and 2, and 68 % for case 3. This is in pursuance with the historical figures provided by Enova, as explained in section 4.5, which implies that the assumed costs were adequate for the cable. Both case 1 and 2 are located further from shore than case 3. The other costs related to the CAPEX are the same for each case, and hence the CAPEX may only be affected from the procurement of the subsea cable.

Both the transformer and subsea cable have a life expectancy of 30 years. A floating wind turbine is the only other energy resource with an equal life expectancy. A floating wind turbine could be more suitable to provide power to an offshore fish farm, than onshore power supply. The wind turbine produces surplus power, making it possible to increase the power demand of the fish farm without the need of a further development of technology. On the other hand, shore power has a lower CAPEX and OPEX than a floating wind turbine, which may be more cost efficient. However, shore power is limited by the available power in the grid, and an increase of the power demand could lead to an expensive development of the infrastructure.

An uncertainty regarding the CAPEX and OPEX calculations is the measured distance from shore to the facilities, hence the length of the subsea cable. This was done by utilizing map data and measurement tool from NVE. It was assumed that the subsea cable could be laid in a straight line from the connection point to the facility. However, in reality, this may not be possible. Islands and reefs, or other interests of matter, may be obstacles to meet. On the other hand, an additional length of 2 km was added to the overhead line, in order to take the depth of the sea, curves and variations into account. This may give a better estimate for the total subsea cable length. However, it is still uncertain if a 2 km additional length is sufficient, as the sea curves and variations are unknown.

The OPEX for shore power to an offshore facility may be higher than the ones calculated. There are no existing offshore fish farm with shore power per today, and specific historical figures, for maintenance, do not exists. The OPEX is calculated based on general values for both the subsea cable and substation. These costs may be higher due to the location of the fish farm. The total OPEX for each facility includes a cost for maintenance on the subsea cable. On the other hand, the maintenance includes an inspection of the cathodic protective gear, as explained in chapter 4.5, which is not required annually. The calculated OPEX will hence not reflect upon the actual annual OPEX for onshore power supply. It may decrease for the years where an inspection is not necessary.

In addition, the OPEX is dependent on the electricity cost and network tariff. They may change, and can fluctuate both annually and monthly, depending on the power situation. Therefore, an exact annual OPEX can be difficult to calculate, as it is difficult to predict future electricity costs and network tariffs. However, the presented results may be a good indication of how much electricity and network tariff will contribute to the total annual OPEX.

The suitable connection points are based on the peak values of the power demand of each case, which may not be suited for an increased power demand. If the increased power demand is not available at the connection point, it can decrease the security of supply to the site and other end users connected to the same grid. In addition, an increased power demand can trigger further grid investments, and hence lead to a more expensive investment cost. A solution can be to evaluate other connection points, if the power demand is increased. Another solution can be to implement shore power in combination with other energy resources in order to cover the increased power demand without triggering grid investments.

Other fish farms nearby the facilities, or other offshore industries, which request connection to the grid, have not been accounted for in this thesis. It could lead to a higher demand of grid capacity, if more industries request grid connection at the same locations. This may be crucial in the rural areas where the grid is weak, as explained in chapter 4.2. If a load is connected where the maximum power demand is reached, new grid investments are needed, which are expensive.

On the other hand, if more offshore industries or facilities request shore power connection in the same area, it could reduce the investment cost for each facility or industry. This is in pursuance with the results presented if four fish farms are connected to the same substation. For case 1 and 2, the total investment cost is reduced to a third of the investment cost of one facility, and for case 3 it is reduced to 50 %. The OPEX for all cases does not decrease as much as the CAPEX, as it is assumed that the four facilities have the same power demand. The results indicate a more cost efficient solution per meter subsea cable added. Therefore, it may be more profitable for each facility to implement a shared subsea cable with an increasing distance from shore.

The calculation of CAPEX for shore power to a four facility solution has some uncertainty. For both case 1 and 2, the substation is assumed to be installed at the bottom of the sea. This assumption may lead to a more expensive investment cost for the substation than the one utilized in this thesis. It could be assumed that the subsea substation will have a higher investment cost than the substation placed on the feed barge or onshore. A subsea substation may need more equipment and have a different structure than a normal substation. In addition, it can be assumed that the annual cost of inspection of the substation will increase, which may lead to a higher OPEX for each facility. The presented results may be more realistic for case 3, as the substation is placed on Blikvær.

On the other hand, the solution presented for a four facility solution may not be in pursuance to a realistic scenario. It is unlikely that four facilities will be built and put into operation at the same time. An alternative solution could be that the first farm in operation invests in a substation, and subsequently distributes the power to other farms which request shore power connection. New farms could invest in a subsea cable connection to the first farm, in order to get access to the grid.

For this to work, the first farm has to be able to distribute power, and the substation has to be built in order to supply several farms with power. It could potentially lead to a decrease in CAPEX for each facility equal to the cost reductions presented in the results. However, this is dependent on how many facilities that connect to the first farm.

An overall result of the LCOE for shore power, shows that the LCOE increases when the location of the fish farms is further from shore. This is due to the calculated CAPEX and OPEX as they increase with the length of the cable. Shore power may be a cost efficient solution if the facility is not located too far from shore, and this is the main reason why shore power is not as relevant far offshore. If located far offshore, the battery and diesel hybrid solution may be more cost efficient, as this solution has a lower CAPEX. For Ocean Farm 1, the LCOE for shore power is higher than the diesel battery solution, and the same applies for the OAOF in area 23.

The LCOE for shore power is the lowest compared to the other energy solutions for both case 2, for area 21, and case 3. This can be due to the life expectancy for shore power equipment being high. However, the LCOE may be higher than the ones calculated. All the equipment for shore power has to withstand rough weather conditions and may be exposed to large mechanical strain, as the equipment is installed at sea. This can decrease the life expectancy, and hence increase the LCOE. In addition, the usage of the diesel generators has not been accounted for. This could increase the LCOE, as the fuel cost is higher than the cost of electricity. On the other hand, the diesel generators can be expected to be used in a small time period, as there is limited need of maintenance for shore power equipment.

The results show that a shore power connection from Ocean Farm 1 to Svellingen at Frøya will have a total CAPEX of more than 33 MNOK, as shown in Table 8.1. This connection is, however, not in pursuance with the closest power grid to Ocean Farm 1. A connection to the grid at Froan, which is closer, could have resulted in a lower investment cost, due to the subsea cable length. On the other hand, this is not possible because Froan does not have the capacity to cover the power demand of Ocean Farm 1. Meanwhile, a connection to Froan could result in a higher CAPEX because the connection would trigger new upgrades and investments of the existing power grid on the islands.

Frøya is an island with both inhabitants and industries which need power. A new grid connection may influence the security of supply, especially if there are several customers connected to the same transmission line. However, this is not likely as the grid at Frøya is well developed. In addition, the transmission lines run at a lower voltage level than what the lines are rated for, and are able to provide higher voltage levels if needed. Considering that the lines at Frøya run at 11 kV, a substation is needed for the new connection. If the transmission lines at Frøya run at the same rated voltage as the subsea cable, the investment cost could have decreased, as the onshore substation could have been replaced by a circuit breaker.

