UiT The Arctic University of Norway

Faculty of Science and Technology

Modeling and simulation of power and energy demands to dimension an alternative energy supply for the aquaculture industry

Use of OpenModelica to develop an applicable simulation model for the energy and power demands

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Øyvind Hokland

Master's thesis in Technology and Safety in the High North…TEK-3901…July 2020

Preface and acknowledgement

This thesis concludes my Master of Science degree in Technology and Safety in the High North at the Faculty of science and technology, UiT – The Arctic University of Norway. This master's thesis was completed during the spring of 2020.

I wish to thank my main supervisor Dr. Karl Gunnar Aarsæther for valuable assistance and discussions about the thesis and research along the way, my secondary supervisor Prof. Mohamad Mustafa for valuable knowledge regarding hydrogen fuel cells and battery technology and Tore Håkon Riple, at Marine Construction, for supplying valuable data regarding power and energy consumption from a selection of feed barges. I also wish to thank my fellow students, family and friends for continuous support and motivation.

Øyvind Hokland

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Abstract

The purpose of the research is to investigate whether feed barges currently running on diesel generator can be powered by alternative energy sources where power from shore is limited. Through data collection, several models are developed in OpenModelica to represent the power and energy distribution on a feed barge. Using the Power Systems library provided in OpenModelica, it has offered benefits of modeling complex power systems put together by several simpler models. User-friendly, preset components from the Power Systems library provides simplicity for that matter. A diesel and battery-electric model is developed to dimension the battery to account for different power strategies throughout a production cycle for the farmed fish. The result from dimensioning of the battery provide some clues on how to dimension alternative energy providers to replace the diesel generators.

Variations in the power consumption makes feed barges a good candidate for hybridization with a battery as an energy buffer to either shave the power peaks or used as a source to cover the base loads. By utilizing batteries, alternative energy sources and carriers are made available in order to reduce emissions from diesel generators.

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Nomenclature

CO_2	=	Carbon Dioxide
FC	=	Fuel Cell:
GH_2	=	Gaseous Hydrogen
g	=	Grams
GWh	=	Giga watt hours
H_2	=	Hydrogen
H_2O	=	Water
HFO	=	Heavy Fuel Oil
ISOC	=	Initial state of charge
kg	=	Kilograms
kWh	=	Kilo watt hours
LH_2	=	Liquid Hydrogen
LNG	=	Liquid Natural Gas
LOA	=	Length Over All: Used in ship geometry
MGO	=	Marine Gas Oil
MAB	=	Maximum Alloved Biomass
MWh	=	Mega watt hours
O_2	=	Oxygen
PMS	=	Power management system
PEMFC	=	Proton Exchange Membrane Fuel Cell: A common type of fuel cell
RPM	=	Revolutions per minute
SOC	=	State of charge
TWh	=	Terra watt hours

1 Introduction

1.1 Background

Modern aquaculture locations consist of fish cages collocated with a feed barge. The feed barges purpose is to deliver feed to the fish cages through a feed distribution chain, which connects feed silos on the barge with feed spreaders in the cages. The distances from the barge to the cages can range up to 1000 meters and the feed is therefore transported from barge to spreader through pipes with pressurized air. The compressors used to compress the air in the feed system is the largest consumer of electrical power on the barge.

Production locations for aquaculture are distributed along the coast and placed where there are good conditions for water exchange and sheltered weather conditions but not necessarily close to infrastructure and electric power from shore. Diesel generators are therefore a common power source on-board the feed barges, and they are dimensioned to deliver the required power during feeding, even though feeding takes place during short periods each day.

To reduce greenhouse gas emissions related to aquaculture, it's necessary to substitute the energy requirement which today is delivered by diesel generators. Some feed barges are powered by electricity from shore where this is possible, but one can also imagine other energy storage or carriers on-board the feed barge. To consider different solutions one needs information about the power and energy consumption on the feed barges, and how the power is distributed between the different consumers onboard. This gives the base for modeling and simulation of the whole feed barge energy system.

1.2 Objective

The objective of this thesis is to develop an applicable simulation model of the energy and power system on a feed barge. The purpose of this is to investigate how the feed barges currently running on diesel generators can be powered by alternative energy sources where power from shore is limited.

The objective will be achieved through the following methods:

- Data collection and analysis: Gather data from current aquaculture locations regarding power and energy consumption throughout a period. Perform the necessary analysis of this data for the ability to utilize this data to develop a simulation model.
- Numeric modelling: A simulation model will be developed to simulate the behaviour of the power and energy consumption on a feed barge. Criteria to be taken into account is the locations biomass capacity, the stage of the fishes' life cycle, the water temperature, power for heating on the barge, general hotel power for daily operation and power from cage lights.
- Dimensioning of a hybrid energy system: Dimension a battery to a desired size to cover loads in specified power consuming scenarioes on the barge, then calculations on fuel consumption from generators are executed for the ability to dimension alternatives for the diesel generators.
- Case study: Perform a case study on a specific sparsely populated location. The area will be simulated with all nearby aquaculture locations connected to the distribution power grid, using the same criteria as from the numerical modelling.

2 Aquaculture from a technical point of view

Aquaculture or fish farming is a way of feeding farmed fish to a specific size required on demand. Ocean-based fish farming occurs most commonly in open fish cages where the fish is separated from the external environment with nets (Misund, 2019). Aquaculture is an industry based on production licenses, meaning that the proprietor gets an exclusive license to operate on general public area. It is stated that the proprietor at all times follows the authorities' terms and conditions concerning the operation and general value creation. Breeding permissions on popular farmed fish like salmon, trout, and rainbow trout is limited to quantity, which means that it's allocated when the ministry decides. This is since farmed fish like those have a high demand and the ministry, therefore, controls the growth for the environment and market. Maximum allowed biomass (MAB) is delimited on two levels; company and location level. This means that at any point in time the company's current standing biomass cannot exceed the company's MAB, and each location can't exceed its determined MAB.

An aquaculture location can contain several fish cages at once depending on the location and the company's license. The primary source of feeding the fish is with a feed barge. A feed barge is customized to meet the requirements of the aquaculture location. The customization of the barges ensures that it can withstand the local weather and sea conditions and sized to meet the buyers' requirement regarding feed capacity and the feed systems power demands.

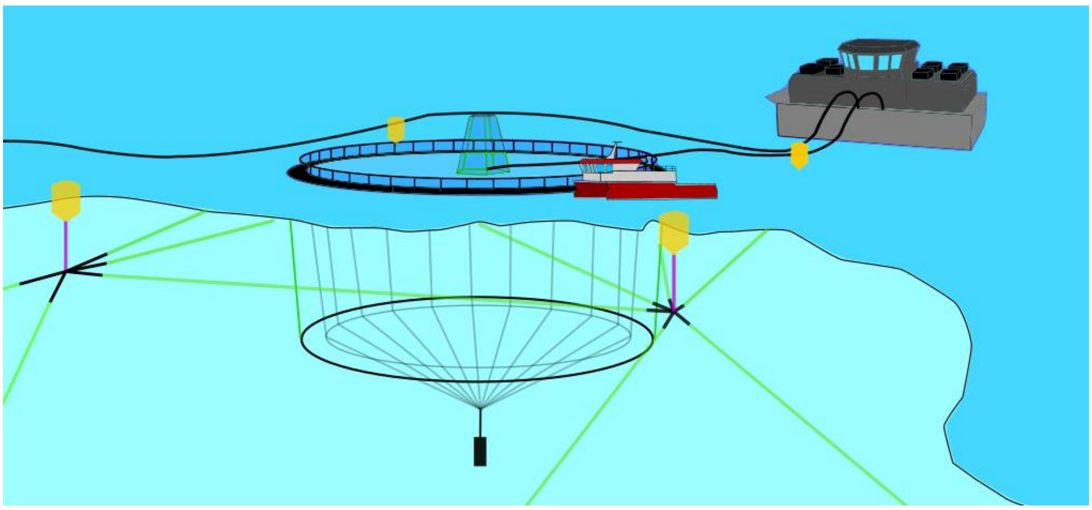

Figure 2.1 Illustration of the basic installations on an aquaculture location

Figure 2.1 illustrates how a typical aquaculture location is assembled. The location includes the feed barge itself, which main purpose is to supply feed to the fish cages through feeding pipes. In the middle of the cage a rotor spreader is in place to evenly distribute feed in the fish cage. The fish cages are supported with mooring lines, shown as green tensioned lines with yellow floating buoys marking the connections between the mooring lines. At the bottom of the fish cage a center weight is placed together with a bottom ring weight to maintaining the volume of the fish cage.

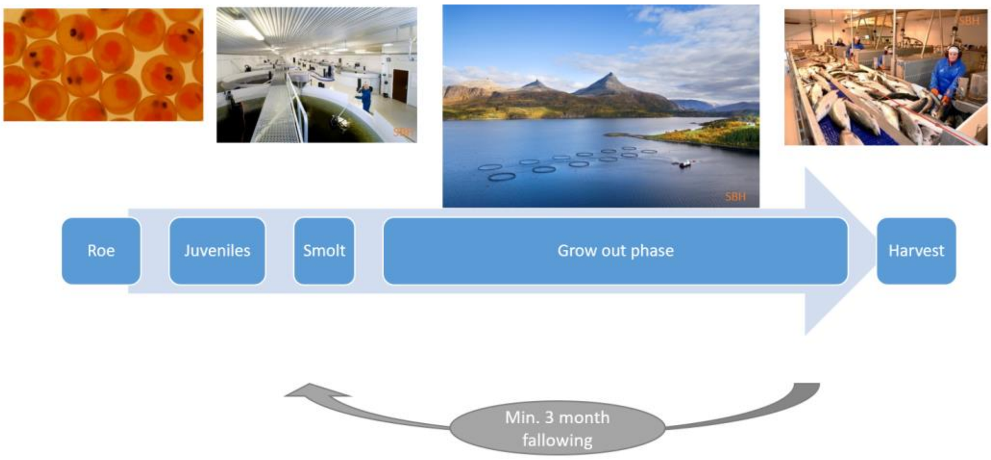

Figure 2.2 The fish's production cycle (SinkabergHansen, u.d.)

Ocean based aquaculture is a part of a larger production process which begin at land-based facilities. Figure 2.2 shows the fish's production cycle. The first part of the fish's production cycle takes place in a hatchery where roe and milk are mixed to get fertilized eggs. This may happen at a single facility but breeding and fertilization is often done in separate and specialized plants. Farming of juveniles is done indoors in fresh water. The fish eggs are stored in tubs and hatched after a certain number of days. The first period in the life of the juveniles, they breed of a plum bag on its stomach. After a while they are big enough to eat regular dry feed, and later enters a stage of "smoltification" where they are accustomed to saltwater and are called smolt. The fish then ready to live in salt water and can be put out in fish cages, and enters the so called grow out phase (SinkabergHansen, u.d.). When the fish enters the grow out phase the weight is in the region of 75g to 200g depending on growth strategy for the individual production firms. The grow out phase lasts about 14 - 18 months, dependent on growth conditions, before the fish is ready to be harvested from the ocean-based aquaculture site and transported to at a slaughter and processing plant. At the end of the production cycle the fish is ideally around 5kg, while some sites may grow the fish to 6kg for specialized whole-fish products for the Asian market. There is a minimum requirement of 3 months before the aquaculture location can put fish back in the fish cages. This is called fallowing, and is a proven way to avoid diseases and lice on the fish farm where the fish cages are emptied and cleaned (Lovdata, 2008). Total production time from roe to harvest is about 18 – 24 months.

2.1 Sea based aquaculture facilities

Sea based aquaculture facilities contain the feed barge which contain the power production, or distribution in case of shore power connections, and the main consumers. The cages on the site are connected to the feed barge in the case of power requirements. However, a number of vessels are used to support the grow-out phase which expand the energy requirement for sea-based aquaculture beyond the feed barge. The feed barge remains the main consumer of energy and is the only continuously operating equipment. The feed barge and aquaculture support vessels will be presented below to show the different capacities of power and energy demands in sea-based aquaculture.

2.1.1 Feed barges

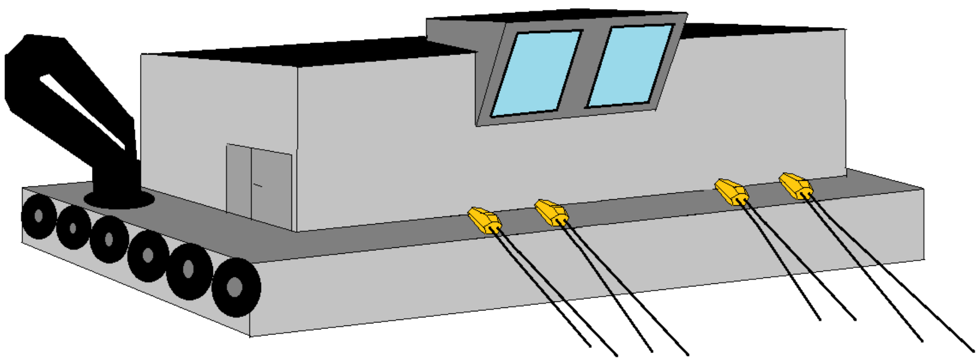

Figure 2.3 Simple illustration of a feed barge with 4 feed selectors

A feed barges purpose is to ensure safe, efficient and beneficial feed of the fish at the aquaculture location. A feed barge is a floating construction located either inshore or offshore and must withstand rough sea and weather to ensure the workers a safe work area.

Each feed barge is custom made to meet the customers' requirements, whether located in tropical waters or the arctic. Feed barges come in a variety of sizes depending on the size of production at the aquaculture location and how it should handle the locations' sea and weather conditions. The feed barges feed capacity ranges from about 100 tons up to 850 tons depending on the requirements (AKVA group, 2019). Installations onboard include safety equipment, silage systems for handling dead fish, feed silos and dosage systems, feed transport to cages, generators, cargo handling equipment, surveillance room, living quarters, cameras and sensor systems to guarantee full control of the operations at the location.

2.1.2 Primary power consumers on feed barges

The primary power consumers on feed barges are the pneumatic conveying system used to distribute feed to the cages, drive the feed rotor spreaders and base loads from auxiliary functions on the feed barge. Sea cage lighting is an auxiliary base load since high powered lighting is used during the winter months, adding a considerable base load which is only active for approximately 50-60% of the year.

2.1.2.1 The pneumatic conveying feed system

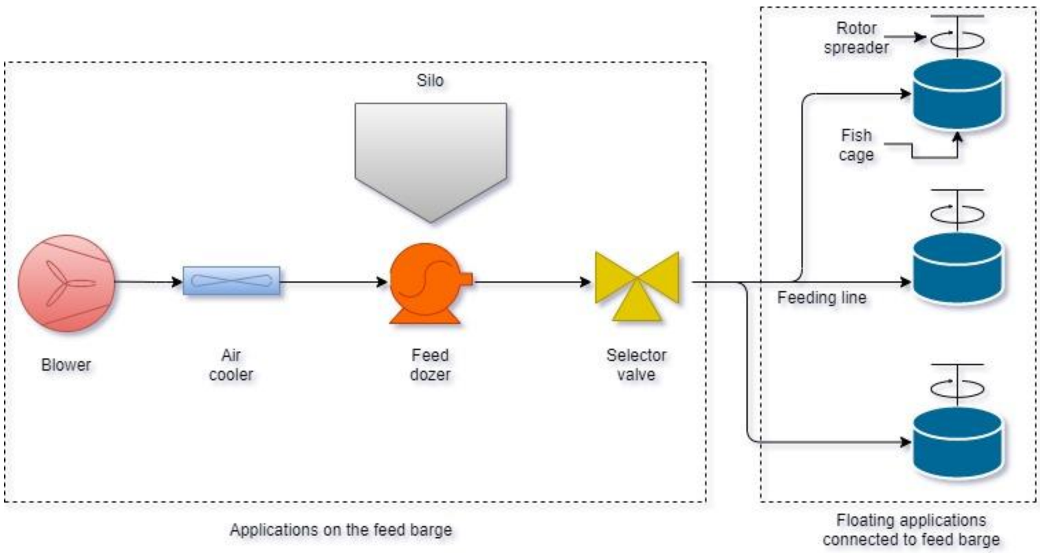

Figure 2.4 Basic principles of the pneumatic conveying feed system

The primary consumer of power, the feed system, follows the principles of a pneumatic conveying system, simply illustrated in Figure 2.4. A pneumatic conveying system utilizes the technique of gas under pressure to transport granular solids in pipes. The system is characterized by four recognizable zones which are a necessity for the entirety of the system. Describing the four zones as follows.

Prime mover: The prime mover is the element in a pneumatic system which provides the system with the required gas pressure. These pressure sources are named feed blowers in aquaculture. The blowers supply the feed lines with the required system pressure and are known as the largest consumer of energy in the feed system.

With increasing pressure follows an increase in temperature. Assuming the compression to be adiabatic and the volume to be constant, the temperature rise during the compression follows the equation:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k} \quad (1)$$

Where T_1 and T_2 are the input and output temperature values, p_1 and p_2 are the input and output pressure values, and k is the specific heat ratio (Klinzing, Rizk, Marcus, & Leung, 2010).

It is, therefore, necessary to cool the air before mixing it with the feed. Cooling takes place to reduce damage on the feed itself due to high temperatures which dissolve the fats in the feed. In order to avoid damaged feed, an air cooler is used. The air cooler has an inlet port, an outlet port and in between the ports, a loop ensures that the seawater extracts heat from the air.

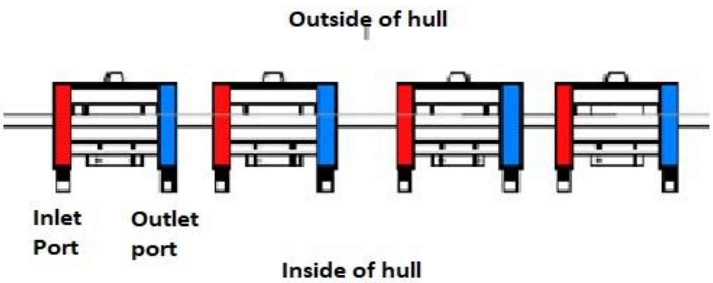

Figure 2.5 Cooler loops as seen from above

Figure 2.5 shows an image of four air cooler loops. The part in red displays the hot air inlet and the blue part displays cooled air in the outlet port. This approach follows an isobaric process, meaning that the pressure is constant at the inlet and outlet ports. The following equation describes the theoretical behavior of this process:

$$PV = nRT \quad (2)$$

Where *P* is the pressure, *V* is the volume, *n* is the number of moles in the gas, *R* is the universal gas constant which is 287 $\frac{J}{kg\ K}$ for air and *T* is the gas temperature (Cengel & Boles, 2015). The air temperature prior to the cooling loops is typically about 100-120C and the acceptable gas temperature for mixing transport gas and feed pellets is about 10-20C.