How cost efficient shore power is for the OAOF is determined by where the facility is to be placed. The results in Table 8.3 display that shore power to area 21 is less expensive than area 23. This is mainly due to the total subsea cable length. In addition, the shore power connection to Engvika for area 21 does not need a substation onshore in order to establish a connection to the onshore grid. Therefore, it is less expensive to establish a shore power connection to area 21 than area 23. On the other hand, Engvika is an extreme point in the grid at Rebbenesøya, and potential voltage losses must be taken into consideration. An alternative could be to install a substation onshore in order to increase the capacity in Engvika and to avoid voltage losses, but this would increase the total CAPEX.

Shore power to area 7 has not been considered for the OAOF. The main reason for this, is the distance from shore to area 7, which is approximately 100 km. If the same cable costs are utilized for this distance, a total cable cost of over 100 MNOK can be assumed. In addition, this cost will most likely increase because a cable of higher rated voltages, larger cross-sectional area and capacity is required. Shore power may therefore not be relevant if the OAOF is to be placed in area 7. On the other hand, if shore power is established to the area, it could connect more than one offshore industry to the grid, for instance, several fish farms.

The result shows that a shore power connection to Spidercage will have a CAPEX of more than 15 MNOK. However, for a shore power connection from Gjessøya, the additional connection from Blikvær to Spidercage has not been taken into consideration for the calculation of the total CAPEX. This additional cable has to be installed, which will increase the CAPEX. However, if this cable is a low voltage cable with a distance equal to approximately 2 km, at a lower cost per km, this cost will be insignificant compared to the total CAPEX. However, Spidercage can not be placed too far from Blikvær if this assumption is to be applied.

There are several factors that have to be taken into account when dimensioning an onshore power supply system. Some of them have been accounted for in this thesis, but a complete technical analysis should be performed on the basis of the power demand. This includes both a load and short circuit analysis. The necessary equipment can then be chosen on the basis of these analysis. The CAPEX and OPEX can then be analysed for each different electrical component, and further evaluated, in order to optimize the system. This procedure could be more optimal, and more correct, when dimensioning an onshore power supply system. On the other hand, the costs calculated in this thesis may provide a good estimate and indication of which cost range onshore power supply for offshore fish farms will be within.

In addition to cover the power demand of the facilities, shore power can be utilized to supply the aquaculture service vessels with power when operating at the facility. However, it may not be cost efficient for the live fish carrier and fish feed carrier to use shore power, as it may result in a higher peak power at the facility. Further, it can lead to an increased network tariff, as this is determined by the highest power peak of each month. A solution can be to install batteries at the facility, which can be utilized as a peak shaver when the vessels are connected. An advantage of this solution is the potentially reduced CO_2 emissions from the vessels. On the other hand, batteries have a high CAPEX, and thus the cost efficiency of an installation of batteries should be compared to the increased network tariff.

9.7 Shore power hybrid solution

A solution of shore power in combination with batteries was evaluated as it gives the potential to connect to several connection points onshore compared to shore power alone. As the batteries will operate as a peak shaver, it is not required as much available capacity from the grid as for shore power alone, which increases the number of suitable connection points. This can potentially lead to less voltage drops in the existing onshore grid, and it can increase the security of supply to both the fish farm, and to other users of the grid. In addition, as the solution can be designed according to the maximum available capacity in the grid, there is a lower risk for the investment to trigger grid investments.

On the other hand, this solution will only function if the power demand is fluctuating and if there is enough excess power to charge the batteries. When there is not enough excess power, or capacity in the batteries, the diesel generators are used to cover the power demand. This will increase the CO_2 emissions compared to shore power alone.

The shore power hybrid solution might be a more suited solution for an offshore fish farm compared to shore power alone. The shore power hybrid solution has a lower CAPEX compared to shore power alone, mainly due to the cable investments. On the other hand, the solution has a slightly higher OPEX and it emits CO_2, due to the usage of the diesel generator. At the same time, the LCOE is 80 % higher than for shore power, due to the batteries. Shore power hybrid may not be suited for longer distances as this will require a higher voltage cable than the 12 kV cable assumed. The solution will also depend on an island, or land, with grid possibilities nearby, which is rare further offshore. Because of this, shore power alone may be better suited at certain distances.

A hybrid solution combining shore power with battery cabinets and diesel generators, has a low CAPEX compared to some of the other hybrid solutions, as shown in Figure 8.8. However, the CAPEX of the shore power hybrid may be higher than the one calculated. The cable cost may be higher, as it is dependent on the distance from shore and the maximum available grid capacity. In addition, it is assumed four battery cabinets. This number could be increased, depending on the power demand at the fish farm. This could potentially lead to a higher CAPEX than the one presented in the result.

As presented in Figure 8.9, shore power hybrid has the second lowest OPEX compared to the other energy solutions. However, the OPEX may be higher. The maximum available capacity from the grid, 100 kW, is only an assumption and could be lower. At a lower capacity, less off the power demand of Ocean Farm 1 will be covered by the electricity from shore. This means that the battery cabinets will not get the same amount of excess power for charging and the operation time for the diesel generators will be increased. This will lead to a higher diesel fuel cost, and hence lead to higher CO_2 emissions.

There is a large difference in the calculated LCOE for shore power hybrid and shore power alone, as seen in Figure 8.10. However, the LCOE for shore power alone may be higher, as the operation time of the diesel generators has not been accounted for in the calculations. If this was taken into consideration, the results for LCOE might be more similar, as low usage of diesels generators results in higher LCOE. On the other hand, it can be assumed that the LCOE for shore power hybrid would be higher than for shore power despite this. This is due to the batteries included in the hybrid solution having a low life expectancy, compared to shore power equipment, resulting in a high LCOE.

Neither the OAOF nor Spidercage have been evaluated for this solution. However, the solution could be suitable for the OAOF if the facility was located closer to shore, which could result in a low CAPEX and OPEX compared to shore power alone. This solution could also be a suitable option for Spidercage when in operation. The available power at the connection point, at Gjessøya, is low and limited to power peaks equal to 250 kW. It could be more optimal to install batteries in combination with shore power in order to cover the highest peak values. In order for this to work, there has to be enough excessive power from the grid to charge the batteries, which is determined by the power demand of Spidercage.

9.8 Fuel cell hybrid solution

A fuel cell in combination with batteries and diesel generators was evaluated as a suitable solution for offshore fish farms. The fuel cell has a constant capacity, used to cover the demand at the farm in addition to charging the batteries. The batteries are implemented in the solution in order to use the reaming capacity from the fuel cell for each hour sufficiently. The stored energy can further be used for peak shaving and reduce the operation time of the generator, resulting in less CO_2 emissions. It is assumed that the solution is realistic for an offshore fish farm, despite the technology being expensive and difficult to implement.

The thesis only addresses a fuel cell solution at Ocean Farm 1, since this is the only case where local production of hydrogen is planned. With time, it can be expected for hydrogen production and fuel cells to mature and become commercial technologies in Norway. This can allow the technologies to become an alternative energy resource to several of the offshore fish farms. The principle will be the same as presented for Ocean Farm 1.

By doubling the vessel frequency at the farm, the CAPEX can decrease. The scale of the containers can be lower, as hydrogen can be transported more rapidly to the farm. However, larger tanks are cheaper than smaller ones, when looking at the cost per kg. This may be due to all the fixed costs that are embedded to the investment, and have to be paid, despite the size of the tank. A less expensive tank could have been chosen in order to decrease the hydrogen tank CAPEX further. On the other hand, a tank from Hexagon does give a good indication of the current investment cost.

When determining the maximum capacity of the fuel cell, the average energy consumtion over a year was calculated to be 81 kWh at Ocean Farm 1. If there was an infinitely large battery, with no SOC window between 20 and 80 %, then an 81 kWh fuel cell, could have been the most ideal solution. However, this may not be the case, as there are several restrictions, primarily regarding storage on board the fish farm. The capacity was determined by evaluating different capacities in the script. While a 125 kW fuel cell covers 94.7 % of the power demand, a higher or lower fuel cell capacity could have been chosen. A close to 100 % renewable solution could have been achieved with a larger capacity. Despite this, a completely renewable solution could have led to a higher CAPEX and OPEX.

Although the fuel cell has a rather low capacity compared to the oversized wind turbines, the fuel cell covers a larger part of the power demand. This may be due to the hydrogen being a more reliable energy source, compared to the unpredictable wind speed. As the wind turbines do not extract any power from wind speeds under about 4 m/s, several hours through the year are without any renewable energy production. For the fuel cell however, the capacity may be scaled easily to the specific demand at the farm. In this way, surplus power production can be avoided. The capacity can be set by the request to use more or less of the generator.

The CAPEX for the hybrid solution, including four hydrogen containers, is estimated to be around 20 MNOK. The number may seem rather large, but is however an average cost, according to Figure 8.8. The life expectancy of each solution has not been accounted for in this plot. This could, to some extent, give a wrong impression of the cost for each solution.

The OPEX for the fuel cell solution is however rather high, compared to the other solutions. This is mainly due to both the hydrogen fuel and tanks, although they are expected to decrease in the upcoming years. In addition, if a fuel cell hybrid solution is implemented, the cost could be expected to increase. The increased cost may occur due to factors such as transport, loading of hydrogen tanks and manning being excluded from the OPEX calculations.

Even though the fuel cell hybrid solution appears to be cheap compared to other solutions in Figure 8.8, this is not the case for the LCOE, as seen in Figure 8.10. Due to the fuel cell being easily scalable, the capacity of the fuel cell is adjusted in correspondence to the demand at the farm. Hence, the CAPEX may seem lower than some of the other solutions. However, when comparing the LCOE, the fuel cell solution appears to be the most expensive, in terms of costs per energy produced over the life expectancy. In addition, the LCOE could be higher if the investment cost for the hydrogen tanks were included. The costs are however not included as the hydrogen tanks themselves do not produce any energy.

The batteries constitute to the largest part of the overall LCOE. It can be reasonable to think of a solution without batteries, as hydrogen itself is already an energy storage. It can be cheaper to therefore exclude the batteries and rather use a fuel cell and diesel generator. In this way, the fuel cell solution can come out as a better hybrid solution for Ocean Farm 1, compared to the other solutions. In addition, it can save the farm for a lot of space if the batteries are excluded. On the contrary, the reason for adding the batteries, was to keep the fuel cell capacity to a minimum, instead of scaling it in accordance with the largest peak. In addition, by excluding the batteries, the diesel fuel consumption will increase, and the overall solution will be less eco-friendly.

It can be profitable to invest in a fuel cell with a short life expectancy. This will also apply to the lithium-ion batteries. As fuel cells are a new technology, and lithium-ion batteries are constantly developing, it may be possible to invest in a cheap version with a short life expectancy. As the cost of these technologies are falling rapidly, it might be worthwhile to buy a new, cheaper and more developed model a few years later. On the other hand, this can lead to larger battery and fuel cell waste. These technologies may be hard to recycle, and can hence cause larger carbon footprints. As a consequence, a dilemma of being more eco-friendly or cost efficient rises.

As handling of hydrogen can involve a risk, safety procedures must be established in order to implement this solution. It is therefore important for the hydrogen tanks to fulfill the requirements set by the ISO. If other safety procedures are to be applied, this may lead to higher costs. This can be due to additional crew or equipment required. Many companies might consider other energy carries above hydrogen, due to the risks involved. The attitude towards hydrogen can however change, if the technology becomes more commercial. In addition, diesel generators and some of the other solutions considered, might have a high risk when in operation as well.

LH2 was not considered an option in this thesis, as the power demand of Ocean Farm 1 is not high enough for LH2 to be cost efficient. The tanks required for LH2 storage are more expensive than the ones needed for CH2, which would lead to higher total costs. LH2 will only come in handy if a larger amount of stored energy is needed. If a future facility has a higher power demand, this may therefore be an alternative. LH2 is not as commercial as CH2, but can be a more suited option if there is limited storage space. This is due to the energy density being higher for LH2 than for CH2.

9.9 Solar cells hybrid solution

Solar cells were evaluated to take advantage of the spare area at the facilities, in order for the solar cells to cover some of the power demand. Although, the area available at the farms is small, it could start a transition to more renewable operations for fish farms offshore.

Solar power will only have a small contribution to the power demand compared to wind turbines, fuel cell and shore power. As a consequence, the diesel generators need to cover the remaining power demand of 95.7 to 99.0 %, as it was not suitable to install batteries. However, solar power could potentially be a supplementary energy resource during low power demand periods. Fallowing or low power demand periods are during spring or summer for the OAOF, according to Figure 8.12, which fits well with the solar irradiation, as it is high during these periods.

If PV cells are installed over larger areas, as Figure 8.5 and the corresponding figures for case 2 and 3 illustrate, the potential power output will increase, and there might be a need for a storage solution for surplus power. This will lead to an additional investment cost. On the other hand, if there is only surplus power a small part of the year, it might be more profitable with no batteries and only utilize diesel generators for the low solar irradiation periods. However, if the periods of fallowing and low power demand are going to be taken advantage off, batteries are needed. Solar power and batteries could be the only energy resources used during these periods. If a smaller battery capacity was chosen it could have been more suited for these periods, in order to charge more often. On the other hand, this may lead to a higher investment cost.