Mixing and acceleration: After the air has been pressurized and cooled down to an acceptable temperature, feed is added into the flowing air stream. This process is considered as a critical stage in the system. The reason for this is because the feed at rest added into the flowing air stream causes a significant change in momentum. In order to deal with the change in momentum, an acceleration zone is present, as shown in Figure 2.6. The required length of the acceleration zone is dependent on the size of the feeder, the solids, and the system conveying pressure (Klinzing, Rizk, Marcus, & Leung, 2010). The acceleration zone can be seen in feed barges as long straight pipe sections immediately after mixing of transport gas and solid.

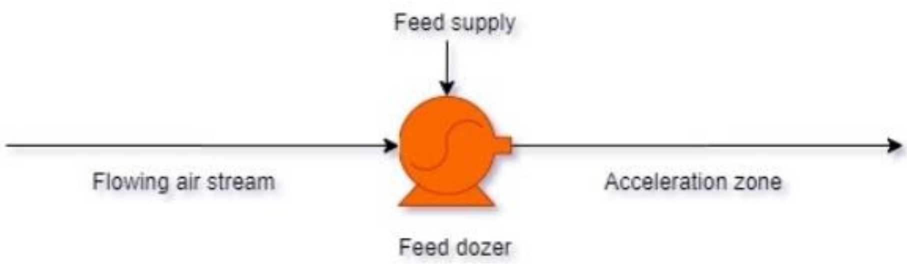

Figure 2.6 Illustration of the acceleration zone after the feed dozer

Conveying zone: After leaving the acceleration zone, the pressurized air-feed mixture passes through a selector valve. The selector valve is responsible for distributing the feed to the desired fish cage. Depending on the choice of the selector valve, it can connect up to 60 feed pipes (AKVA group, 2019). Between the selector valve and the separation of the mixture in the fish cage, there is a conveying zone. The conveying zone consists principally of piping which can travel up to 1500 meters. The longer the conveying zone is, the higher the pressure loss becomes, and the prime mover is sized accordingly. The conveying zone is also characterized by several bends that contribute to pressure loss in the flow due to deceleration of the gas-solids mixture (Klinzing, Rizk, Marcus, & Leung, 2010).

Gas-solids separation zone: The separation between the transport medium and solids differ between regular pneumatic conveying systems and pneumatic aquaculture feed delivery systems. The transport medium is discarded and used to propel both the solid and the rotary feed spreader.

When the gas-solids mixture has reached the end of the conveying zone in the fish cage, the rotary feed spreader distributes the feed uniformly over the water surface. Technically speaking the gas and the solids are separated from each other where the gas releases into the atmosphere and the gravitational forces cause the solids to spread into the fish cage.

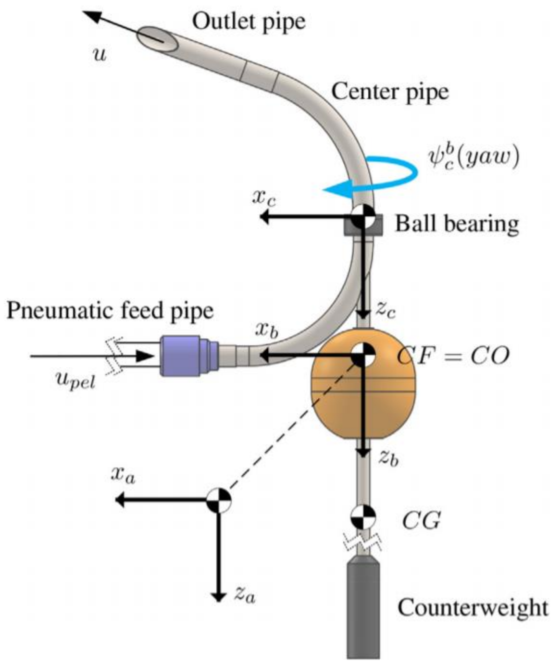

Figure 2.7 Principles of a rotary feed spreader (Skøien, Alver, & Alfredsen, 2017)

The spreader is attached to a floating buoy and is held upright with a submerged counterweight placed beneath the buoy, as seen in Figure 2.7. The spiral geometry of the outlet pipe along with a ball bearing enables the spreader to rotate when the air pressure in the pipe is present (Skøien, Alver, & Alfredsen, 2017).

Advantages and disadvantages: Some advantages and disadvantages characterize such a pneumatic system. It allows for dust-free transportation directly from the silos, and it does not require many human resources to operate, convenient distribution of solids (feed) to different fish cages at the location and has low maintenance. Some disadvantages in the system are the high power consumption leading to high fuel consumption and huge power variations in the transition between regular operation on the barge itself and hours of feeding (Klinzing, Rizk, Marcus, & Leung, 2010).

System	CCS-32	CCS-63	CCS-90	CCS-110
Feed pipe size	32 mm	63 mm	90 mm	110 mm
Wall thickness	2,9 mm	4 mm	7 mm	6,3 mm
Feed data				
Pellet size	5-7	9-12	17-25	25+
Max. Feed capacity [kg/hour]	648	2520	5220	5220
Max. feed rate [kg/min]	10,8	42	87	87
Min. feed rate [kg/min]	1,2	2,4	3	3
Transport lengths				
Max. Pipe length	300	600	800	1400
Maks. feed rate with max. Pipe length [kg/min]	3,6	12	10	30
Power consumption				
Feed blower	7,5	15-18,5	22-30	45
Selector valve	0,18	0,18	0,18	0,18
Feed dozer	0,37	0,37	0,75	0,75
Screw/sluice	1,5	1,5	1,5	1,5

Table 2.1 Specification of the CCS feed systems from AKVA group whereas the blue column is the applied system for this thesis (AKVA group, 2019)

Table 2.1 shows the four conveying system specifications belonging to AKVA group. The Akvasmart CCS-90 system, highlighted in light blue in table 2.1, is broadly used and will also be considered as the base system for this project. The CCS-90 system is characterized by a feed pipe size of 90 mm and depending on the composition of components on the barge itself, it will have blowers with power consumption ranging from 22 – 30 kW. The pipe size and the capacity of the blowers are the dimensioning components, and then the feed dozer is sized accordingly. However, depending on the pipe length, the available feed rate will vary. For the CCS-90 system, the maximum feed rate is 87 kg/min. Assuming that the maximum feed rate is close to the barge, the feed rate at the maximum pipe length at 800 m is 10 kg/min. The reason for the loss in feed rate is mainly to overcome the saltation velocity. Saltation velocity in pneumatic conveying systems is when the solids starts to settle at the bottom of a horizontal pipe. This means that in all parts of the pipe, the conveying velocity must overcome the saltation velocity. The loss in feed rate over pipe length is caused by friction between the air-feed mixture and the internal pipe walls and occurring pipe bends which cause a change in momentum.

2.1.2.2 Power demands of hotel, underwater cage lights and heating

Where the feed power contributes to the highest peak power, there is a significant contribution to the total energy consumption from other power consumers as well. These consumers are categorized as hotels, underwater lights, and heating. The hotel load takes care of electricity which is used by different items, such as televisions, computers, chargers, lighting and surveillance equipment. Underwater lights are installed to delay the sexual maturing of the fish and to provoke their appetite during periods of darkness throughout the year. Usually, the lights are turned on in October and turned off in April. Heating refers to the general heating of the feed barge itself including heating of water and heating of technical areas and work and living space.

Lights for a single site may consume upward to 30 kW of power alone as a constant load when in periods of activation. Later on, in the chapter covering numerical modelling in Section 4.2, the measured power from lights is found to be 1,8 kW per fish cage from collected power consumption data from operational feed barges. Lights are installed in the individual cages and the total power from lights will depend on how many cages a location has available.

2.2 Aquaculture support vessels

There are different types of aquaculture support vessels, and they are designed with respect specialized assigned tasks. Typically, those tasks include transport of live fish, delivery of feed, delousing, an inspection of cage nets and underwater equipment and transport of people and equipment. The support vessels contribute to the total energy consumption related to the operation of an aquaculture location. In the following subchapters, the most common support vessels will be summarized here.

2.2.1 Live fish carriers

Typical live fish carrier

	Value	Unit
LOA	60	m
Displacement	2500	ton
Main engine	2000	kW

Table 2.2 Data from modern live fish carriers

A live fish carrier is characterized as a unique vessel for transportation of live fish across far distances. These vessels have onboard tanks, or wells, which circulate fresh seawater, so that live fish, typically salmon or trout, can be transported from an aquaculture location to a fish processing plant. The circulation of seawater happens due to the forward speed of the vessel. In the fore of the well, an inlet port lets fresh seawater pass through and mix with the fish. In the aft of the well, there is a valve, enabling the seawater to pass out of the well causing a circulation of fresh seawater. Some vessels may transport live fish in closed wells for parts of the voyage. In order to ensure excellent quality of seawater in the wells, Oxygen is pumped into the wells. Carbon dioxide is therefore filtered out with a water aerator, which separates CO2 from the water.

Figure 2.8 Illustration of a live fish carrier

From Figure 2.8 an illustration of a live fish carrier is represented. Typical live fish carriers have a loading capacity of 1800-2500 m^3 equivalent to up to 300 tons of live fish and available engine power of up to 2500 kW at 1000 rev/min.

Live fish carriers are the most power-consuming vessel that visits the aquaculture location. The first interaction with the live fish carrier happens while transporting smolt to the aquaculture location. When the smolt has grown to harvestable fish after about 18 months in saltwater, the live fish carrier will transport the fish to a fish processing plant. However, in between the stages of smolt to grown harvestable fish, there will be internal sorting by size, splitting of fish from one to several cages and delousing, which require interaction with a live fish carrier. Internal sorting is done to ensure similar weights in the different fish cages. Internal sorting is known to increase growth and reduce sickness (Rostein, u.d.).

2.2.2 Feed vessels

Typical feed vessel		
	Value	Unit
LOA	80	m
Displacement	5700	ton
Main engine	2100	kW

Table 2.3 Data from modern feed vessels

A feed vessel is characterized as a unique vessel for the transportation of pelletized feed. The feed vessels get their cargo at designated feed factories, either carried in bulk or bags depending on how the vessel function. When carried in bulk, the feed unloads to the feed barge with help of a pneumatic conveying system similar to feed barges.. When carried in bags, the bags are ripped open so that the feed falls down a tray and transports directly into the silos on the feed barge. It is also possible to unload bags with a crane to quay and then transport it with another service vessel to the feed barge.

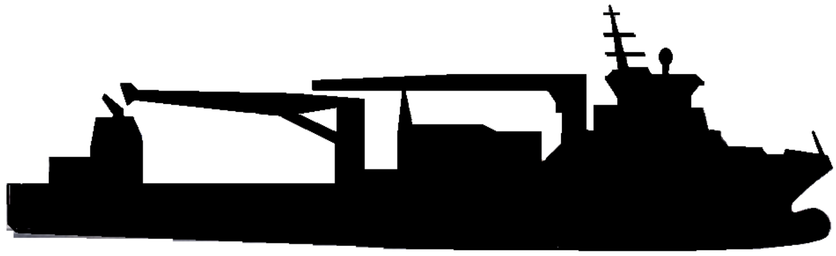

Figure 2.9 Illustration of a feed vessel

The frequency of visits to aquaculture locations by feed vessels depends on the current stage in the fish's life cycle. Assuming that the required daily feed is 1% of the available biomass at the location, the frequency of visits will continuously increase throughout the fish life cycle. For example, a location with a biomass capacity of 6000 tons will have to feed about 60 tons each day which results in 420 tons per week. With a feed on barge capacity ranging from 100 tons up to 850 tons (AKVA group, u.d.) the feed vessel will have to visit the location around 1 to 3 times a week in the last stages of the production cycle. For a location with a biomass capacity like this, a 100-ton capacity feed barge would not be a suitable option as the feed storage capacity is too small.

Feed vessels, almost exclusively, are always in transit. That means they continuously move between a selection of aquaculture locations and feed plants. A movement pattern of 3 feed vessels over 30 days in the spring of 2017 is shown in Figure 2.10 below.

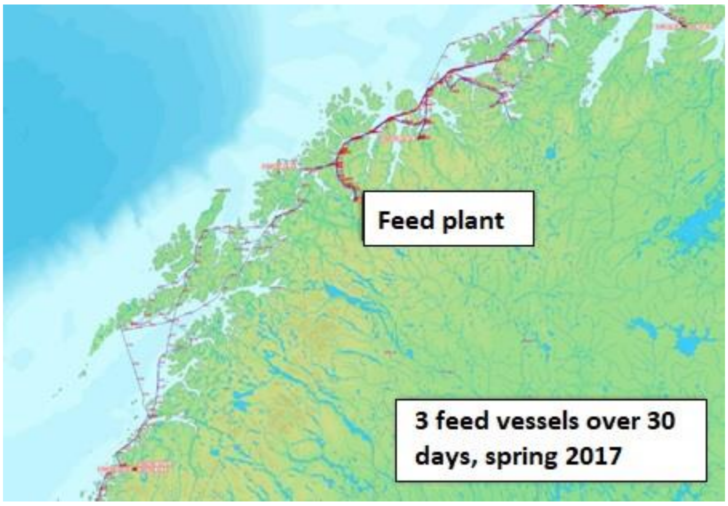

Figure 2.10 Movement patterns for three feed vessels over 30 days in the spring of 2017. Gathered from AIS data of the Norwegian Maritime Authority.

2.2.3 Workboats

Work boats (15 m catamarans)		
	Value	Unit
LOA	14,99	m
Displacement	30	ton
Main engines	2 x 300	kW

Figure 2.11 Data from modern 15 m catamarans used in aquaculture

Workboats associated with aquaculture locations contribute to the daily operations on the fish farms. Such operations include smaller crane operations, assisting live fish carriers collecting fish from the cages, transport of humans and equipment, and general inspection of equipment on the location. Typical tasks would be cleaning and inspection of cage nets to ensure acceptable living conditions for the farmed fish and prevent escaping of fish due to weaknesses in the cage net. Other tasks could be ROV-operations (remotely operated vehicle) typically used for inspection, assistance during treatment of lice and anchor-handling. Designated workboats are developed for specific operations. A few examples are diving vessels, tugboats and cleaning vessels. Each operation requires its distinctive power consumption depending on time usage and type of activity.

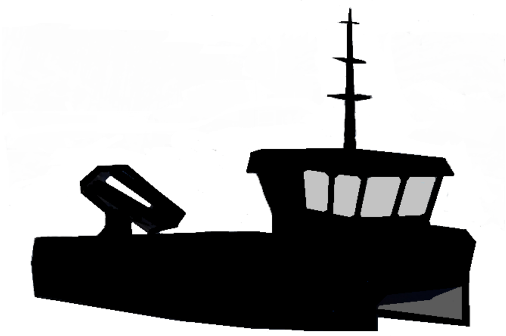

Figure 2.12 Illustration of a catamaran used for aquaculture

The workboats come in different sizes and hull shapes, depending on the requirements and size of the fish farm. Most of the new workboats today are twin hull catamarans vessels. The catamaran design increases stability and allows a larger deck space to, for example, ease the practical use of cranes and winches. The catamaran design has allowed the workboats to increase in work deck area and crane capacity while remaining below 15m of length. This peculiar design choice is motivated by regulations for vessels above 15m of length. While diesel engines have powered the conventional propulsion systems on such vessels, today's shipyards are building vessels with hybrid and fully electric propulsion systems. The development of electrification is done intentionally to reduce emissions. Other advantages are noise reduction from the vessel when both running and idling. The noise reduction causes a desirable working environment on the vessel. Each operation involving a workboat will require its distinctive power consumption depending on the type of work that is done.

3 Energy sources and carriers

In this chapter, an overview and a brief explanation of the relevant energy sources and carriers are presented. The chapter will include an examination of the energy content for each energy source and carrier and a presentation of installed power and energy consumption for the vessels presented in the previous chapter.

In Figure 3.1 below, a graph for the installed power on the different vessels (data from chapter 2) and the feed barge itself is presented. The installed power for the barge is gathered from data obtained from a company designing and building feed barges, the presented power is the maximum rated feed power for this barge.

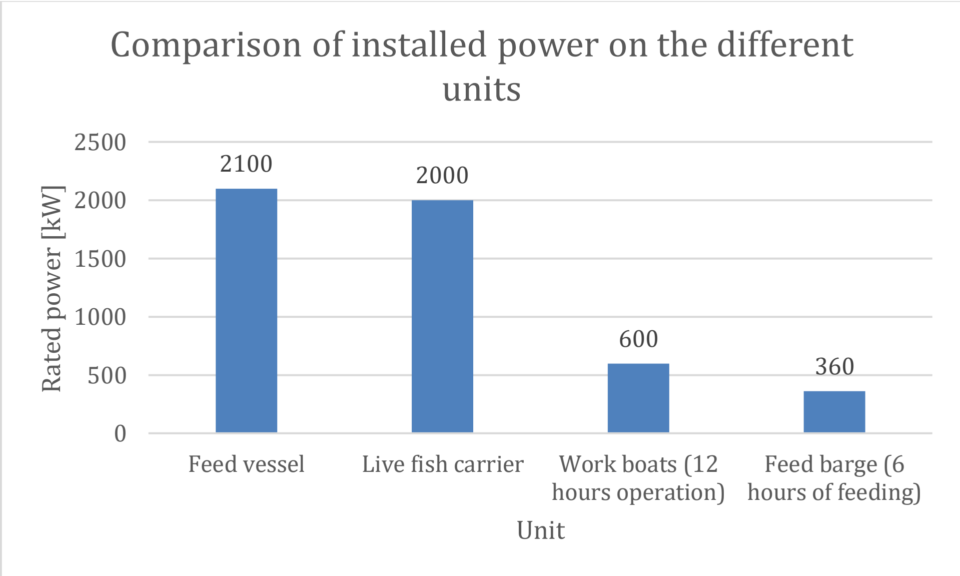

Figure 3.1 A comparison of installed power on units related to aquaculture

From Table 3.1 the energy consumption for the different vessels is shown. Larger vessels such as feed vessels and live fish carriers are dimensioned near maximum effect for normal operation, whereas the feed barge and work boats vary in load and are therefore dimensioned accordingly.

	Rated power [kW]	Energy consumption (full days operation) [kWh]
Feed vessel	2100	37800
Live fish carrier	2000	36000
Work boats (12 hours operation)	600	7200
Feed barge (6 hours of feeding)	360	3240

Table 3.1 Assumed energy consumption for a full day operation

Power distribution on board feed barges is based on electric power, and equipment is electrically driven and connected to the local transmission grid on-board the barge. The electricity for the barge is either produced on-site from fossil fuel sources or drawn directly from a shore power connection. The most common feed barge power system configuration is with a set of diesel generators producing electrical power to meet the power demands on the feed barge. The stored chemical energy on a typical feed barge can be calculated from the fuel tank volumes and compared to other energy carriers.

	Diesel fuel	LNG	LH_2	Batteries	
Total energy stored	257	257	257	257	[MWh]
Specific energy	11,80	13,90	33	0,07	[kWh/kg]
Density	940	440	71,00	630	[kg/ m^3]
Energy density	11092	6116	2343,00	45	[kWh/ m^3]
Volumetric storage onboard	23,20	42	110	5711	[m^3]

Table 3.2 Energy content and storage volume compared for different energy sources/carriers

From Table 3.2 a comparison of different energy sources and carriers is shown. The reference energy storage is 257 MWh and is based on feed barge specification from the company Marine Construction. The specific energies and densities for MDO, LNG and LH_2 are found from (NCE Maritime CleanTech, 2019) and for batteries (Corvus Energy, u.d.) respectively.