The areas currently exploitable for installation, are too small to make a substantial difference in the usage of the diesel generator. On the other hand, if the offshore fish farms were located only 1 km from islands, solar cells could be installed on land. This potential area at the islands can make a difference in the diesel fuel consumption. This is, however, dependent on the conditions at the islands, as they might not be suited for a large area of installation. In addition, this will require a subsea cable from the islands to the farms, which may not be profitable. Nevertheless, the solar cells installed on land would have a less expensive installation cost compared to the solar cells customized for offshore conditions. In addition, they would have a longer life expectancy, which again could make a connection from the facility to land by subsea cable profitable.

In this thesis, there are several factors impacting the results considering the solar cells hybrid solutions. This involves the solar irradiation extracted, which had a horizontal angle of 180°. The irradiation could increase if the solar cell angle was optimized. Furthermore, solar cells are more efficient in a cold climate. An offshore PV installation could therefore be more efficient than a land based installation. On the other hand, these advantages might not affect the power output enough to compensate for the high CAPEX and OPEX for offshore PV cells.

The potential power from solar cells were only calculated in theory, and will not reflect upon the actual power output at the facility, where there can occur unknown ambient conditions. Moreover, the advantages considering cold climate and an optimized angle were not considered in the calculations or compared to a land based installation, and how much these advantages would affect the power output will be unknown.

The life expectancy of commercial land based PV cells is 25 years, while it is 10 years for offshore PV cells. To consider a PV cell with a longer life expectancy offshore, the solar cells can be customized. This can reduce a potential cost for a new installation every decade. However, the offshore solar cells might last longer than the life expectancy of 10 years, and the additional cost to customize might not be worthwhile. A longer life expectancy will increase the total power output over the life time. The total power output can also be increased by installing PV cells with higher efficiency. These alternatives will both have an additional cost to the CAPEX for an offshore installation of solar cells.

Regardless of the improvements, the areas for a potential installation are small, and it might not be profitable as the power output will not increase substantially. On the other hand, storms and other ambient conditions may wear out the solar cells fast, or they could be destroyed if they are not customized for offshore conditions. However, solar cells offshore are not very common, and it is therefore difficult to comment if the improvements will withstand the ambient conditions even for an offshore customized solar cell.

The total LCOE for solar cells, including generators, is around 6 NOK/kWh for every case. The LCOE plots can be seen in Figure 8.10 for case 1, and the corresponding figures for case 2 and 3. The total LCOE is relatively low compared to the hybrid solutions of shore power, fuel cell, offshore and onshore wind turbines in case 1. However, it has one of the highest LCOE for both case 2 and 3.

Even though the total LCOE is low compared to the other hybrid solutions, the LCOE is between 2.94 to 3.60 NOK/kWh for offshore solar cells alone, which is high. In comparison with the LCOE of 0.83 NOK/kWh for onshore solar cells, as presented in chapter 5.3, the values for offshore solar cells are approximately four times higher. This may be due to the extra expenses for materials, installations and the distance personnel have to travel for maintenance and installation work.

The CAPEX for offshore solar cells are low compared to other technologies, as seen in Figure 8.8 and the corresponding figures for case 2 and 3. In addition, the OPEX for offshore solar cells are very low compared to the fuel cell technology in case 1, and slightly lower compared to diesel battery and diesel generator alone, as seen in Figure 8.9 and the corresponding figures for case 2 and 3. However, the costs are high in relation to the amount of energy produced, and hence it may not be cost efficient to install solar cells at an offshore fish farm.

The locations for the OAOF and Spidercage might be the most optimal, considering the solar irradiation. This may be due to the midnight sun and colder weather conditions in northern Norway compared to the location of Ocean Farm 1. On the other hand, the polar night will not cause any solar irradiation during winter seasons, when the power demand often is the highest. However, the solar irradiation in the whole country will be low during the winter, and hence not be a very decisive factor.

Floating solar cells were not considered a potential solution for any of the cases. However, floating PV cells are under development and testing for potential offshore operation. If this technology is commercialized it can increase the solar power's contribution to the total power demand at the facility to a reasonable CAPEX and OPEX. Since the PV cells are floating, they will only need a connection to the facility, and hence they can be placed independent of the offshore location for the facility. This can be favorable considering the industry needs to apply for concession before they can build new renewable energy offshore at a specific location, in accordance with the Offshore Energy Act.

9.10 Wind turbine hybrid solutions

Hybrid wind turbine solutions were evaluated due to the vast potential in wind power in Norway. Wind turbine technology, both onshore and floating, has also developed rapidly over the last years, and can be a relevant option in the future as the costs decrease further. An advantage of using floating turbines is that the turbines are placed at sea, away from populated areas, and will not be as exposed to local displeasure as onshore turbines can be. Battery cabinets were included to exploit the surplus power produced of the wind turbines.

The onshore and floating turbines cover a large portion of the power demand, both over 70 % for all the cases. The turbines cover such a large portion of the power demand due to the turbines being oversized for all the facilities, resulting in a great deal of surplus power. This results in the power demand being mostly covered by renewable resources, and the solutions are hence eco-friendly to a large degree. As a consequence, the diesel fuel costs and CO_2 emissions will be reduced, compared to the scenario of only utilizing diesel generators. In addition, the produced power of the wind turbines may be higher in reality, as measurements during some hours were not extracted, and are hence registered as 0 m/s.

The floating turbine hybrid solutions may not be the best options, mainly due to the high CAPEX, as seen in Figure 8.8 and the corresponding figures for case 2 and 3. The high investment cost is primarily caused by the technology currently being immature and not sufficiently developed. In addition, the floating turbine would have to be approved in the area. The areas surrounding the facilities are currently not being evaluated as suitable for offshore wind turbines, according to Figure 5.6, which would make it difficult if these solutions were to be implemented.

The onshore turbine hybrid solutions will have a lower CAPEX than the floating, though higher than all the other energy solutions. This may play a large role in whether the solution is suitable or not, as it may not be cost efficient. A solution can be that the local network company sets up the turbine at Froan or Blikvær. The produced electricity can further be sold from the network company to the fish farms. Since Froan has a rich bird life, an onshore turbine on this island group may not be a possibility, as it most likely will interfere with the ecosystem in the area.

On the other hand, the diesel fuel costs for both of these solutions are relatively low compared to other hybrid solutions, as seen in Figure 8.9 and the corresponding figures for case 2 and 3. However, the OPEX for the turbines in all the cases lead to a high total OPEX for the solutions. The OPEX for the floating turbine is not a precise value, as it was calculated from a ratio between the LCOE for onshore and floating turbines, which will include an uncertainty.

The life expectancy of the turbines are between 20 and 30 years, and both the turbines produce a large amount of power, resulting in a low LCOE, as seen in Figure 8.10 and the corresponding figures for case 2 and 3. Despite this, when including the LCOE of the battery cabinets and diesel generators, the total LCOE becomes one of the highest compared to the other solutions. Only the fuel cell and shore power hybrid solutions have a higher LCOE. This is mainly due to the LCOE of the batteries, as they constitute to a large portion of the total LCOE, because of their short life expectancy.