It worth noting that Table 3.2 is by no means a guideline on how the actual installations of the different energy sources and carriers on board, it is a comparison to show the differences in energy content. For example, a 5711 m^3 battery pack equals 74 standard shipping containers and is not a feasible solution. Battery packs will be discussed further in subchapter 3.2. The table also relies on the chemical energy content of the energy carriers and neglects losses when this energy is converted to electrical energy.

A similar calculation can illustrate the amount of energy needed for a single day of operation for sea-based aquaculture in Table 3.3. It is worth noting that the table shows fuel mass, not accounting for the low density of hydrogen, refer to Table 3.2 for fuel densities.

Fuel consumption over 24 hours	Diesel fuel [kg]	LNG [kg]	LH_2 [kg]
Live fish carrier	4068	3453	1455
Feed vessel	4271	3626	1527
Work boats	1220	1036	436
Feed barge (6 hours of feeding)	275	233	98

Table 3.3 Fuel consumption from different energy sources/carriers

3.1 Fossil fuels

3.1.1 Diesel fuel

Diesel fuel is refined from crude oil and is exclusively used in compression ignition engines. Diesel fuel is a well-known fuel primarily used in long-distance transport at both sea and land. The fuel is highly available and has a well-developed infrastructure both on- and offshore. Diesel is stable and in liquid form at room temperature and has a high energy density of 11092 kWh/m^3 compared with other fuels, as observed in Table 3.1. These properties make it very suitable for onboard storing on any vessel given its relatively high energy density. Furthermore, diesel is not very flammable, and it is therefore able to be stored in functional areas for maximum utilization of space. Area efficiency is beneficial for vessels and barges where space is a crucial factor. Transport and storing of diesel are also known to be thoroughly developed and is not very demanding.

The drawback of diesel is emissions. Diesel holds the highest CO2 emissions compared with other conventional marine fuels such as LNG and liquid petroleum gas (LPG).

3.1.2 Liquefied natural gas

Liquefied natural gas (LNG) is natural gas that has been cooled to its liquid state at approximately -163 °C. When liquefied, the volume of natural gas has been decreased by a factor of 1:600 compared to its gaseous state (EIA, 2019). Because of its low boiling point, it is required to store the LNG in insulated tanks (DNV, 2019). LNG is the cleanest fossil fuel available for commercial use as of today. With that said, there are no sulfur oxides (SO_x) emissions related to LNG combustion, and the nitrogen oxide (NO_x) emissions are lower than those of diesel fuel (DNV, 2019). However, CO2 emissions remain.

3.2 Lithium-ion batteries

A battery is an electrochemical energy storage system that inverts chemical energy into electrical energy. The battery cell contains a positive electrode with an excess of protons, a negative electrode with an excess of electrons, and an electrolyte which allows transport of electrons between the positive and negative sides in the cell, known as the cathode and anode.

Research on batteries has been implemented at an increasing rate in the past decades. Moreover, there is a promising candidate for the future of batteries, namely lithium-ion cells. Lithium-ion cells more than doubles in energy density compared to tradition lead-acid cells, which for long has been the standard in car and boat batteries. The increase in energy density opens new possibilities for utilization in vessels and vehicles where weight and space are some of the determining factors in the choice of a power source.

However, by taking a closer inspection of Table 3.2 lithium-ion batteries are in for a fierce competition, energy density wise. Nevertheless, batteries based on lithium-ion technology provides advantages where other energy sources might not. Lithium-ion batteries have good power regeneration capabilities. Most relevant in the car industry (regeneration in the downhills will in advance slow the cars speed) and not so relevant in the boat industry where all power is used for propulsion. Except for emissions from production of batteries, they do not release emissions during their life time, but will need careful handling when it’s time for replacement in order to recycle the components and dispose of harmful substances. Electric power systems powered by batteries are known to have much less noise than diesel generators and less moving parts and no consumption of lubrication and coolant fluids means that service and repair cost are low.

Installing lithium-ion batteries is related with a high investment cost and its low energy density makes batteries less suitable for high energy demanding units. This is especially the case for crafts that operates far from shore and travels far between ports. The capacity of the batteries is known to be considerably reduced in sub-freezing temperatures, though installing them on a feed barge where the temperature is kept comfortable with respect to working conditions, low temperatures for the batteries might not be a problem. Batteries can be charged with use of diesel generators, wherever necessary. However, batteries are a good alternative for buffering instantaneous power demands combined with both diesel generators and access to shore power.

3.3 Hydrogen powered fuel cells

While fossil fuels are prevalent and batteries are most suitable for buffering energy, there are alternative energy sources for stationary units such as feed barges. Hydrogen is the first and the simplest element in the periodic table. It consists only of one proton and one electron. Since its atomic weight is 1,008 [g/mol] it is also the lightest element. Under normal conditions, hydrogen is found only combined as two hydrogen atoms forming a hydrogen molecule (H_2) (Pedersen, 2019).

Proton-exchange membrane fuel cells (PEMFC): Is a device that creates electrical power using fuel such as hydrogen and an oxidant, in this case Oxygen. The byproduct is pure water (H_2O) and heat. The efficiency of a PEMFC is somewhere around 40 – 60% (DOE, 2006).

The PEMFC setup consists of an anode where the hydrogen is applied, a cathode where the Oxygen is applied, and a membrane known as the electrolyte. At the anode side, the H_2 is ionized to form protons, which still is a hydrogen atom (H^+) only lacking an electron. In the middle of the cell, the membrane prevents direct contact between the Oxygen and the hydrogen, which may cause a very explosive reaction.

Instead, the protons (H^+) are allowed through the membrane while the electrons are forced to take a detour around the membrane. This transport of electrons is what generates electricity. Moving the electrons from the anode to the cathode will enable us to take advantage of the process by using the electricity created from the moving electrons to for example run an electrical engine or even charge a battery. Since this process also creates heat, the excess heat is possible to use as heating for buildings.

When the electron reaches the cathode, it allows the Oxygen to react with the hydrogen and the product from this reaction will be H_2O, also known as water.

3.4 Shore power

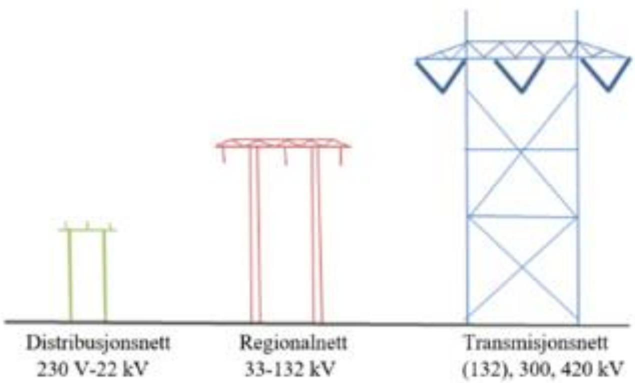

Figure 3.2 Construction of masts in the power grid (NVE, 2018)

Shore power is electricity supplied from power plants onshore to vessels and floating constructions located at the docks or moored at a relatively short distance from shore. Shore power is an efficient alternative to supply electric power on-board floating units which noticeably will reduce emissions from greenhouse gases. Challenges related to shore power are present, and this applies to insufficiently developed power grids (Ingebrigtsen & Glomstein), as well as available electric production capacity.

In 2018 the total power production in Norway was 147 TWh, and 95% of the total power production was from hydropower alone. Wind power and thermal power generation accounted for the remaining 5%, with 2,6% wind power and 2,4% thermal power.

The Norwegian power grid is made up of a transmission grid, a regional grid, and a distribution grid. Figure 3.5 gives an illustration of what it looks like in reality. To transmit electricity between the grids, a transformer is used. The transmission grid is the main supply of power. This grid connects the power from the manufacturers to the consumers. The transmission grid mainly holds a voltage of 300 or 420 kV, while some places 132 kV is used (NVE, 2015).

The regional grid is the connecting link between the transmission grid and the distribution grid. It usually holds a voltage of 132 or 66 kV (NVE, 2015). The regional grid is owned and operated by public and private power companies but is strictly regulated by the government. Some end consumers get their power directly from the regional grid such as hospitals, airports, and larger enterprises.

The distribution grid is the last supply of power to reach the consumer, including households, services, and industry. It usually holds a voltage of 22 kV and down to 230 V (NVE, 2015). Due to increasing power consumption by consumers because of demands on electrification and an increasing amount of electric vehicles, a need for the development of the distribution grid is present (Olje- og energidepartementet, 2014).

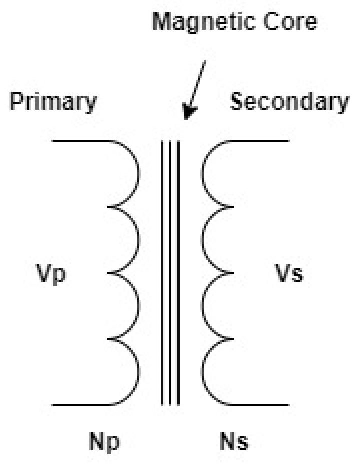

Figure 3.3 Basic principles of a transformer

To transform the voltage from one grid to another a transformer is used. The electric circuit, shown in Figure 3.3 shows the basics of how a transformer is functioning. Where V_p is the primary voltage V_s is the secondary voltage, N_p is the primary number of windings, and N_s is the secondary number of windings. The windings are not connected electrically but are linked with a magnetic core. The voltage output is controlled by the number of windings and can either be increased or decreased depending on the preferred output (Electronics tutorials, 2019).

4 Research method

The method used for studying the power and energy demands of an aquaculture site is a combination of data collection, analysis and numerical modelling of both power consumption and power production for a feed barge.

4.1 Data collection and analysis

In the technical analysis part, data regarding power distribution and energy consumption has been collected from an operating feed barge on an aquaculture location. Where Hera, a feed barge of the type FarmBase 630[1], delivered by Marine Construction to Cermaq Finnmark at a location called Olderfjord has been used as a reference feed barge. This data was converted to a common format for comparison and was used to observe both the operational pattern of the feed barges, as well as sizing of the relevant loads for the power consumption numerical model.

4.2 Numerical modeling

Numerical modeling in this project is used to describe the physical conditions regarding power and energy consumption throughout the fish's life cycle on a feed barge. The model is based on collected data, as presented in the previous subchapter 4.1. The objective of the modeling is to create an ideal physical behavior of the power distribution and energy consumption on a feed barge. To achieve this, an open-source software called OpenModelica has been used for this occasion. The objective of the modeling is to create a model that represents an ideal physical behavior of the feed system on a feed barge and using the power systems library integrated with OpenModelica be able to create a complete system of several aquaculture locations. OpenModelica is a feasible solution to develop a detailed model of the power consumption and distribution on a feed barge.

4.2.1 Open Modelica

OpenModelica is an open-source modeling and simulation environment based on the Modelica language. The term open-source is used where software design is publicly accessible, which makes it available for developers to inspect, modify, and enhance (Opensource.com, u.d.).

OpenModelica is a mathematical and equation-based language which allows for acausal modeling. This means that the model inputs and outputs don't need to be fixed. Equation-based

[1] The term FarmBase 630 describes the loading capacity of the barge in tons.

classes are therefore used.to describe the functionality of the model. The term class is used to describe the language concept as OpenModelica is a textual class-based language. More specifically a class describes a component from the OpenModelica library (Fritzson & Thiele, 2016).

Each class in the Modelica hierarchy is divided into its own domains. Examples of such domains could be mechanical, electrical, fluid, etc. For the classes in each domain Modelica then again allows you to model in multi-domain, which means that you can combine properties of each domain independently with each other. Also called multi-domain modeling.

Modelica allows for visual acausal component modeling, which means that the physical structure of the model is maintained, and that visualization of each class is close to reality. This allows the spectators for an easy understanding of the model compared to traditional block diagrams (Fritzson & Thiele, 2016).

An important feature of Modelica (which is widely used in this thesis) is object-oriented modeling, and that a model may consist of a collection of other models. For example, you can easily build more complex models from simpler sub-models to illustrate more complex behavior and use object orientation to reuse and combine models into new systems. This applies to power and energy consumption models used to simulate a feed barge, which consists of various sub-models. This same model is used together with the diesel-electric model and part of the case study on Senja to simulate behavior in the power grid. The specific Modelica library that is used specifically for this purpose is the power systems library which will be explained later on.

4.2.2 The power systems library

The power systems library was developed to model electrical power systems at different level of detail in a compact and user-friendly matter. This is executed by using phase system components which permits one instance of a component with different equation systems operating within the component itself. The power systems library is an appropriate tool to model production, distribution and consumption of electric energy. It contains both AC and DC models for the most common components as well as definitions for electrical the reference system, such as modelling both in the inertial frame and the more efficient DQ and DQ0 reference system. The DQ and DQ0 reference system rotates with the power frequency and in that way, you avoid simulations of the fluctuations in the AC systems. The DQ and DQ0 systems allows one to focus on the active and reactive power relationships. This is beneficial when simulating longer time series, for example when simulating power consumers that varies through a longer time period (Winkler, 2017).

The power systems library includes pre-set components that can be used to represent both AC and DC as well as power generations from rotating machine devices. The components from the power systems library used for modeling the feed barge energy system is loads, transformers, bus-nodes, generators, terminals, inverters and rectifiers.

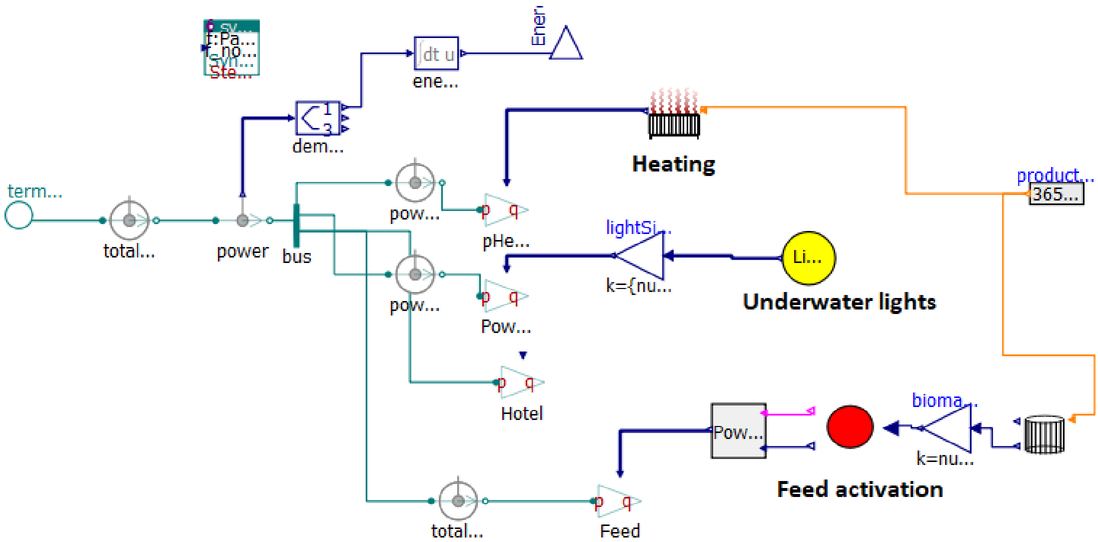

Figure 4.1 Model of the feed barge energy system

From Figure 4.1 the load model of the feed barge energy system is shown. This model will be used to simulate the total power using different power sources later on. The feed barge energy system is also used to dimension an alternative power source. The model represents the different power consumers that exists on a feed barge. The different consumers of power are then distributed into four main categories and they are as follows; power used for heating, underwater cage lights, hotel power and feed power. A further elaboration of each power consumer will be described in the following text.

Power used for heating will strongly depend on the current ambient temperature. The temperature will vary throughout the year depending on the current season and geographical location. To simulate the heat power distribution throughout a year, the power consumption is assumed to follow a period of a sine wave. The peak period of the sine wave will demonstrate the coldest part of the year where the heat power consumption is assumed to be at its maximum. Whereas the minimum period of the sine wave will demonstrate the warmest part of the year where heat power consumption is assumed to be at its minimum. This is illustrated in figure 4.3 below while showing both active and reactive power in the power circuit. Active power is the real dissipated power while reactive power is the power which alternates between the load and the source, also known as watt-less power.

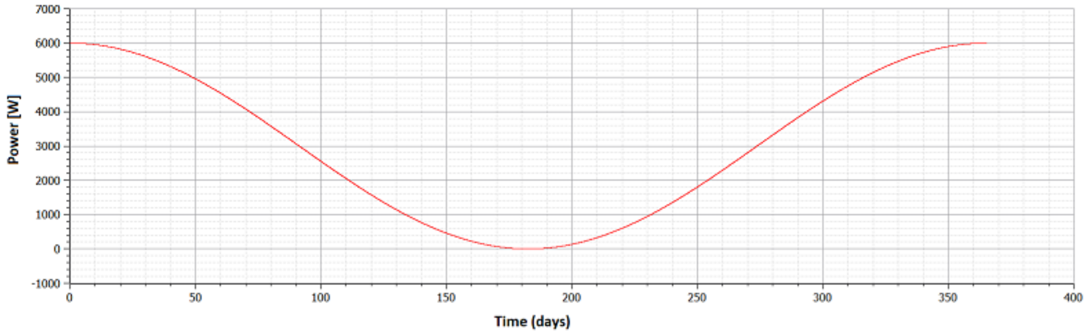

Figure 4.2 Power distribution from heating simulated for a year

Underwater lights are important in aquaculture to stimulate growth by increasing appetite and postpone sexual maturing of the fish. The underwater lights are utilized in months of low light and are typically turned on from October to April and turned off from May until September. The simulated power from underwater lights is assumed to be 1,8 kW per fish cage and the total light power consumption will therefore depend on the amount of fish cages on the location. For example, an aquaculture with 8 cages will provide 14,4 kW of power to the lights. Figure 4.3 illustrates the interval periods and the relative power consumption from the underwater lights.

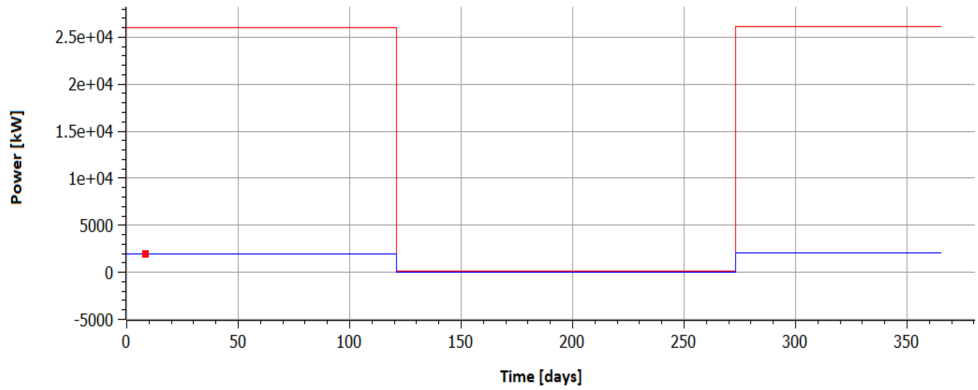

Figure 4.3 Power distribution from underwater cage lights simulated for a year

Diesel and battery electric power system: From Figure 4.4 a hybrid-electric simulation system is presented. The model includes three diesel generators and one battery that provides the available power demand. A power meter is measuring the actual power running through the circuit provided by the four power sources. A preprogrammed power management system (PMS) gathers data from the power sensor located behind the busbar. The busbar connects the power lines from each power source and distributes the power to the consumers. Power from the battery and generators are provided as direct current (DC) and an inverter is therefore necessary to convert DC to alternating current (AC). The power load model is based on AC to be compatible with a connection to the power grid.

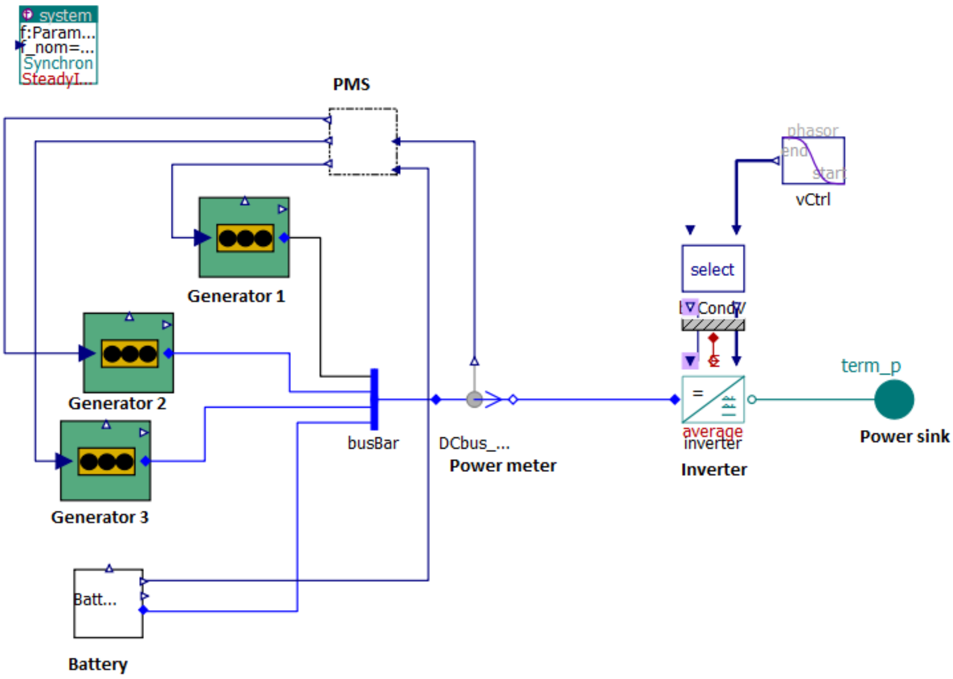

Figure 4.4 Hybrid diesel and battery electric power model

Diesel generator: The diesel generators are modeled as a constant speed driven permanent magnet generator. A preset permanent magnet generator is used from the PowerSystems library and a PID (proportional-integral-derivative) controller controls the actuated current for the generator to deliver the power demand. The PID controller calculates error values between a desired set point and a process variable and applies a correction based on proportional, integral and derivative terms. The power from the preset permanent magnet generator in PowerSystems delivers power as DC by using a rectifier to convert alternating current from the generator. The model also calculated the specific fuel and total fuel consumption from the model based on data given in (Amdahl, et al., 2014) for a medium speed diesel engine.

Battery: The battery is based on the DC battery component from the PowerSystems library. The battery component acts as an ideal battery with constant voltage. The battery model was developed with equations to calculate the total amount of energy delivered to the system, while neglecting energy used to charge the battery. This mechanism gives possibilities of sizing an alternative energy source by investigating the necessary amount of energy to be delivered. Included with the battery model is a state of charge (SOC) component. The SOC is governed by the PMS to manage the charge and discharge of the energy in the battery in a defined matter.

Power Management System: The PMS controls the production of energy and distributes the load between the producers (generators) and the battery. The battery will be both a power load during charging and power source during discharge. The power management system may implement strategies for distributing the load such as distributing the power demand evenly to all generators, or to prioritize optimum load on one or more generators. Design of a complete PMS system is outside the scope of this thesis, but a PMS with two power strategies for battery-diesel-electric power systems was implemented: "Peak-shaving" and "Cover Bottom", where the battery is either used to cut the peak power demand on the generators or used to cover low-power situations and delivering all power from the battery.

The PMS makes optimizing decisions regarding usage of the power sources. The implemented PMS relies on if-else statements to identify solutions to manage the battery and generators. The if-else statements in the PMS unit is based on different scenarios depending on the power demand. The three diesel generators are simulated with different rated power. This means that depending on the current power demand, the PMS unit can create different optimal configurations of the generators in combination with the battery based on information that the PMS receives. The battery is either treated as an extra load to be covered or assumed to provide the rated power. The decision of when the battery should be recharged is in the PMS and the battery is cycled between 20% and 95% state of charge. This is done to optimize the working conditions for the battery in order to increase its lifetime.

4.2.3 Biomass model

The primary function of the feed barge is to deliver feed to the fish. Establishing a biomass model is essential to carry out the necessary data about amount of feed and the power and energy consumption as a result of this. The amount of feed that is required varies with the total biomass available in the fish cages at the location. A rule of thumb is that the daily feed requirement is about 1% of the total biomass. The growth rate of the farmed fish is dependent both on sea water temperature and size. In general, the relative growth rate is largest for smaller fish (ratio of increase in weight over time) and the optimum growth temperature for salmon is about 14 – 16 °C.

The growth rate of salmon is shown in Figure 4.5 with a daily weight increase in % as a function of average weight and temperature.

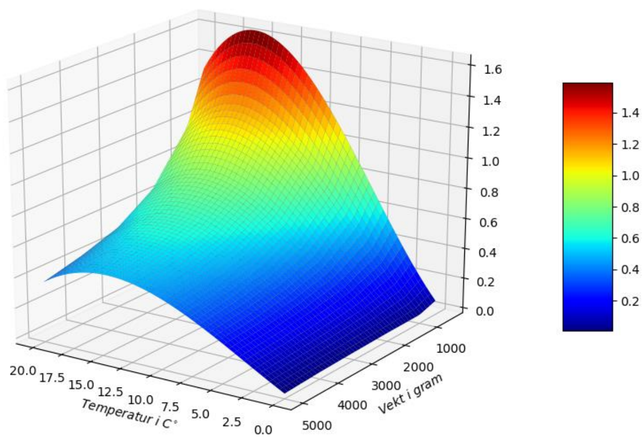

Figure 4.5 Growth rate of salmon as a function of temperature and the average weight in grams

The amount of energy and instantaneous power required to deliver feed will vary over the production cycle as increasing amount of feed is required to be dispersed in the fish cage as the biomass grows. The change in power is not only due to increased mass flow in the feed conveying system during feeding, but also due to an increase in pellet size as the fish grows.

A biomass growth model was developed in OpenModelica to represent growth from an initial weight based on growth rate in Figure 4.5. The model requires sea-water temperature as an input and models the increase in weight as a function of average weight which is a state in the model.

$$\frac{d(averageWeight)}{dt} = f(T_{sea\,water}, averageWeight) \qquad (3)$$

Where $T_{sea\,water}$ is the average water temperature in Norway seen in Figure 4.6 below, and $averageWeight$ is a state variable integrated in time by Modelica. The total biomass in the net cages is then the product of number of individuals in each cage, the number of cages and the average weight. The average weight is used to calculate a feed demand (1%) to be delivered in a 24-hour period.

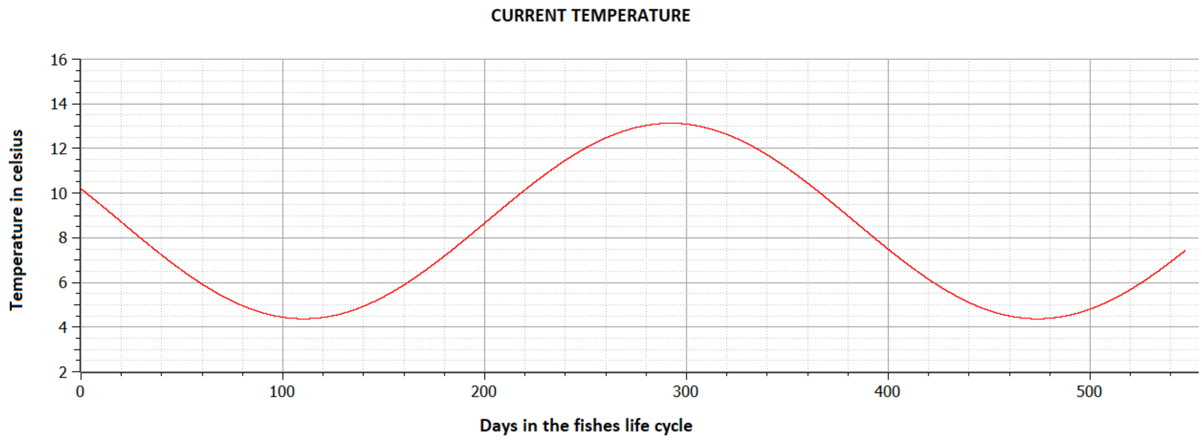

Figure 4.6 Average sea water temperature through the production cycle

In Figure 4.7 the average weight is simulated based on the growth rate from Figure 4.5 and the average sea water temperature as seen from Figure 4.6.

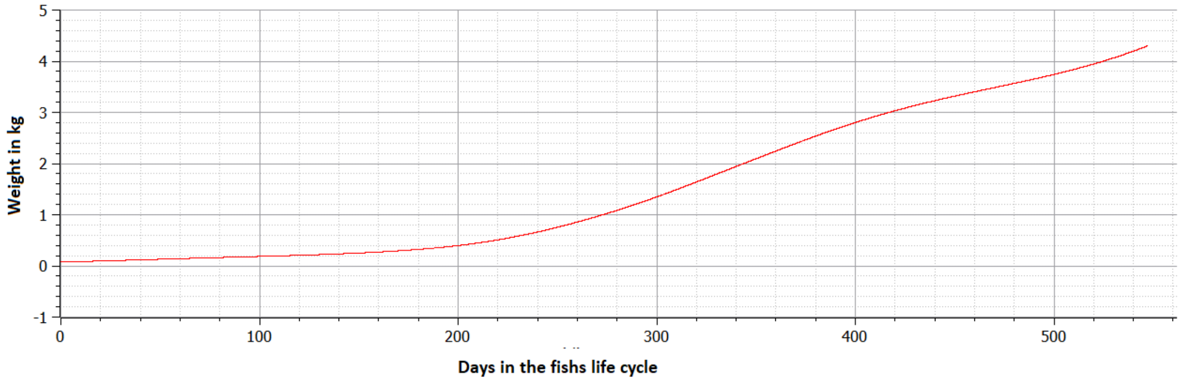

Figure 4.7 Average weight based on average sea water temperature

Feed system activation: The activation of the feed system is dependent on the amount of feed to be delivered. Smaller fish in lower temperatures may only be required for the larger biomass levels at the end of the production. A feed activation and power demand are calculated from the amount of feed to be delivered and the average weight of the fish. The pressure drop in the pneumatic feeding system is proportional to the mass flow rate and pellet size.

Four feed regimes were selected for different amount of feed demand: start, small medium and large sizes with thresholds between the classes. Each class contained a template of feed systems activation times over a 24h period. The mass flow of feed for each 24h period was calculated as the sum of activated times divided by the required feed. The demanded power from the feed system was taken as a base, or idle, power together with quadratic power increase as the mas s flow approached the nominal mass flow of the feeding system.

$$P_{feed}(\dot{m}) = P_{base} + a\left(\frac{\dot{m}}{\dot{m}_n}\right)^2 \qquad (4)$$

Where a was found by matching the equation with the rated power of the feed system and $\dot{m}_n$ is the nominal mass flow. The rated power and nominal mass flow were set based on the specification of AKVA groups CCS feed system.

4.3 Dimensioning of an alternative energy source/carrier

To dimension an alternative energy source or carrier it's essential to carry out the necessary information about the energy and power requirement on the feed barge. OpenModelica is a suitable modeling and simulation environment to calculate power and energy distribution between power sources to supply power to the consumers. For example, a battery in a hybrid system is therefore convenient to dimension based on results on power consumption from OpenModelica.

There method of dimensioning an alternative energy source in this project will be to investigate the period of the production cycle with the largest power consumption and then develop configurations that acts accordingly. A hybrid system consisting of three diesel generators and a battery will act as the base system to further dimension the correct size of the battery pack. In order to dimension the battery pack, it is important to consider what the purpose of the battery pack will be. The battery can either work as the primary source of energy with occasionally charging from diesel generators, used mainly for peak shaving during feeding hours or covering the base load in-between feeding hours. The energy demands of the load model can then be used to dimension the required energy from alternative sources, such as the amount of hydrogen required to supply the feed barge.

Scenario: For the relevance of this thesis the objective will be to develop a battery pack that can work as a peak shaver in the latest stages of the production cycle where the peak power consumption is high. In this case the battery should be capable to cover most of the power and energy consumption in the early stages of the production cycle where the power and energy demand are low.

When the battery is dimensioned, the investigation of fuel consumption from the diesel generators is relevant to consider other alternative energy sources that can replace the generators. This is done to achieve a total emission free power generation from the feed barge. Hydrogen represents itself as a feasible alternative. Comparing the efficiency from the diesel generators with efficiency from the hydrogen fuel cells, a calculation on hydrogen consumption will be introduced.

Battery pack size [kWh]	Rated battery power [kW]
115	120
173	120
230	120

Table 4.1 Specifications on battery packs from (AKVA Group, u.d.)

As of 2019, AKVA group has offered Diesel-Battery hybrid feed barges. Table 4.1 shows battery specifications from AKVA group. The rated battery power of 120 kW will be used to simulate the scenario as mentioned above. The battery that is developed in the simulation model will operate between 95 and 20%. This is to preserve battery life as it is known that batteries that completely discharge and fully charge every cycle will have a shorter battery life (Yoshio, Brodd, & Kozawa, 2009). From here, dimensioning the size of the battery pack will follow a simple iterative method to ensure that the battery operates in-between the boundaries of 95% and 20% in periods of activation.

5 Results

In this chapter results from collected data from operative locations will be presented and analyzed. The data is from specific time periods and will be used as a base for further development of the model. Data and figures from actual designs are also collected. This gives information about the installed power, number of generators, number of feeding lines and related components in the feed system and available fuel storage on board.

From the collected data, a model is developed involving the total energy consumption and its main power consumers. What is also considered is the fish's life cycle. This affects the rate and volume of feeding and is a significant factor when it comes to the total energy consumption over the fish's life cycle. On a day to day basis, it is estimated that 1% of the weight of the available biomass must be fed. An approach of how the fish grow through its life cycle is therefore developed. To substantiate the total feed rate and volume when compared to fish growth, parameters regarding saltwater temperature throughout the year is also considered.

A case study is also performed. The case takes place on Senja, considered as a relatively sparsely populated area with a known limited capacity in the power grid. It is therefore a suitable location to investigate if electrification with shore power could be a feasible solution.

Dimensioning of an alternative energy source and a hybrid solution will also be presented on a later stage in this chapter.

5.1 Daily average power consumption

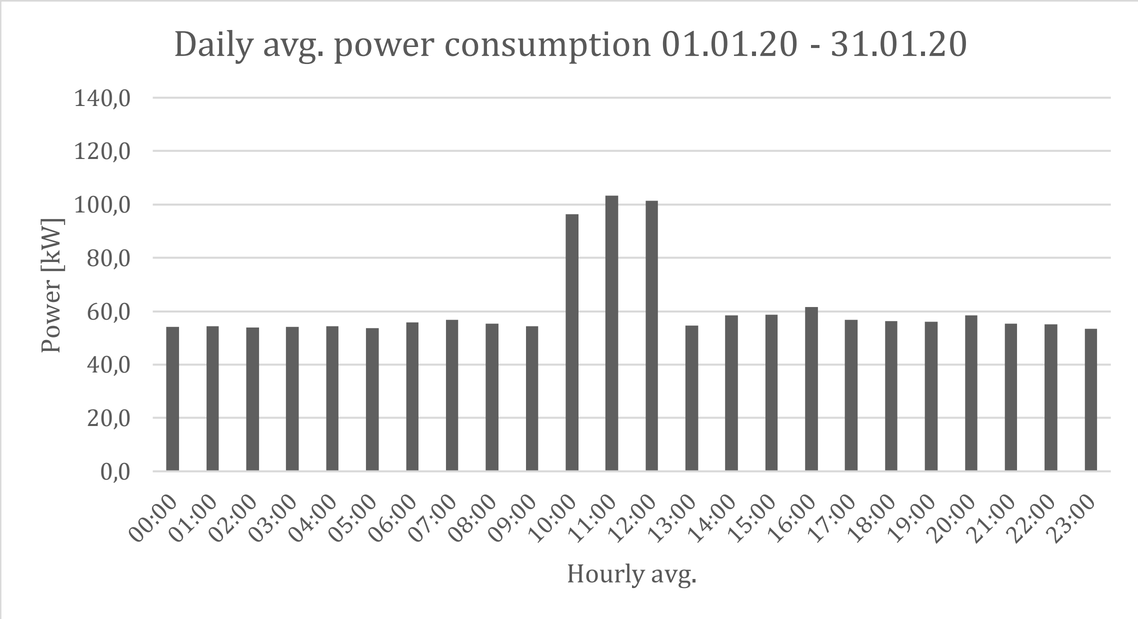

Figure 5.1 Daily average power consumption 01.01.20 - 31.01.20

Figure 5.1 shows the daily hourly average power consumption over a month for a feed barge in the Finnmark region. This data is collected for January. It is worth knowing that the total power consumption on a feed barge is highly dependent on the amount of available biomass at the fish farm. In the early stages of the farmed fish life cycle, the required amount of feed is limited. This results in lower power consumption from the feed system because less feed is required per unit time and feeding hours per day is also limited. From Figure 5.1 It emerges that feeding starts at 10:00 and ends at around 12:00, a total of 3 hours of feeding per day with a peak load of about 96 kW. The peak load in this figure is somewhat smaller than the actual data it is based on shows. The reason for that is because this is the average measured daily power consumption per hour, while the source data gives measures per 20 minutes. Hence the data is somewhat smoothed out. Therefore, the source data shows a higher peak value. However, the total energy consumption is correct since it is based on average measurements.

The baseload from Figure 5.1 is relatively high at around 55 kW. This is explained by the need for cage lights which consume around 25 – 28 kW, the remaining load comes from day to day hotel operation and power used for heating. The base load is very little affected by the averaging fort the figures as a result of the average measurements per hour. This is because the base load is relatively constant throughout the day.