The life expectancy of the onshore turbine is 20 years, according to NVE, while the floating turbine has a life expectancy of 30 years, according to Equinor. Despite of these values, the onshore turbine may have a longer life expectancy than the floating turbine. This can be due to less mechanical stress, as the weather conditions are often calmer onshore. An onshore turbine will not experience the stress of waves and other factors that a floating turbine must endure. If the onshore turbine was assumed to have a longer life expectancy than the floating, it could have resulted in a lower LCOE for the onshore turbine.

The LCOE values for the turbines presented in the results were specifically calculated for each case. The calculated LCOE for the onshore turbines are very similar to the LCOE for an average wind power plant, given in Table 5.4. The LCOE of the onshore turbine in case 1 is slightly higher, and the LCOE in case 3 is somewhat lower, as shown in Appendix E. This can be caused by the different amount of produced power at the sites. The LCOE is expected to decrease to 0.27 NOK/kWh by 2020, according to NVE. If this is the case, both of the calculated values of LCOE are higher. However, the LCOE calculations are based on a CAPEX from 2017, and may not reflect upon the actual CAPEX in 2020.

The calculated LCOE for the floating turbines are all higher than the LCOE given in Table 5.5. One of the main reasons for this can be the difference in capacity of the turbines. The LCOE given in the table is for a 5.64 MW turbine, while a 2.3 MW turbine is used in all simulations and calculations. However, the LCOE of the floating turbine in case 3 is rather similar to the given LCOE.

The length of the subsea cable for the floating wind turbines is set to be 1 km. Due to depth and variations on the seabed, the turbine will be placed closer to the facility than 1 km. This length was set in order to prevent the subsea cable to account for a large part of the total cost. However, the small distance could lead to noise pollution from the turbine. This can further affect the fish at the farms, which is not preferred. With a greater distance, the cost of the cable will be higher. The CAPEX of the floating turbine is, on the other hand, too large for the additional cable cost to make such a difference of the total cost.

Floating turbine can be placed almost anywhere, and is not dependent on a connection to shore, which is one of the main advantages. Therefore, the turbine can be placed in accordance to the location of the fish farm. This is a possibility as sea depth will not be a delimiting factor. Other energy solutions, such as onshore power supply and onshore wind turbines, will be dependent on a certain distance from shore, to be cost efficient. By using a floating turbine, an increase of the distance from shore may not increase the costs of the solution.

As all the wind speed measurements are taken onshore, the results of the floating turbines will not reflect upon the produced power offshore. The offshore wind speed would probably be higher, as seen in Figure 5.5, resulting in a higher power production. This could further lead to a lower LCOE for the floating turbines, and the solutions being more cost efficient.

A floating turbine can be placed close to the OAOF in all the areas focused on. The CAPEX, OPEX and fuel costs are assumed to be the same for all the areas, even though the calculation of wind power production is only done for area 21. As area 7 is placed further offshore, it might have higher wind speeds than measured near area 21, which would result in higher power production. On the other hand, the floating hybrid solution for area 7 must be able to go longer periods without refilling of diesel fuel, as it most likely will have rougher weather conditions compared to the other areas. This can make it difficult for the aquaculture service vessels to operate frequently at the facility.

Neither the onshore nor floating turbines are dimensioned for the facilities, which results in a large amount of surplus produced power. There are several ways to exploit this power for future projects. A possibility for the onshore turbine of Ocean Farm 1 can be to sell the surplus power to the nearby island group Froan, where the turbine could be placed. The 38 residents on the islands have to receive power, which are currently done by a subsea cable from Frøya. By establishing a micro-grid on the islands, the surplus power from the wind turbine can be sold, and thereby supply the residents. This can be an advantage for Froan, as the existing grid is currently weak. If this is to be implemented for the floating turbine, an additional subsea cable will be needed to the island group from the turbine.

As the island group near Spidercage has no residents, the surplus power will have to be sold to the mainland, at Gjessøya, which will require an additional subsea cable to shore. This will increase the total costs of the solution, though it may resolve the problem of surplus power. This can, on the other hand, strengthen the grid and increase the capacity at Gjessøya.

Another possibility can be to deliver power from the same wind turbine to several fish farms. This is a possibility for both the onshore and floating turbine. All the cases are currently independent units. In the future, if the companies decide to have several units at the same location, a single wind turbine can be able to supply all the facilities with power. The resulting CAPEX can then be reduced, by dividing the investment cost on several farms, similar to a shore power connection of four facilities. This can make the solution of using wind power more cost efficient, as wind turbines of this size are expensive.

On the other hand, placing several facilities near each other can increase the risk of disease infection. Spidercage is going to be placed far from other farms for this exact reason. Considering environmental challenges, it may therefore not be desirable to place several units at the same location.

A third possibility for surplus power can be to charge aquaculture service vessels at the fish farming sites, though this will require a charging point at the locations. This will further lead to additional costs, which are not desirable, as the wind turbines are expensive. The vessels will also have to be directly charged at times with high wind power production, as the battery cabinets only have a capacity of 540 kWh, and will hence not be able to cover both the power demand at the farm and vessels. As wind speed varies throughout the year, this will be hard to plan. A more secure approach can be to invest in more battery cabinets at the facility, which will only be used to charge the vessels. Surplus wind power of such magnitude, for both the onshore and floating turbines, will perhaps be able to charge many battery cabinets.

Surplus wind power can also be used to produce hydrogen, which is planned at Hitra. For the onshore turbines, this can be done at the islands they are to be placed at. The produced hydrogen will be a way to store the surplus energy. The hydrogen can either be sold or stored to be used at the fish farms as an additional fuel in the diesel generators. However, this solution will require hydrogen tanks for storage, which can be expensive and will take up space at the farms. Hydrogen can also be used as a single fuel in an ICE, though this is not optimal. Another option can be to use the hydrogen in a fuel cell.

If implementing hydrogen production from the surplus power of the floating turbines, they will have to transmit the power to shore, using additional subsea cables. For Ocean Farm 1 and Spidercage, this can be a short cable to the nearby islands. Both area 21 and 23 for the OAOF will require a longer cable, increasing the total costs of the solutions. As area 7 is at such great distance from shore, hydrogen production may not be cost efficient in this area. It would require a subsea cable of approximately 100 km, which would significantly increase the total costs of the solution.

The wind turbine of 3.45 MW was chosen due to the costs given in Table 5.4, which only applies to turbines over 3.0 MW. The surplus produced power at Ocean Farm 1 would be less if a smaller wind turbine of 600 kW was utilized, although the usage of the diesel generators would increase three times, as shown in Appendix D. This would further result in a larger amount of CO_2 emissions. On the other hand, the 3.45 MW turbine is oversized in comparison with the power demand of the farm, and the 600 kW turbine can thus be more suited. However, smaller turbines can often be more expensive per kW, as they are not as commercial. It can therefore be more cost efficient with a turbine of a larger scale, if solutions for the surplus power are implemented.

Another solution could have been to install smaller turbines on the facility, dimensioned for the specific power demand of the farms. This could decrease the surplus power, though smaller turbines may not be able to withstand the rough weather conditions offshore. A smaller floating turbine could be impractical, due to high waves and rough weather conditions.

For both the onshore and floating turbine hybrid solutions, nine battery cabinets were chosen for all the cases. This was to exploit as much surplus power as possible. In the solution of a floating turbine in case 2 and an onshore turbine in case 3, the batteries cover a larger portion than the diesel generators. A smaller number of cabinets would lead to higher surplus power and an increased usage of the diesel generators. More usage of the diesel generators would possibly lead to shorter life expectancy and higher CO_2 emissions.

On the other hand, a smaller number of battery cabinets would decrease the total CAPEX for the solution. Three diesel generators are already included in the CAPEX to ensure reliability of supply, thus only the OPEX and fuel costs of the solution would increase with a smaller number of battery cabinets. The LCOE of the diesel generators could decrease, as they would produce more power, which could result in a lower total LCOE. Despite this, the battery cabinets do not constitute a large amount of the total CAPEX, and it may not make a difference if the number of cabinets are reduced.

Bottom fixed turbines were not taken into consideration for any of the cases, as the sea depths exceed what is currently fitting for this technology. The potential area for bottom fixed turbines is too far away from area 23, and was hence discarded. The same potential area is identified by the NDF as an area that can be suitable for offshore aquaculture in the future, as shown in Figure 2.5. An option can therefore be to place the OAOF in this area and utilize a bottom fixed turbine, if this area becomes recommended for offshore aquaculture. This option can be more cost efficient than utilizing floating turbines, as bottom fixed technology is more commercial.

9.11 Further work

To improve the results of the case study some areas of technologies should be further investigated. In addition, some areas are not accounted for in the simulations in this thesis due to lack of information or time, though can be relevant for future facilities. If one of the solutions presented are to be realized, it will require a more thorough investigation than the one presented in this thesis.

Power demand
An hourly power demand resolution does not incorporate short peaks. Therefore, a more detailed data analysis has to be conducted, to prevent the calculated systems from becoming unstable.

In order to understand how a change in investment costs, fuel, demand trend and weather data affect the energy solutions configured, a detailed sensitivity analysis should be conducted.

If aquaculture service vessels are electrified in the future, and a connection to an offshore fish farm becomes profitable, they can have an impact on the power demand of a fish farm. This will require further detailing and analysis to dimension the farm with sufficient technology.

Management system
In this thesis, the management system was constructed in Matlab. If any of the energy solutions are to be implemented, an energy management system is required. This is to monitor and regulate when the different energy elements will be utilized to cover the power demand.

Shore power
If shore power is to be implemented for any of the cases, a complete technical analysis should be performed on the basis of the power demand. The electrical equipment will then be chosen based on this analysis.

A connection from a fish farm to an existing shore power cable is a possibility. This will only be relevant in areas where other offshore industries already exist, and is supplied with power from the mainland grid.

Hydrogen
A redundancy solution can be considered for a diesel generator malfunction or failure of supply vessel to reach the site on time. The backup system can include a 3 m and 185 kg H_2 container. This will be fixed at the farm and be able to cover at least a daily consumption. The container will give an extra investment cost.

It is also interesting for further work to see how an increase in vessel frequency may affect the total cost of hydrogen containers in order to find a more optimal solution.

Floating solar cells
This new and innovative technology can be a more sufficient solution in the future if it evolves and the costs is reduced. Floating PV cells are under development and testing for potential offshore operation. This technology can develop to be commercialised in the future, and potentially increase PV cells contribution to a facility offshore.

Bottom fixed and floating wind turbines
Areas suitable for bottom fixed turbines should be considered for future facilities, as this technology is currently more commercial compared to floating. Floating turbines can be more relevant in the future, when the technology is more commercial, and the costs have decreased.

Wave power
Wave power can be relevant as an energy resource for an offshore fish farm in the future, and can be optimal because of their simplicity. This demands more dedicated research, and a reliable and well developed technology. One solution can be to establish synergies with other offshore industries, which may be advantageous for both planning and technological development.

Synergies
Offshore fish farms can explore the possibility of synergies with cultivation of other species. This can potentially increase the production without increasing the power demand. In addition, offshore fish farms can evaluate cultivation of other species at the farm when in fallowing.

Biofuel
There is a lot of bio waste from fish farms, which can be collected and made into biofuel in the form of liquid or gas. This can possibly replace the diesel fuel used in the diesel generators today, and is a possibility that should be investigated in the future.

10 Conclusion

The aquaculture industry in Norway has to explore new areas in order to increase the production of fish in a sustainable manner. To meet the requirements of the Paris Agreement by 2030, the current and projected offshore fish farms need to emit less CO_2. These farms will also need reliability of supply while being located in exposed areas. The most cost efficient solution will be determined by the lowest LCOE. Both the LCOE and CO_2 emissions combined will give the most suitable solution for the offshore fish farms.

The shore power hybrid solution has a high LCOE, and will depend on grid possibilities nearby, which are rare further offshore. The solution will reduce CO_2 emissions, although it will not be cost efficient due to the additional costs for batteries. Currently, the fuel cell hybrid solution is too expensive as it is a new and emerging technology. Therefore, it is not the most suitable solution for offshore fish farms, even though it is the most eco-friendly of the hybrid solutions presented for case 1.

There is not enough exploitable area at the offshore farms for the solar cells to cover the annual power demand to a large degree. The considered onshore and floating wind turbines are oversized, which lead to high costs and a great amount of surplus power. Therefore, it is not cost efficient to install neither solar cells nor wind turbines. Even though the wind turbines reduce the CO_2 emissions significantly, it is not enough to compensate for the high costs. They will only be suitable if sufficient solutions are implemented to exploit the surplus power.

For Ocean Farm 1, the battery and diesel generator solution has the lowest LCOE. However, the solution does not reduce the CO_2 emissions enough in order to achieve the climate goal of Norway in accordance with the Paris Agreement. This will thus be considered a short-term solution. Shore power alone has a slightly higher LCOE compared to the battery and diesel solution. In addition, it is assumed to not emit any CO_2, which only applies if the solution is to operate without any malfunctions or usage of the diesel generators. The solution will not be cost efficient if the farms are located further from shore than the cases presented in this thesis.

Based on the results, shore power alone is the energy solution with the lowest LCOE for Spidercage and area 21 for the OAOF. Shore power is assumed to not emit any CO_2, and is hence the most suitable solution at these locations. For Spidercage, this solution is more cost efficient compared to their projected energy solution and the diesel generator alone, with regard to CAPEX and OPEX. The battery and diesel generator hybrid solution has the lowest LCOE for case 2 and 3, when disregarding the shore power solution. For the OAOF and Spidercage, the solutions of, respectively, floating and onshore turbines will be the most eco-friendly hybrid solutions.

To summarize, none of the energy solutions are cost efficient compared to the diesel generator alone, with the exception of shore power at Spidercage. Shore power will satisfy the power demand of an offshore fish farm, in the most eco-friendly manner of all the solutions evaluated in this thesis.