The power used for feeding is about 42 kW as observed from Figure 5.1. As the rated power specification of a feed blower is 30 kW from Table 2.1, it's fair to assume that the feeding takes place in two separate cages with two feeding lines running on medium power from the blowers

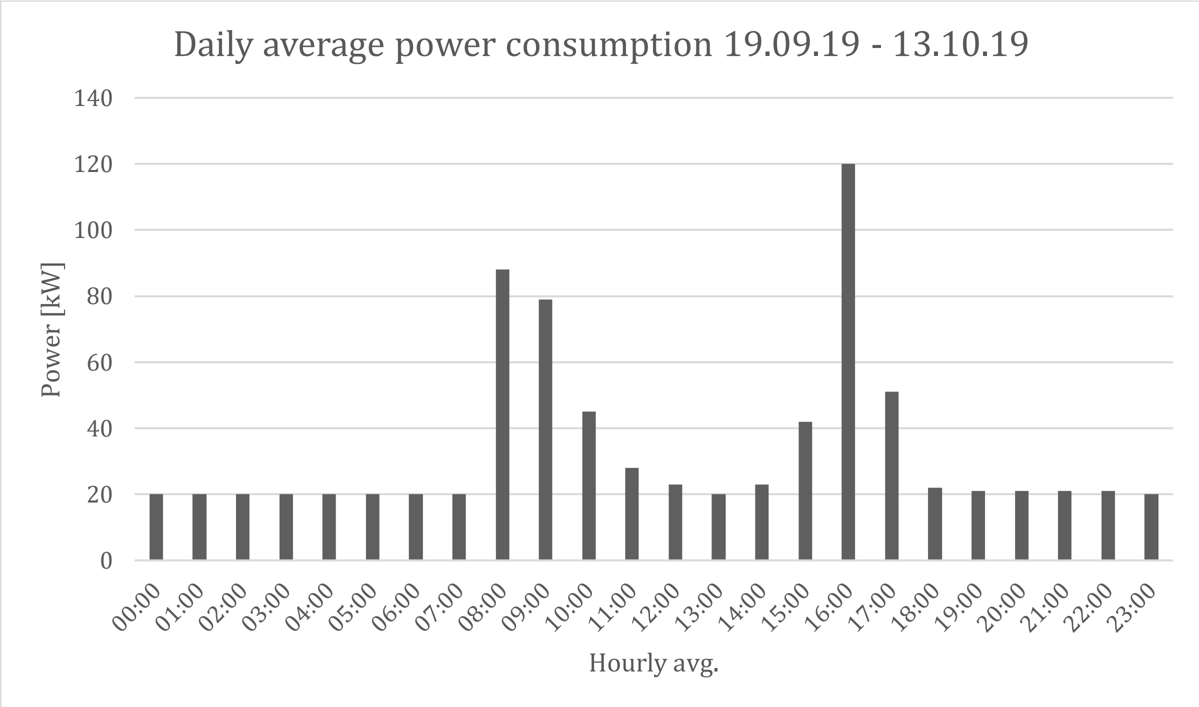

Figure 5.2 Daily average power consumption from 19.09.19 - 13.10.19

Figure 5.2 shows the daily average power consumption for September on a feed barge in the Vestland region This fish farm feeds 2 times a day with intervals between 08:00 to 11:00 and 15:00 to 17:00. Comparing Figure 5.2 with Figure 5.1 it's clear that the baseload is highly reduced from about 55 kW to around 20 kW. The main reason for this is the elimination of cage lights which occur in a shorter time period further south in Norway, in this case the Vestland region. Also, the power used for heating is reduced because of increased temperatures in the summer. Although the base load is reduced, the overall peak load is slightly increased. The explanation of this is because the farmed fish is in a later stage of its life cycle, causing it to need more feed to grow at the required rate. From Figure 5.1 the pure feed power is a mere 42 kW whereas the pure feed power from Figure 5.2 is 68 kW in the morning feed interval and around 100 kW in the afternoon feed interval.

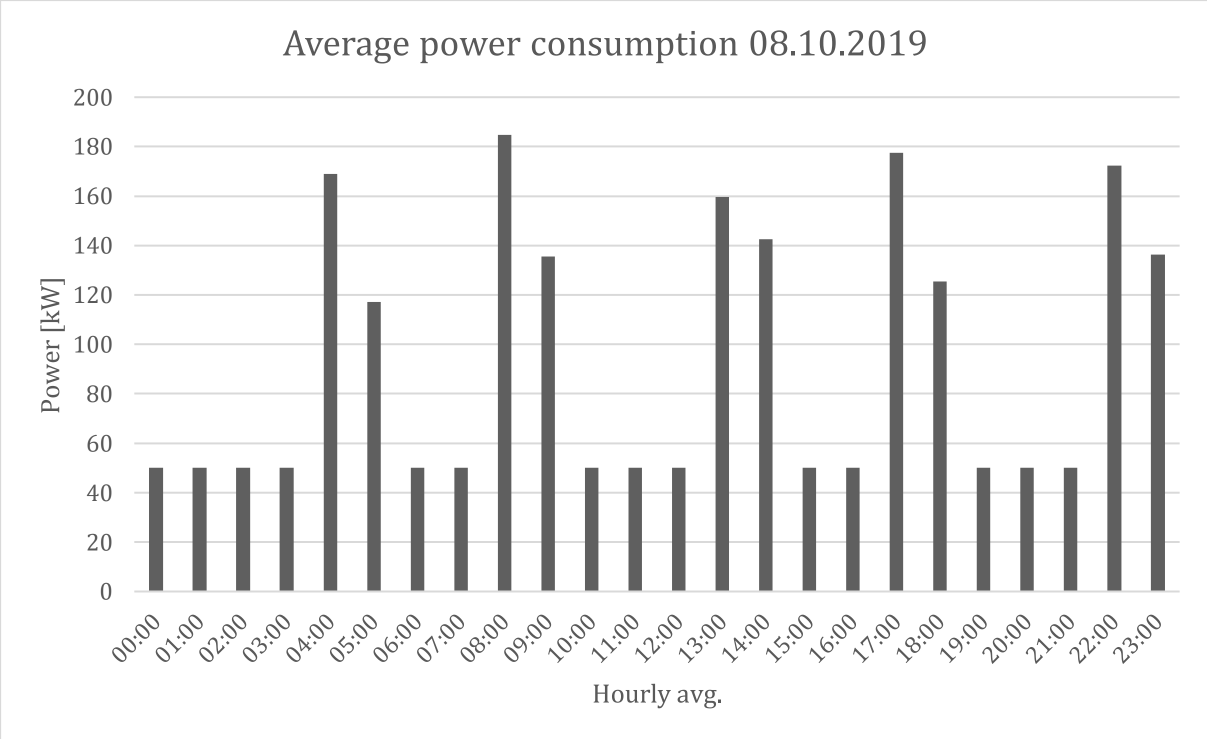

Figure 5.3 Average power consumption 08.10.2019

Figure 5.3 shows the daily average power consumption in the late stage of the production cycle. This barge feeds 5 times a day with 2-hour intervals. The intervals are 04:00 – 05:00, 08:00 – 09:00, 13:00 – 14:00, 17:00 – 18:00 and 22:00 – 23:00, with a peak load of about 180 kW. The base load is around 50 kW which implies that cage lights are on. 16 cages will give a power of 28 kW for the cage lights, where the remaining 22 kW is consumed by heating and hotel which might be a fair assumption, given that there is no further information about this barge. The second hour of the feeding is consistently lower than the first hour which can be explained by appetite of the farmed fish, as the appetite will decay the further into the feeding intervals one comes.

Cage lights: Figure 5.4 shows how the daily power consumption for a barge in February and what the power consumption could look like if the cage lights were turned off. Closer observations from Figure 5.4 shows that the contribution from cage lights of about 28 kW is approximately the same as what the power from the feed system contributes with between 09:00 and 13:00, which is about 30 kW. With a constant load from the cage lights they have a high contribution to the total energy consumption in months of activation (typically from October to

April). Because the energy demand from cage lights is high it has a big impact on dimensioning the battery for base load coverage.

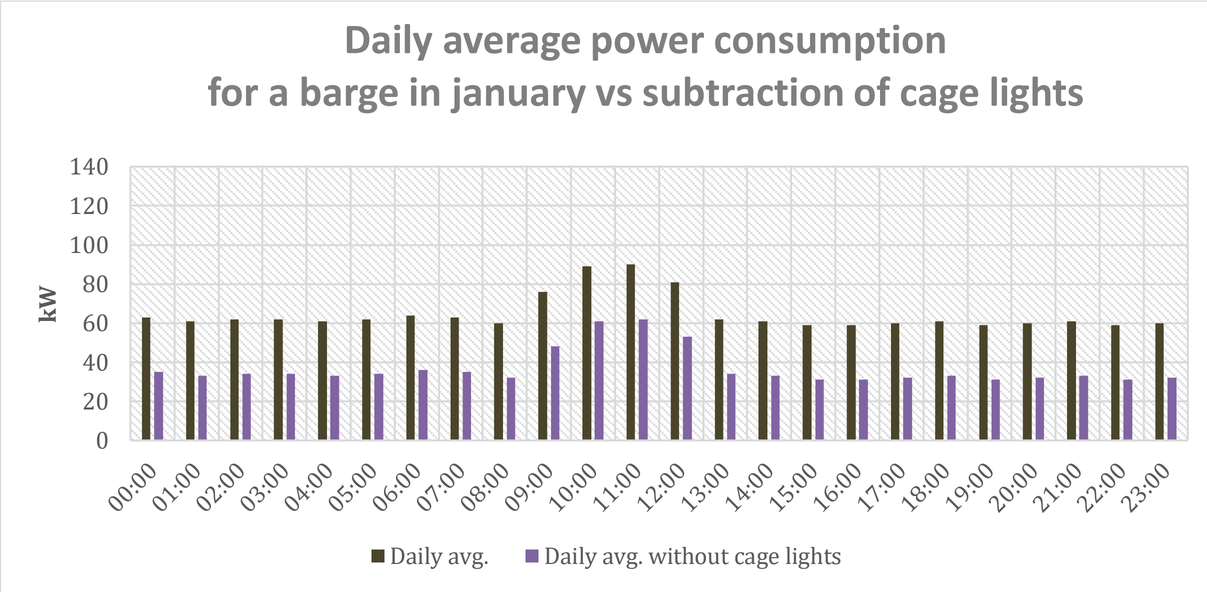

Figure 5.4 Daily average power consumption with and without cage lights

5.2 Feed barge energy model and detailed power consumption

In this subchapter the detailed power consumption is to be investigated and this is further developed by making a model in OpenModelica. The activation of the feed system together with the base load for 1. January and 1. July is shown below for four different assumed biomass sizes. These activation times and feed power are sized according to the data presented in the previous section. The parameters that is used for three different feed intervals are as follows:

Number of cages	8
Individuals in each cage	120 000
Small fish	0,2 kg
Medium fish	1,5 kg
Large fish	4 kg

The results are shown in Figures 5.5 to 5.10. The feed intervals for the different grow-out stages seen in the previous sections are reproduced in the modelica model.

200 g, 1^{st} of January (small), feed activation from 11:00 – 13:00

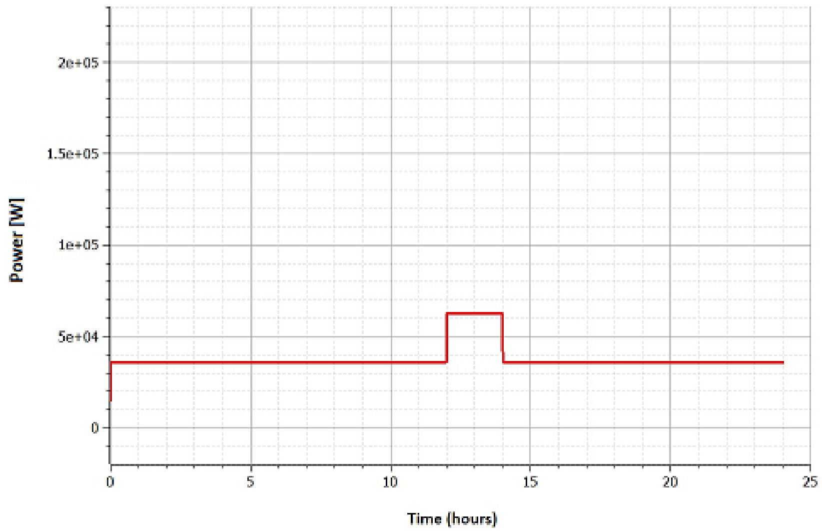

Figure 5.6 Small size fish, feed system (January)

200 g, 1^{st} of July (small), feed activation from 11:00 – 13:00

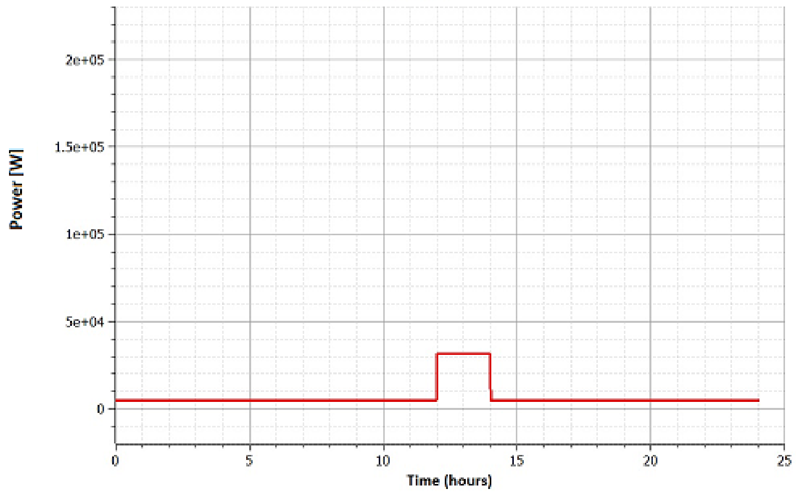

Figure 5.5 Small size fish, feed system (July)

1,5 kg, 1st of January (medium), feed activation from 10:00 – 11:30, 15:00 – 17:00 and 20:00 – 21:00

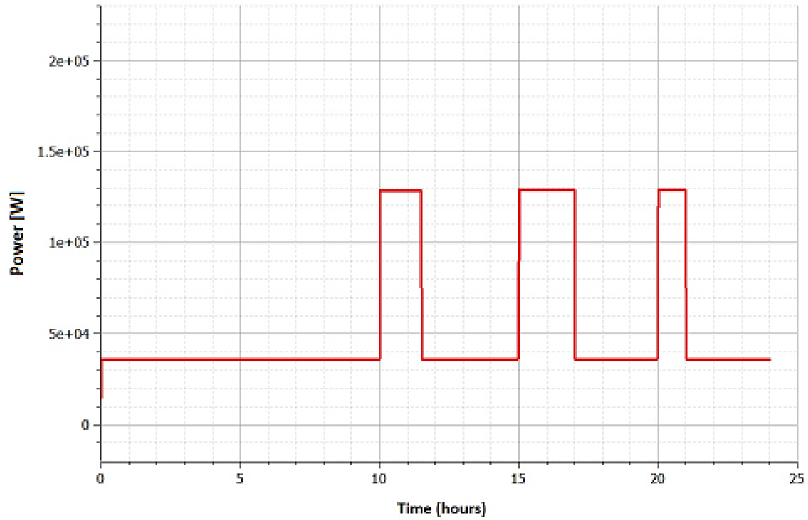

Figure 5.8 Medium size fish, feed system (January)

1,5 kg, 1st of July (medium), feed activation from 10:00 – 11:30, 15:00 – 17:00 and 20:00 – 21:00

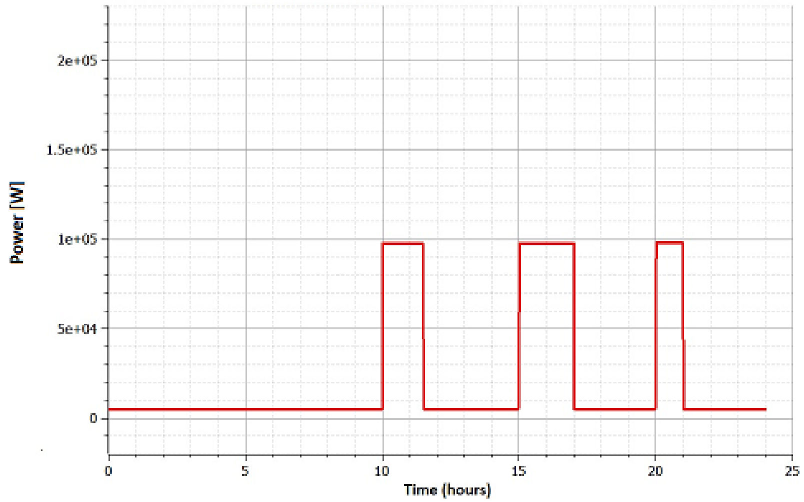

Figure 5.7 Medium size fish, feed system (July)

4 kg, 1st of January (large), feed activation from 08:00 – 10:00, 12:00 – 14:00, 16:00 – 18:00 and 20:00 – 22:00

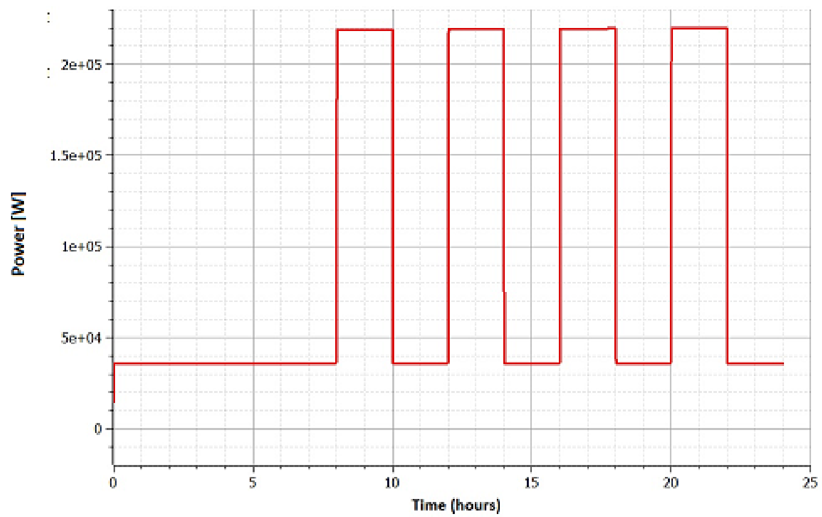

Figure 5.10 Large size fish, feed system (January)

4 kg, 1st of July (large), feed activation from 08:00 – 10:00, 12:00 – 14:00, 16:00 – 18:00 and 20:00 – 22:00