All the solutions presented consist of existing technologies, even though some are more developed than others. Some energy technologies will mature and be more relevant in the future. All the results will have an uncertainty, as the power demand for each case is given in an hourly resolution. Further investigation of all the solutions is necessary if they are to be implemented, although the results provide a good basis for possible electrification of offshore fish farms.

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A Additional costs for onshore power supply

Table A.1 gives an overview of the installation cost for different equipment required for onshore power supply. The table does not include the installation cost for the subsea cable.[39]

Table A.1: *Installation cost for onshore power supply excluded cable lay out.[39]*

Installation	**Cost** [NOK]
Termination of cable onshore and fastening point	16 500
Placing of substation offshore	8 500
Laying of cable in generator room	16 500
Fastening point for the cable offshore	16 500
Termination of transformer room	11 000
Commissioning of substation onshore	11 000
Installation of cable board onshore	5 500
SUM	**85 500**

Table A.2 gives an overview of fixed cost for different material and equipment required for onshore power supply.

Table A.2: *Overhead costs for material and equipment.[39]*

Item	**Cost** [NOK]
Estimated cost cable bridges and tightening	20 000
Cable barrel	7 500
Ventilation	7 500
Cable board	27 000
Fitting material	5 000
Discharge stocking	6 000
Termination of cable, per cable	30 000
Cable downlead in mast	5 000
Rating plate	1 000
Earthing/isolating transformer	20 000
SUM	**129 000**

B Description of offshore concepts

13 of the concepts which were given development licences can be placed offshore. Table B.1 and B.2 describe these concepts further with technical description, number of licences and MAB. Both Pipefarm and Reset are still waiting on approval in January 2020.[152]

Table B.1: *Offshore facilities with development licences and technical description.[6, 152]*

Facility	Technical description
Ocean Farm 1	• Independent, semi-submersible unit with rigid steel structure • Number of licences: 8 • MAB: 6 240 tonnes
Havfarm 1 and Havfarm 3	• Independent units with an open, steel frame structure • 1: Stationary anchored from the bow • 3: Dynamic positioning • Number of licences: 21 • MAB: 16 380 tonnes • Energy source: shore power, generator
The Egg	• Closed facility with construction in composite-material • Number of licences: 6 • MAB: 3 120 tonnes
Atlantis	• Continuous submerged facility • Number of licences: 1 • MAB: 780 tonnes
Arctic Offshore Farming	• Semi-submersible unit with rigid steel structure • Number of licences: 8 • MAB: 5 990 tonnes
Produksjonstank	• Semi-closed facility with rigid steel structure • Number of licences: 4 • MAB: 3 120 tonnes
Aqua Semi	• Semi-closed, semi-submersible facility • Number of licences: 4 • MAB: 3 120 tonnes

Table B.2: *Offshore facilities with development licences and technical description.[6, 152]*

Facility	Technical description
Smart Fishfarm	• Overall solution for open sea • Number of licences: 8 • MAB: 6 240 tonnes
Spidercage	• Semi-closed facility with motion compensated fish cage • Number of licences: 4 • MAB: 3 120 tonnes
The Stadion Basin	• Closed, floating basin • Number of licences: 3 • MAB: 1 849 tonnes
Havliljen	• Submersible sea facility • Number of licences: 2
Pipefarm	• Closed, floating facility • Has applied for 9 licences and 7 020 tonnes
Reset	• Facility in sea • Has applied for 10 licences and 7 800 tonnes

C Resistance and reactance values for Cu-cables

Table C.1 shows the resistance, R, and reactance, X, values for Cu-cables at different rated voltage levels and at two different cross-sectional areas. The cross-sectional area $3 \times 25mm^2$ means that three conductors each of a cross-sectional area of $25mm^2$ constitute the conductor material.[169]

The tabulated values are collected from an excel form for calculations of voltage and power loss for cables and lines. The excel form is received from BKK, as a part of an email correspondence.

Table C.1: *Resistance and reactance values for Cu-cables at different rated voltages.[169]*

Rated voltage	**12 kV**		**1 kV**	
Cross-sectional area	R [Ω/km]	X [Ω/km]	R [Ω/km]	X [Ω/km]
$3 \times 25mm^2$	1.200	0.150	0.727	0.082
$3 \times 50mm^2$	0.641	0.130	0.524	0.079

D Comparison of wind turbines

The capacity of the onshore wind turbine used in all simulations and calculations is 3.45 MW. This wind turbine is not dimensioned for any of the fish farms focused on, and results in a large amount of surplus power produced by the turbine. Table D.1 compares a 600 kW turbine with the 3.54 MW turbine. The generator, wind power and batteries are given in percentage of covered power demand in 2019 at Ocean Farm 1. Surplus wind power is given in percentage of total produced wind power.

Table D.1: *Percentage of covered power demand in 2019 of Ocean Farm 1 by a generator, wind power and batteries for the 600 kW turbine and the 3.45 MW turbine. In addition, the surplus wind power as a percentage of total produced wind power.*

	Wind turbine 600 kW	**Wind turbine 3.45 MW**
Generator	36.3 %	12.0 %
Wind power	57.6 %	79.9 %
Batteries	6.12 %	8.08 %
Surplus wind power	62.8 %	93.2 %

E Costs of energy solutions

The following appendix gives a detailed description of the CAPEX, OPEX and LCOE results for each solution for each case.

E.1 Case 1

Table E.1 shows the CAPEX of each energy element used in the energy solutions for Ocean Farm 1. Number 1 is the battery and diesel generator hybrid, 2 is shore power and 3 is shore power hybrid. Further is 4 fuel cell hybrid and 5 solar cells hybrid. Lastly, 6 is onshore turbine hybrid, 7 is floating turbine hybrid and 8 is diesel generator.

Table E.1: *The CAPEX of each energy equipment used in the different energy solutions for Ocean Farm 1.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]	**7** [MNOK]	**8** [MNOK]
Diesel generator	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900
Batteries	3.24	-	1.44	0.720	-	3.24	3.24	-
Shore power	-	33.1	6.34	-	-	-	-	-
Fuel cells	-	-	-	2.63	-	-	-	-
Hydrogen tank	-	-	-	16.0	-	-	-	-
Solar cells	-	-	-	-	0.310	-	-	-
Onshore turbine	-	-	-	-	-	42.4	-	-
Floating turbine	-	-	-	-	-	-	86.4	-
Bidirectional	0.750	-	0.750	0.750	-	0.750	0.750	-
DC/AC	-	-	-	-	0.040	-	-	-
Transformer	0.08	-	0.075	0.075	0.075	0.075	0.075	-
Total CAPEX	**4.97**	**34.0**	**9.51**	**21.1**	**1.33**	**47.4**	**91.4**	**0.900**

Table E.2 shows the OPEX of each energy technology used in all the different energy solutions for Ocean Farm 1, in addition to fuel costs.