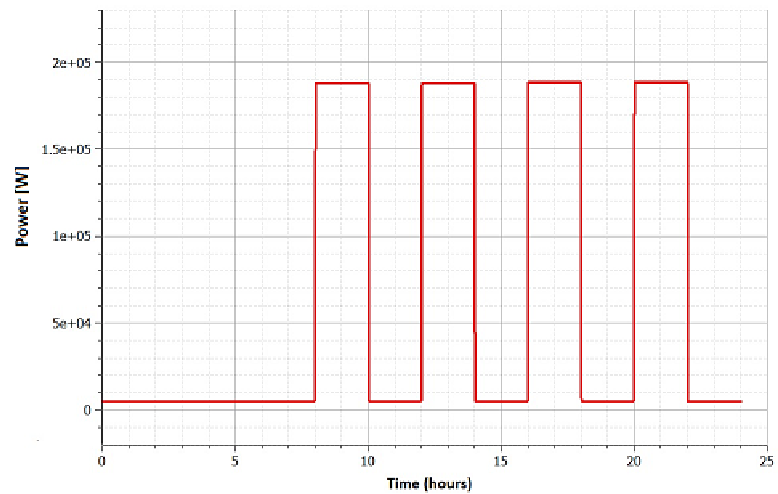

Figure 5.9 Large size fish, feed system (July)

5.3

5.3 Dimensioning of a hybrid energy system

In Figure 5.11 below, peak shaving in hours of feeding January the 1st with fish of 4 kg (late stage in the production cycle) is illustrated. The simulations are of the diesel-battery power production system shown in section 4.2.2, Figure 4.4, coupled with the load model shown in section 4.2.2, Figure 4.1. The PMS allocates power production between the three generators and charge/discharge of the battery to meet the power demand of the load model. The power demand is shown with a blue line and the battery power is shown in red, the power production of the diesel generators is not shown to maintain simplicity of the plots. This period in the production cycle and the time of year is used as a base to dimension the battery. That is because the combination of those periods' answers to the most power and energy demanding periods in the whole production cycle. It does not necessary mean that the two periods always will coincide in a production cycle, but rather a "worst" case scenario which should be dimensioned for. This is because power for cage lights are on, power for heating is at its highest and biomass is about its highest. An assumption that has been done to dimension the battery is that the charge/discharge ratio is 1. Which means that the battery can only be charged with the batteries rated power. In this case where the rated power for the battery is 120 kW the charging power will be equal. The peak power here is 226 kW which means that the remaining 106 kW is covered by the diesel generators. The base load (not including charging of batteries) is 42 kW

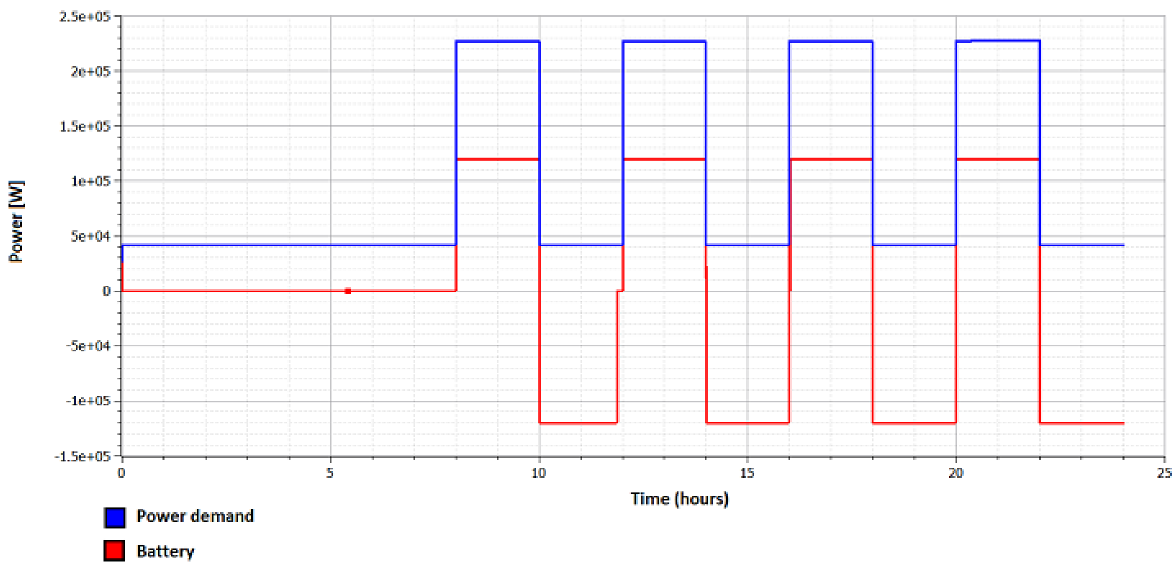

Figure 5.11 Peak shaving 1st of January, 4 kg fish, base load: 42 kW, peak load: 226 kW, battery size: 320 kWh

In Figure 5.12 the batteries state of charge (SOC) is illustrated. Boundaries for charge and discharge levels are set to 95% and 20% as mentioned in subchapter 4.3. The SOC is used iteratively to decide the battery size in kWh. Here, the initial SOC (ISOC) is preset to 100% before the first discharge (feeding time). That is why the first discharge only reaches 25%. The rest of the charge/discharge cycles operates eminently between 95% and 20%. This has been achieved with a battery size of 320 kWh.

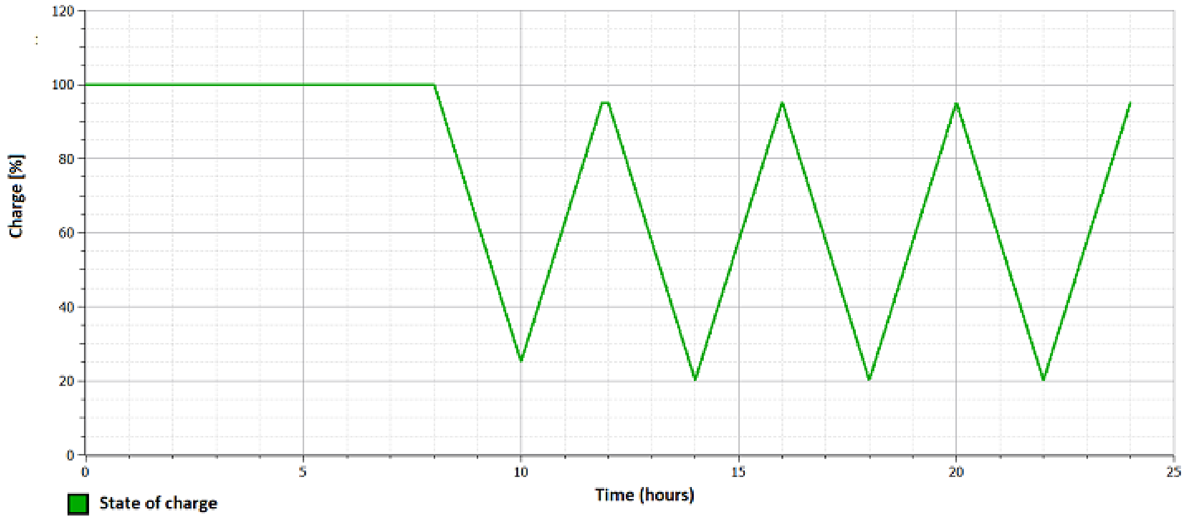

Figure 5.12 State of charge for peak shaving 1st of January, battery size: 320 kWh

In Figure 5.13 the peak shaving for July 1st is shown. The real difference from Figure 5.11 is that the baseload is more or less cut in half. This is because heat power is almost zero as cage lights are off. Yet, the battery performance is the same. The explanation of this is because the peak load is 204 kW and the battery is rated at 120 kW, feed intervals are the same and therefore the execution of the battery remains the same because of the peak shaving method.

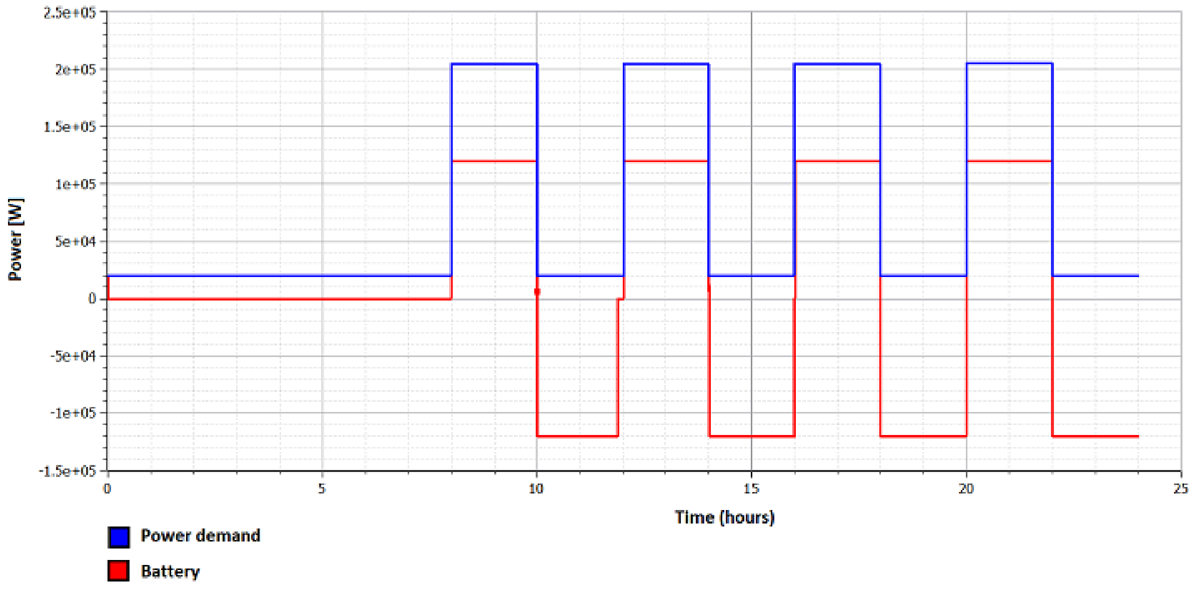

Figure 5.13 Peak shaving 1st of july, 4 kg fish, base load: 20 kW, peak load: 204 kW, battery size: 320 kWh

Since the battery performance in both Figure 5.11 and Figure 5.13 is equal, the SOC in Figure 5.14 is equal as that of Figure 5.12.

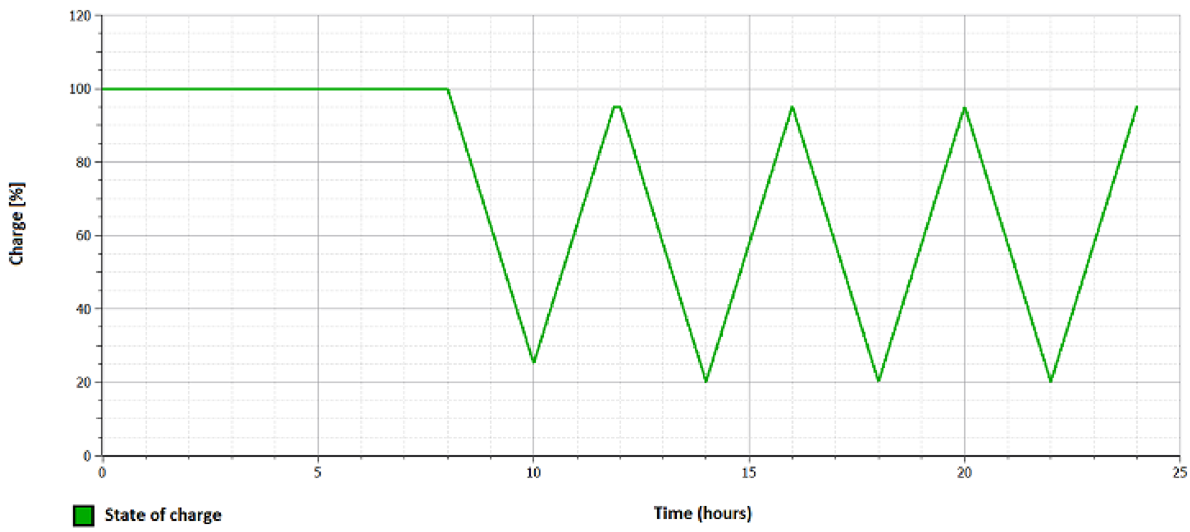

Figure 5.14 State of charge for peak shaving 1st of july, battery size: 320 kWh

In Figure 5.15 the method of bottom power coverage is shown for 1st of January. With an ISOC of 100% the battery can cover all the base load until 6:30 in the morning starting from midnight and covering the base load in between feeding hours the rest of the day. The dip in battery power at the end in each feed interval at hour 10, 14, 18 and 20 is negligible and will need improvements in the PMS.

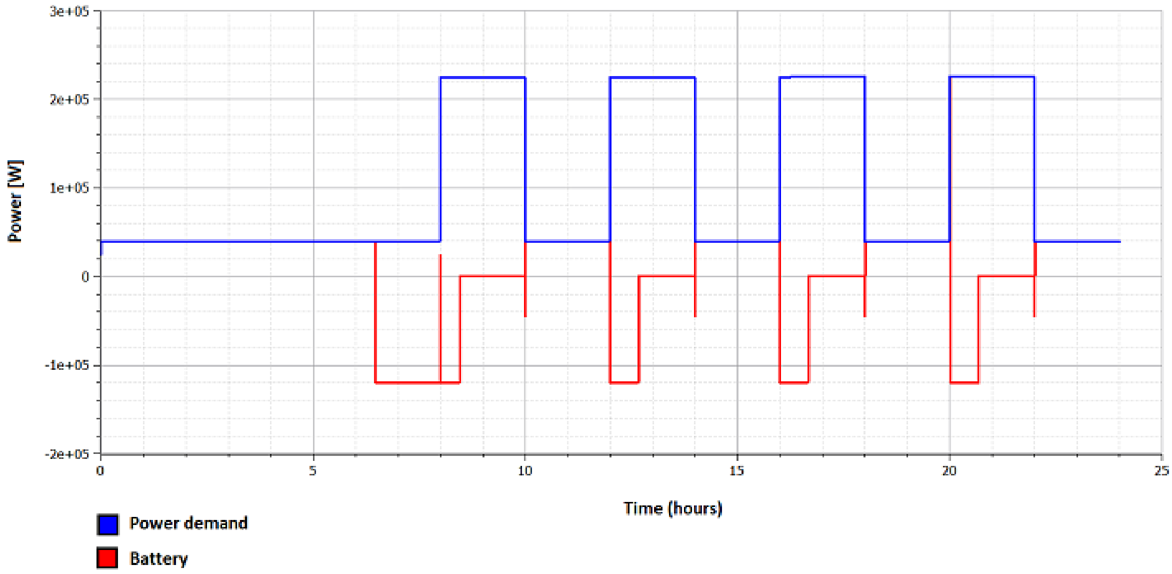

Figure 5.15 Bottom power coverage 1st of January, base load: 42 kW, peak load: 226 kW, battery size: 320 kWh

The battery SOC in Figure 5.16 shows that the battery is charged from 6:30 to 08:30, half an hour into the first feeding. This charge was from 20% to 95%, defined as a full charge cycle. The remaining charges through the day happens during the first 45 minutes of each feeding. This is enough to charge the battery from 70% to 95%, which means that the battery drains 25% in between feedings to cover the base load.

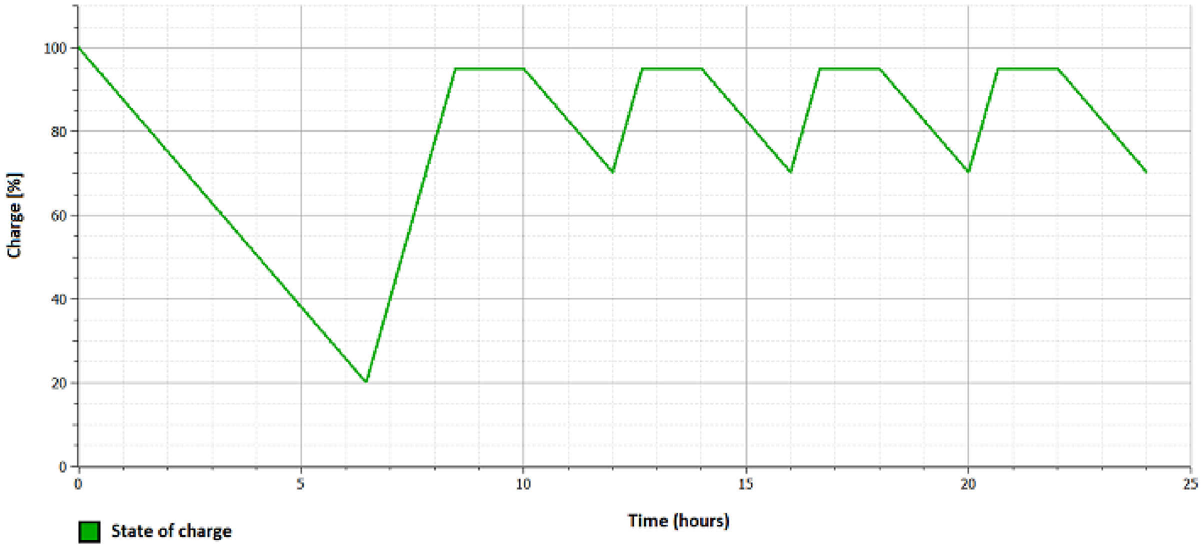

Figure 5.16 State of charge for bottom power coverage 1st of January, battery size: 320 kWh

From Figure 5.17 below the bottom power coverage for 1st of July is shown. The base load here is 20 kW and the battery can therefore cover all the base load both before and in between feedings. The dip in battery power at the end in each feed interval at hour 10, 14, 18 and 20 is negligible and will need improvements in the PMS.