Table E.2: *The OPEX of each energy equipment used in the different energy solutions for Ocean Farm 1.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]	**7** [MNOK]	**8** [MNOK]
Diesel generator	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Diesel fuel	1.48	-	0.132	0.068	1.63	0.202	0.338	1.66
Batteries	0.090	-	0.040	0.020	-	0.090	0.090	-
Shore power	-	0.514	0.372	-	-	-	-	-
Fuel cells	-	-	-	0.079	-	-	-	-
Hydrogen tank	-	-	-	0.320	-	-	-	-
Hydrogen fuel	-	-	-	2.70	-	-	-	-
Solar cells	-	-	-	-	0.003	-	-	-
Onshore turbine	-	-	-	-	-	1.07	-	-
Floating turbine	-	-	-	-	-	-	1.19	-
Total OPEX	**1.60**	**0.554**	**0.574**	**3.22**	**1.66**	**1.39**	**1.65**	**1.69**

Table E.3 shows the LCOE of each energy technology used in all the different energy solutions for Ocean Farm 1.

Table E.3: *The LCOE of each energy equipment used in the different energy solutions for Ocean Farm 1.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]	[NOK/kWh]
Diesel generator	2.20	-	3.54	4.88	2.50	3.14	2.82	2.49
Batteries	1.19	-	11.1	10.8	-	8.49	8.35	-
Shore power	-	3.40	1.16	-	-	-	-	-
Fuel cells	-	-	-	4.39	-	-	-	-
Solar cells	-	-	-	-	2.94	-	-	-
Onshore turbine	-	-	-	-	-	0.394	-	-
Floating turbine	-	-	-	-	-	-	1.23	-
Total LCOE	**3.39**	**3.40**	**15.8**	**20.7**	**5.44**	**12.0**	**12.4**	**2.49**

E.2 Case 2

Table E.4 shows the CAPEX of each energy element used in the energy solutions for the OAOF. Number 1 in the table is the battery and diesel generator hybrid, 2 is shore power for area 21 and 3 is shore power for area 23. Further is 4 solar cells hybrid and 5 floating turbine hybrid. Lastly, 6 is diesel generator.

Table E.4: *The CAPEX of each energy equipment used in the different energy solutions for the OAOF.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]
Diesel generator	0.600	0.600	0.600	0.600	0.600	0.600
Batteries	3.24	-	-	-	3.24	-
Shore power	-	22.0	31.9	-	-	-
Solar cells	-	-	-	0.438	-	-
Floating turbine	-	-	-	-	86.4	-
Bidirectional	0.750	-	-	-	0.750	-
DC/AC	-	-	-	0.040	-	-
Transformer	0.075	-	-	0.075	0.075	-
Total CAPEX	**4.67**	**22.6**	**32.5**	**1.16**	**91.1**	**0.600**

Table E.5 shows the OPEX of each energy technology used in all the different energy solutions for the OAOF, in addition to fuel costs.

Table E.5: *The OPEX of each energy equipment used in the different energy solutions for the OAOF.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]
Diesel generator	0.020	0.020	0.020	0.020	0.020	0.020
Diesel fuel	0.781	-	-	0.881	0.131	0.920
Batteries	0.090	-	-	-	0.090	-
Shore power	-	0.252	0.267	-	-	-
Solar cells	-	-	-	0.004	-	-
Floating turbine	-	-	-	-	1.03	-
Total OPEX	**0.891**	**0.272**	**0.287**	**0.905**	**1.27**	**0.940**

Table E.6 shows the LCOE of each energy technology used in all the different energy solutions for Ocean Farm 1.

Table E.6: *The LCOE of each energy equipment used in the different energy solutions for the OAOF.*

	1 [NOK/kWh]	**2** [NOK/kWh]	**3** [NOK/kWh]	**4** [NOK/kWh]	**5** [NOK/kWh]	**6** [NOK/kWh]
Diesel generator	2.23	-	-	2.66	3.69	2.65
Batteries	2.28	-	-	-	8.45	-
Shore power	-	4.03	5.60	-	-	-
Solar cells	-	-	-	3.60	-	-
Floating turbine	-	-	-	-	1.39	-
Total LCOE	**4.51**	**4.03**	**5.60**	**6.26**	**13.5**	**2.65**

E.3 Case 3

Table E.7 shows the CAPEX of each energy element used in the energy solutions for Spidercage. Number 1 in the table is the battery and diesel generator hybrid, and 2 is shore power. Further is 3 solar cells hybrid and 4 onshore turbine hybrid. Lastly, 5 is floating turbine and 6 is diesel generator.

Table E.7: *The CAPEX of each energy equipment used in the different energy solutions for Spidercage.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]
Diesel generator	0.600	0.600	0.600	0.600	0.600	0.600
Batteries	3.24	-	-	3.24	3.24	-
Shore power	-	15.8	-	-	-	-
Solar cells	-	-	0.233	-	-	-
Onshore turbine	-	-	-	40.3	-	-
Floating turbine	-	-	-	-	86.4	-
Bidirectional	0.750	-	-	0.750	0.750	-
DC/AC	-	-	0.040	-	-	-
Transformer	0.075	-	0.075	0.075	0.075	-
Total CAPEX	**4.67**	**16.4**	**0.948**	**45.0**	**91.1**	**0.600**

Table E.8 shows the OPEX of each energy technology used in all the different energy solutions for Spidercage, in addition to fuel costs.

Table E.8: *The OPEX of each energy equipment used in the different energy solutions for Spidercage.*

	1 [MNOK]	**2** [MNOK]	**3** [MNOK]	**4** [MNOK]	**5** [MNOK]	**6** [MNOK]
Diesel generator	0.020	0.020	0.020	0.020	0.020	0.020
Diesel fuel	2.17	-	2.22	0.131	0.276	2.24
Batteries	0.090	-	-	0.090	0.090	-
Shore power	-	0.571	-	-	-	-
Solar cells	-	-	0.002	-	-	-
Onshore turbine	-	-	-	1.48	-	-
Floating turbine	-	-	-	-	1.70	-
Total OPEX	**2.28**	**0.591**	**2.42**	**1.72**	**2.09**	**2.26**

Table E.9 shows the LCOE of each energy technology used in all the different energy solutions for Spidercage.

Table E.9: *The LCOE of each energy equipment used in the different energy solutions for Spidercage.*

	1 [NOK/kWh]	**2** [NOK/kWh]	**3** [NOK/kWh]	**4** [NOK/kWh]	**5** [NOK/kWh]	**6** [NOK/kWh]
Diesel generator	2.13	-	2.21	3.39	2.79	2.21
Batteries	0.862	-	-	7.87	7.45	-
Shore power	-	1.41	-	-	-	-
Solar cells	-	-	3.14	-	-	-
Onshore turbine	-	-	-	0.302	-	-
Floating turbine	-	-	-	-	0.940	-
Total LCOE	**2.99**	**1.41**	**5.35**	**11.6**	**11.2**	**2.21**

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Electrification of offshore fish farms

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