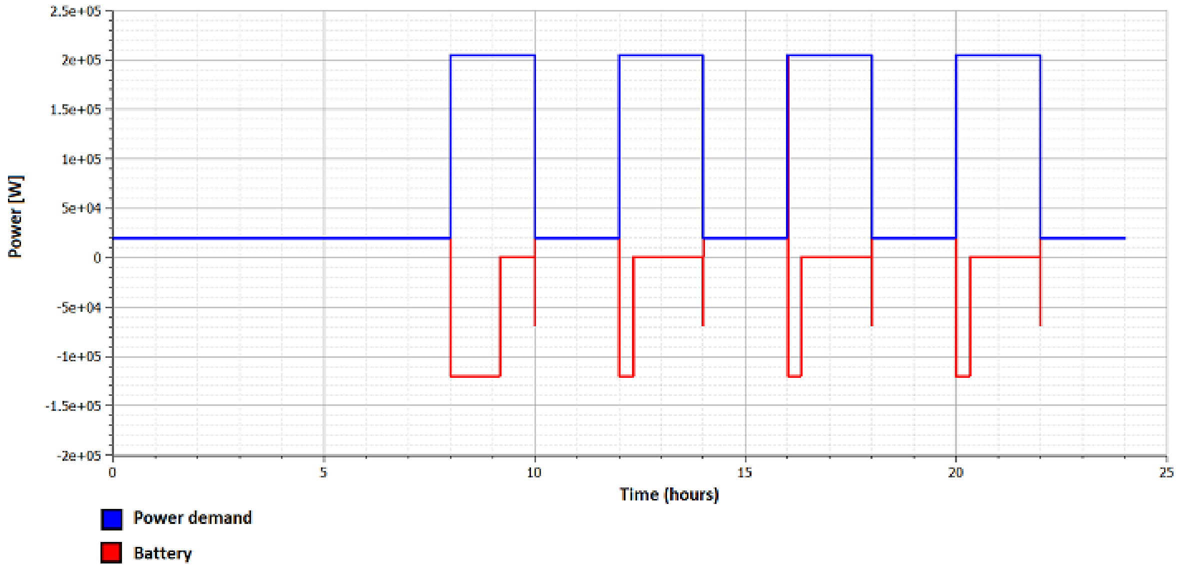

Figure 5.17 Bottom power coverage 1st of July, 4 kg fish, base load: 20 kW, peak load: 204 kW, battery size: 320 kWh

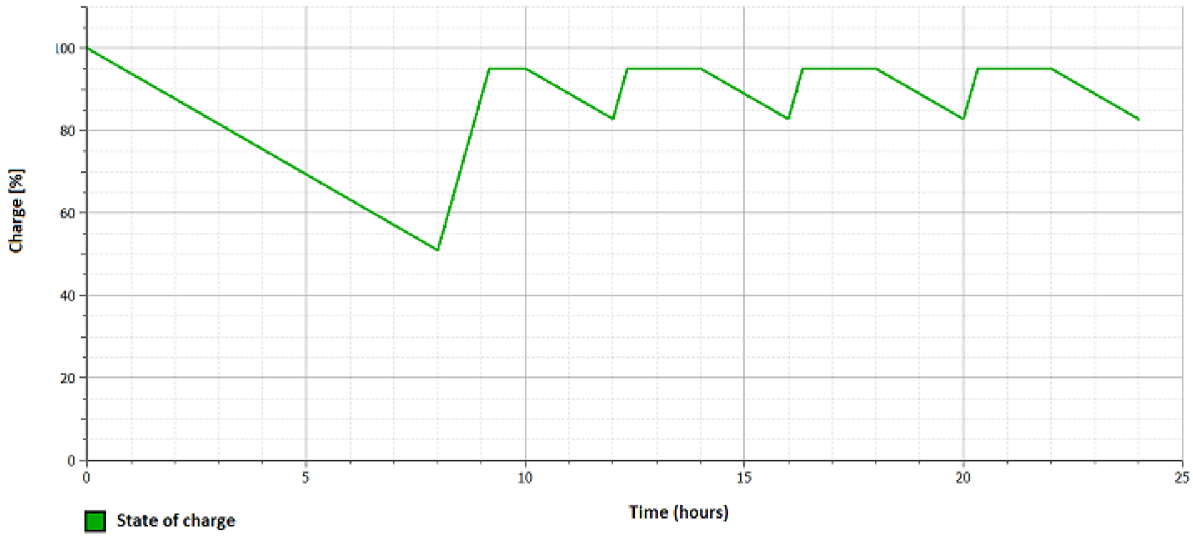

Figure 5.18 State of charge for bottom power coverage 1st of july, battery size: 320 kWh

5.3.1 Energy consumption of a production cycle

The load model was simulated for a full production cycle to show the energy and power demands during the production cycle. This shows the applicability of batteries in the start of the production for the cover bottom strategy and for peak shaving in the later stages. It is also shown that the energy demand increases almost exponentially at the end of the production.

Figure 5.19 below shows how the power demand develops throughout the whole production cycle of 18 months (540 days) by utilizing the load model created in OpenModelica from section 4.2.2. The simulation starts at 1st of July and is defined as day 0 and start day of production from Figure 5.19. In this cage one can observe that the cage lights are engaged in the late stage in the production cycle, which was defined in section 4.3 as a “worst case” scenario of dimensioning the hybrid power system. From Figure 5.19 it is also possible to observe the three different feed activation intervals when already presented by the figures in section 5.2 from earlier. At around 190 days, the feed intervals shift from what was defined as small sized fish feed activation to medium sized fish feed activation. The same process is observed at around 380 days into the production cycle where the feed intervals shift from medium sized fish feed activation to large sized fish feed activation. The cage lights are switched on at 90 days, off at 300 days and on again at 450 days respectively. The maximum power peak reaches almost 250 kW in the end of the production cycle.

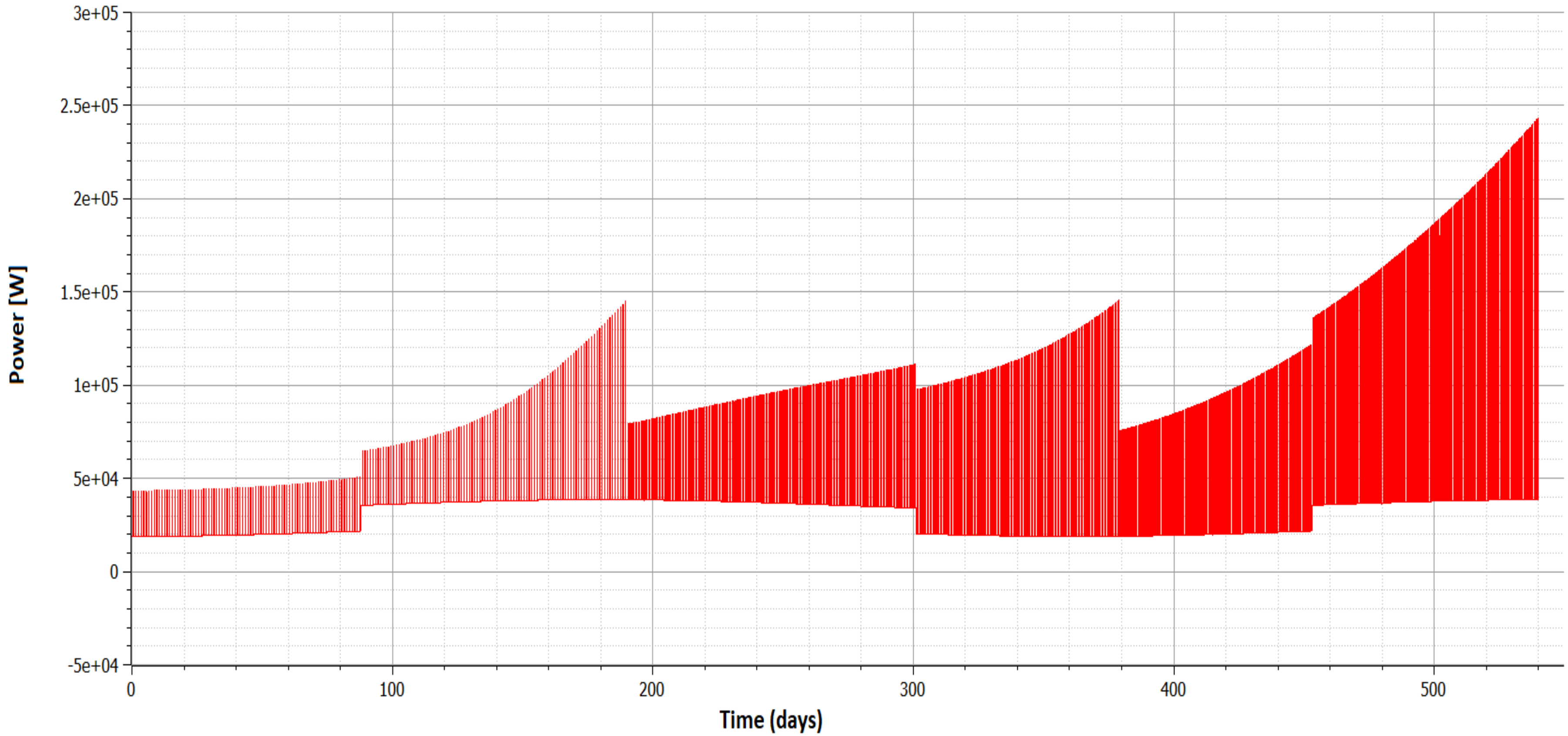

Figure 5.19 Power consumption throughout a whole production cycle of a single feed barge

Figure 5.20 below shows the total energy consumption throughout the whole production cycle. A small curvature in the continuously rising energy consumption is possible to observe. This is explained by the activation and deactivation of the cage lights and the cage lights therefore have a noticeable contribution to the almost exponential increase in energy consumption at the end of the production, in addition to the large increase of feed power consumption. A total of 600 MWh is consumed at the end of the production.

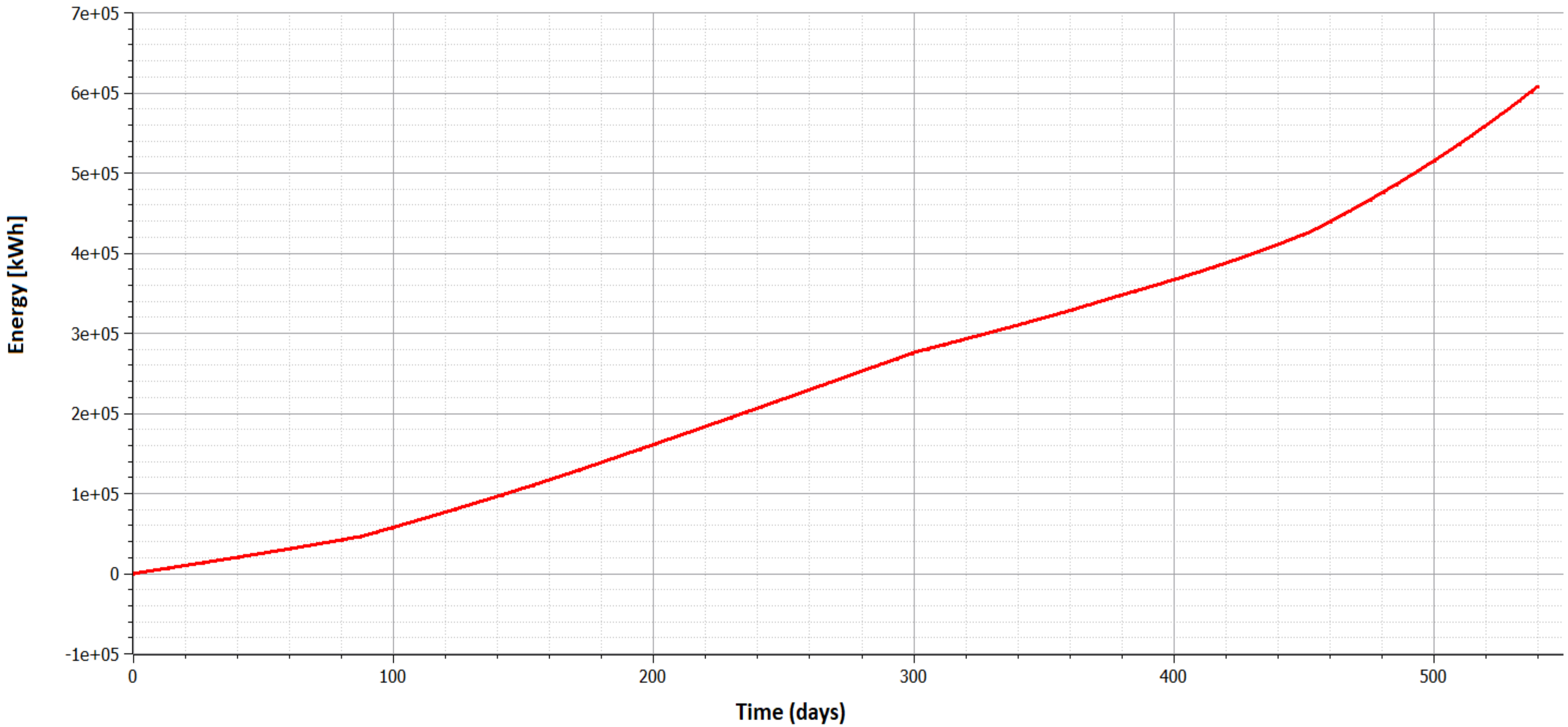

Figure 5.20 Energy consumption throughout a whole production cycle of a single feed barge

Method of reducing emissions with hydrogen fuel cells: Diesel fuel has a CO_2 footprint of 0,27 kg/kWh (Volker Quaschning, 2015). That gives a total CO_2 emission in the production cycle of 162 tons. The emissions can be eliminated by using green hydrogen. The efficiency of a PEMFC is around 50% as described in section 3.3, so that will require a total hydrogen demand of 1200 MWh or 36 tons, to cover the whole production cycle.

From section 3.3, the total energy storage, based on an existing feed barge, is 257 MWh. The calculated volume to store the same amount of energy as hydrogen is 110 m^2, with an actual energy delivery of 125,5 MWh. If this could be a possible solution of hydrogen energy storage on board the feed barge, it is possible to carry out the entire production cycle with 5 refuels with almost emptied hydrogen tanks as shown in Figure 5.21. Utilizing hydrogen as the main energy carrier will require a battery as an energy buffer to assist with peak shaving during feed intervals.

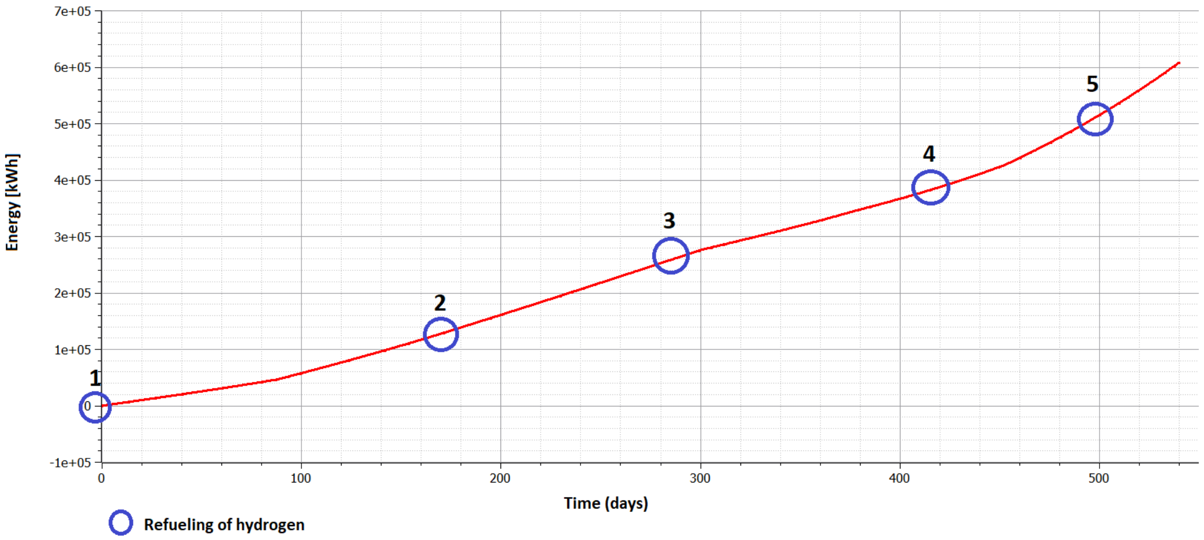

Figure 5.21 Refueling of hydrogen

5.4 Case study on Senja

In this subchapter a case study will be presented. The case study involves all operating aquaculture locations associated with the island Senja. The objective of the case study is to demonstrate what the power and energy consumption from all associated locations could look like if they were connected to the power grid on Senja. A simulation model is developed in OpenModelica by instantiating the load model used previously to represent all the production sites in the region.

5.4.1 Aquaculture locations on Senja

The model is based on the aquaculture locations on Senja and the number of cages, biomass to be fed and feed system power capacity for each site is taken from Table 5.1. The locations MAB is listed in table 5.1 as biomass capacity (Fiskeridirektoratet, 2017). The biomass determines the rated power of the feed system and the evolution of power demands in the model as the biomass grows.

Enterprise	Placement	Location coordinates	Biomass capacity [tons]	Rated Feed Power [kW]
Salmar Farming AS	Skårliodden	**N**: 69° 28.476' **Ø**: 18° 03.801'	6000 t	210
	Vindhammarneset	**N**: 69° 28.104' **Ø**: 17° 36.286'	5000 t	180
	Indre Bringenes	**N**: 69° 29.047' **Ø**: 17° 34.127'	6700 t	240
	Lekangsund	**N**: 69° 02.278' **Ø**: 17° 15.798'	5030 t	180
	Kvitfloget	**N**: 69° 08.725' **Ø**: 17° 38.512'	6615 t	240
Eidsfjord Sjøfarm AS	Kvenbukta	**N**: 69° 13.985' **Ø**: 17° 05.367'	3900 t	120
	Flesen	**N**: 69° 14.816' **Ø**: 17° 01.528'	2700 t	90
Nor Seafood AS	Ytre Jøvik	**N**: 69° 25.230' **Ø**: 17° 20.225'	5400 t	180
	Ytre Lavollsfjord	**N**: 69° 25.161' **Ø**: 17° 17.247'	3600 t	120
	Finnstein	**N**: 69° 19.732' **Ø**: 17° 03.753'	2700 t	90
Flakstadvåg Laks AS	Flakstadvåg	**N**: 69° 11.216' **Ø**: 17° 00.808'	3600 t	120
	Skarvberget	**N**: 69° 08.800' **Ø**: 17° 00.582'	4500 t	150
	Hallvardsøya	**N**: 69° 09.082' **Ø**: 16° 54.357'	4500 t	150
	Gjervika	**N**: 69° 03.021' **Ø**: 16° 53.218'	4500 t	150
	Frovågneset	**N**: 69° 04.123' **Ø**: 17° 03.641'	2700 t	90
NRS Farming AS	Skog	**N**: 69° 28.507' **Ø**: 17° 52.662'	2830 t	90
	Baltsfjord	**N**: 69° 32.783' **Ø**: 17° 46.135'	5670 t	180
	Trælvika	**N**: 69° 31.129' **Ø**: 17° 41.171'	5700 t	210
Biomar AS	Trettevik	**N**: 69° 30.779' **Ø**: 18° 01.165'	7560 t	270
		Sum =	89205 t	3060

Table 5.1 Aquaculture locations on Senja, location coordinates, biomass capacity and rated feed power

5.4.2 Power grid distribution versus aquaculture locations

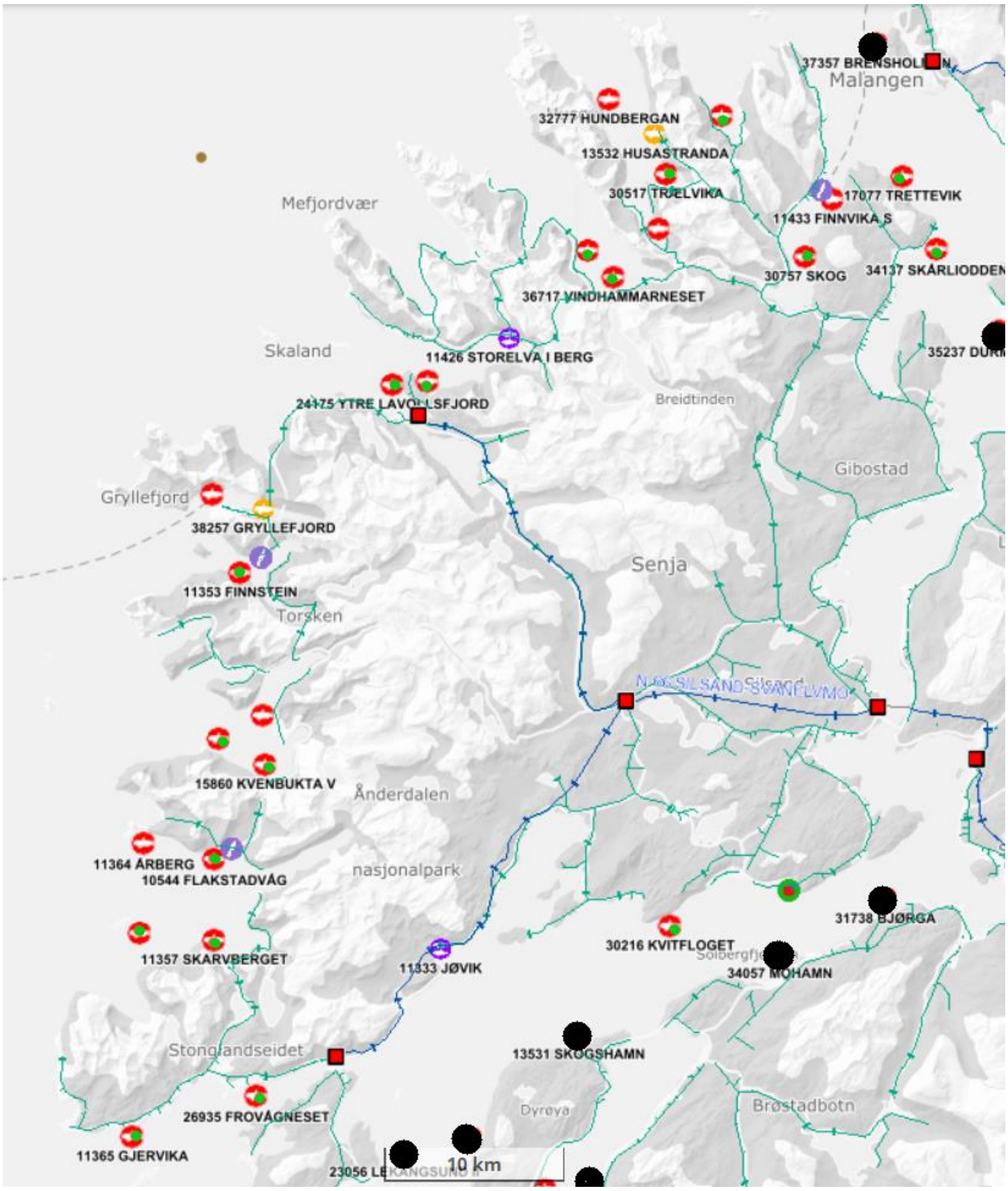

Figure 5.22 Aquaculture locations on Senja compared with the power grid

All aquaculture locations form Figure 5.22 are marked with red circles. Locations with a green dot present in the red circles are locations that are currently active and with an associated active feed barge. They are directly linked with the overview from Table 5.1. Locations that aren't active (no green dots) are currently under fallowing. Fallowing is a proven way to avoid diseases and lice on the fish farm. The fish cages are emptied and cleaned for a minimum period of two months before they can resume farming the cages again (Lovdata, 2009). Coordinated fallowing in a region is a preferred method of production to manage sea lice problems, which implies that production of the facilities will be in phase with each other, resulting in coordinated power demands.

The blue grid from Figure 5.22 represents the regional grid with an available current of 66 kV. The green grid represents the distribution grid with an available current of 22 kV. In the transition between the grids, a transformer is present, illustrated as a red square

5.4.3 Simulated power consumption

The simulation model for the Senja region seen in Figure 5.23, with the grid connection and transformer stations modelled as a slack bus (infinite power) and ideal transformers

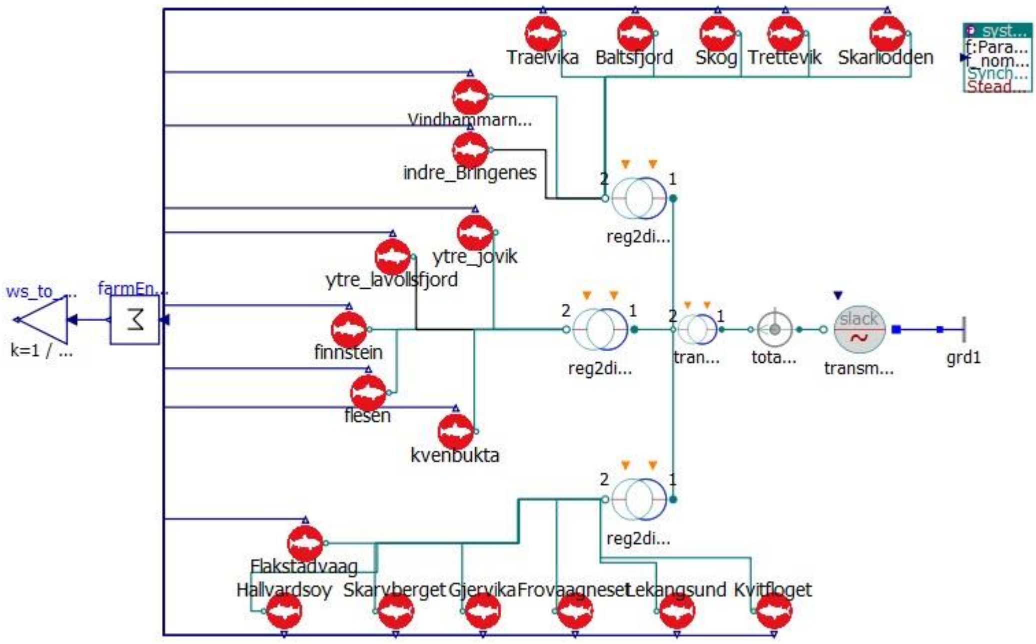

Figure 5.23 The simulation model of locations on Senja developed in OpenModelica

Figure 5.24 below, shows how the power consumption for all feed barges on Senja. The simulation is done with all feed barges operating in the same period of the production cycle and connected to the local power grid on Senja. This shows how the power demand from the power grid will be in a “worst case” scenario. The maximum power consumption is 3,8 MW at the end of the production cycle. If a peak shaving method with a battery of 120 kW of available power on all 19 locations, the power demand from the power grid can be reduced to 1,52 MW. Which is significant. However, the energy demand will remain the same, the peak power demand will be drastically reduced in favor for the power grid.

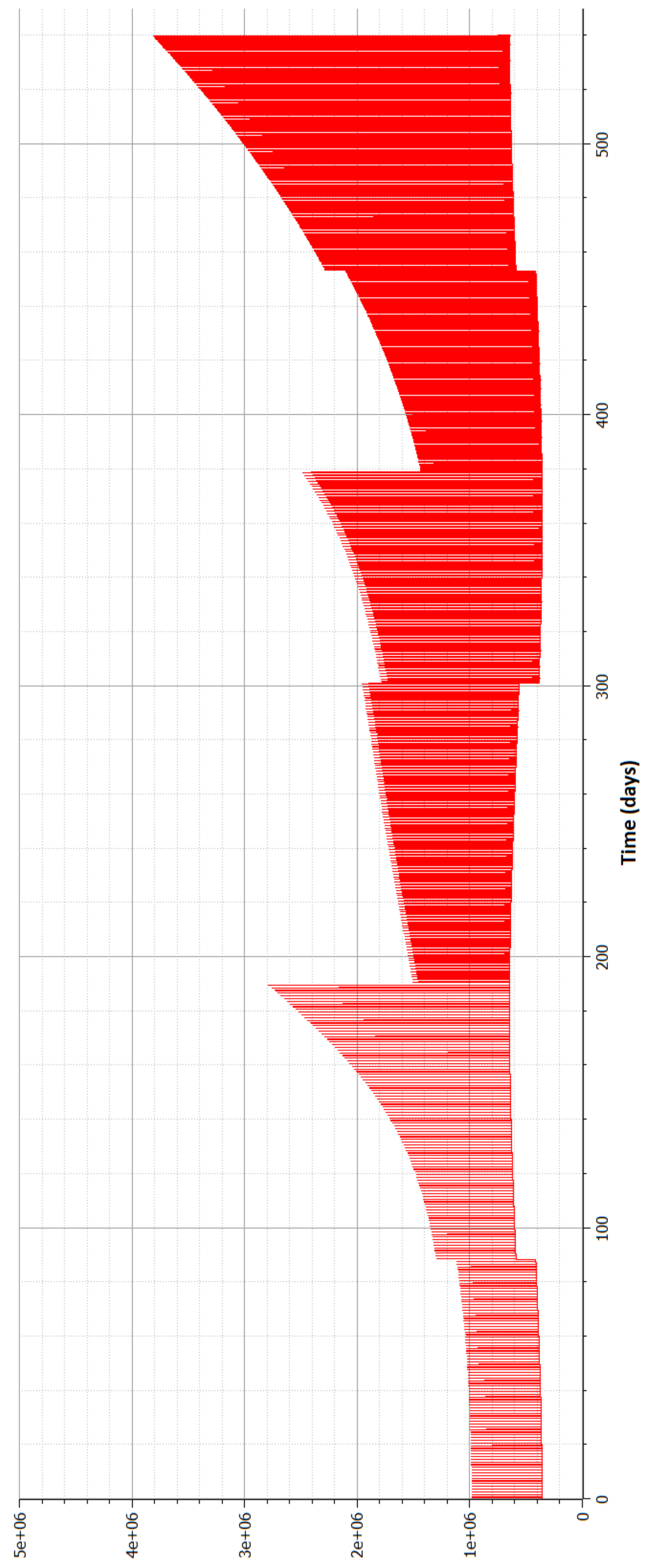

Figure 5.24 Power consumption throughout the whole production cycle of all 19 feed barge located on Senja

6 Discussion

6.1 Numerical modeling

By performing numerical integration methods in OpenModelica it has been possible to simulate a simple power distribution model of a single fish farm, as well as integrating the same model for a whole region. In order to create the power distribution models, several assumptions regarding power consumption have been put. By investigating the collected data from real fish farms, which contained power consumption through days and months in different stages of the production cycle, is was possible to find a relatively good determination of the power distribution to the various consumers. While the exact power consumption from each consumer was hard to determine, the total power consumption was relatively straight forward to compare with the collected data, and thus giving a fairly accurate result. The consumers were divided into power for heating, feed power, light power and hotel power. This is where heat, light and hotel power were used to define the base load and the daily feed power was defined in specific intervals throughout the whole production cycle.

More complex systems were put together to show the development of power and energy throughout the production cycle. One of the most important system to execute was the biomass model. Since power consumption from the feed conveying system highly relies on the available biomass on the location, determining the average growth rate of the farmed fish through the production cycle was important. As a rule of thumb, the feed demand of 24 hours is about 1%, assumptions of the feed power relative to the feed demand were therefore carried out.

6.2 Dimensioning of an alternative energy source/carrier

With the simulation on power and energy consumption carried out from OpenModelica, it has proved that using a hybrid system with battery and diesel generators is possible. By substituting the power delivered from the diesel generators with an alternative energy carrier such as hydrogen it will be possible to operate fully without emissions. Two scenarios were investigated with the battery in this stage of the production cycle, known as peak shaving and bottom coverage. The battery has proven its place in the system to be a feasible solution for both peak shaving and bottom coverage. Since dimensioning of the battery has been executed in the most power demanding stage in the production cycle, the battery is therefore capable of covering a majority of the base load as well as load from the feed system in the early stages of the production cycle where the power demand is still low. A tradeoff by dimensioning the battery for the highest power demand is the investment cost of such a battery size. However, the battery itself does not cut fuel consumption to a significant degree since it relies on generator power on the recharge, its advantage is rather to reduce operating hours on the generators. This leads to less wear and tear on the generators, fewer maintenance intervals as well as fluid changes and less sooting from the generators. In addition, the generators might work on more preferred RPM while charging the batteries giving better fuel efficiency. This will require further development on the PMS unit and research on fuel economy on the specific generators to be fully utilized. Different strategies from the PMS can have different benefits in different stages in the production cycle as well as improving the generators for working at optimal RPM.

Given the results in this thesis there is no surprise that companies such as AKVA group already have delivered several hybrid feed barges to current customers. Comparing results on battery pack size from this thesis with the presented battery pack sizes from AKVA group, it is doubtful that their batteries are capable of covering the base loads in the later stage of the production cycle should it coincide with period of darkness with cage lights engaged in addition to a higher heat power demand. However, the peak shaving method, in this case, should be a more appropriate way, and will still be a good solution.

6.3 Case study on Senja

Concerning the case study in a sparsely populated area such as Senja where limitations in the power grid is a limiting factor, batteries will be helpful in cutting the peak power while maintaining stable current in the power grid. Nevertheless, the energy delivery from the power grid will remain the same but in a reduced power matter, providing a more even energy supply throughout the day and for the whole production. In that way barges located in sparsely populated areas can be electrified from shore while utilizing an energy buffer from det batteries.

7 Conclusion and further work

Using OpenModelica and specifically the power systems library to simulate the power and energy demands in aquaculture is feasible, though more accurate results would require a larger collection of actual data.

Variations in the power consumption makes feed barges a good candidate for hybridization with a battery as an energy buffer to either shave the power peaks or used as a source to cover the base loads. Utilizing batteries allows for more energy carriers and sources to be included, preferably from renewable energy to reduce some of the emissions from fossil fuels.

Dimensioning a power system with a battery for peak shaving in the late stage of the production cycle, will give possibilities of covering large parts of the energy demand with the battery in the early stage of the production cycle. Either as peak shaving, base load coverage or used alone with intermittent charging from generators. Also, a feasible solution to reduce operating hours on the generators.

Energy demands vary according to usage of lights and winter base loads, which implies that pragmatic design of power systems is necessary. There is no optimal design for all conditions.

Further work

More collected data broken down to consumers and for longer time series. The collected data can then be used for a better PMS design, considering an assumed energy consumption prioritizing both power and energy.

Development of more refined models, particularly for the pneumatic conveying system will be necessary.

Works cited

AKVA group. (2019). *Vedlikeholdsmanual Akvasmart CCS feeding system.* AkvaGroup.

AKVA Group. (n.d.). *Batteripakker*. Retrieved Juli 1, 2020, from https://www.akvagroup.com/merdbasert-oppdrett/batteripakker

AKVA group. (n.d.). *Våre Fôrflåter*. Retrieved Juni 7, 2020, from https://www.akvagroup.com/merdbasert-oppdrett/f-rfl%c3%a5ter

Amdahl, J., Berge, S., Dukan, F., Endal, A., Hals, J., Holm, H., . . . Æsøy, V. (2014). *Havromsteknologi - et hav av muligheter.* Fagbokforlaget Vigmostad & Bjørge AS.

Cengel, Y. A., & Boles, M. A. (2015). *Thermodynamics - An Engineering Approach* (8 ed.). New York: McGraw-Hill Education.

Corvus Energy. (n.d.). *Corvus Energy*. Retrieved April 07, 2020, from https://corvusenergy.com/products/corvus-orca-energy/

DNV. (2019). *Assessment of selected alternative fuels and technologies.*

DOE. (2006). *Hydrogen Fuel Cells.*

EIA. (2019). *Natural gas explained*. Retrieved 05 20, 2020, from https://www.eia.gov/energyexplained/natural-gas/liquefied-natural-gas.php

Electronics tutorials. (2019). *Transformer basics*. Retrieved November 10, 2019, from Electronics tutorials: https://www.electronics-tutorials.ws/transformer/transformer-basics.html

Fiskeribladet. (2018). *Fiskeribladet*. Retrieved Mars 27, 2020, from https://fiskeribladet.no/tekfisk/nyheter/?artikkel=64366

Fiskeridirektoratet. (2017). *Tildelingsprosessen*. Retrieved April 2020, from https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Tildelingsprosessen

Fritzson, P., & Thiele, B. (2016). *Introduction to Object-Oriented Modeling, simulation, debugging and dynamic optimization with Modelica using OpenModelica.* Wiley.

iLaks. (2019, September 13). *Flakstadvåg Laks går til innkjøp av hybridløsning for elektrifisering av fôrflåte*. Retrieved December 8, 2019, from https://ilaks.no/flakstadvag-laks-gar-til-innkjop-av-hybridlosning-for-elektrifisering-av-forflate/

Ingebrigtsen, E., & Glomstein, R. (n.d.). *LANDSTRØMSFORSYNING TIL SKIP - FORDELER, MULIGHETER OG UTFORDRINGER.* Sintef.

Klinzing, G. E., Rizk, F., Marcus, R., & Leung, L. S. (2010). *Pneumatic conveying of solids - A theoretical and practical approach* (3. ed.). Springer.

Lovdata. (2008). *Forskrift om drift av akvakulturanlegg*. Retrieved Juni 30, 2020, from https://lovdata.no/dokument/SF/forskrift/2008-06-17-822

Lovdata. (2009, Desember 18). *Forskrift om drift av akvakulturanlegg (akvakulturdriftsforskriften).* Retrieved April 15, 2020, from https://lovdata.no/dokument/SF/forskrift/2008-06-17-822/KAPITTEL_4#%C2%A740

Misund, B. (2019). *Store Norske Leksikon*. Retrieved Mars 27, 2020, from https://snl.no/fiskeoppdrett

NCE Maritime CleanTech. (2019). *Norwegian future value chains for liquid hydrogen.*

NVE. (2015). *NVE*. Retrieved Mars 27, 2020, from https://www.nve.no/energiforsyning/nett/?ref=mainmenu

NVE. (2018). *NVE*. Retrieved Mars 27, 2020, from https://www.nve.no/reguleringsmyndigheten/nytt-fra-rme/nyheter-reguleringsmyndigheten-for-energi/endringer-i-regelverket-om-anleggsbidrag-styrker-vernet-av-kundene/

Olje- og energidepartementet. (2014). *Et bedre organisert strømnett.* Oslo: Regjeringen.

Opensource.com. (n.d.). *opensource.com*. Retrieved Mars 27, 2020, from https://opensource.com/resources/what-open-source

Pedersen, B. (2019). *Store Norske Leksikon*. Retrieved April 3, 2020, from https://snl.no/hydrogen

Regjeringen. (2015). *Norwegian Salmon Farming*. Retrieved April 2020, from https://www.regjeringen.no/no/dokumenter/norwegian-salmon-farming/id2461650/

Rostein. (n.d.). *Sortering*. Retrieved from https://www.rostein.no/tjenester/

SinkabergHansen. (n.d.). *Settefisk*. Retrieved Juni 30, 2020, from https://sinkaberghansen.no/produkter/settefisk/

Skøien, K. R., Alver, M. O., & Alfredsen, J. (2017). *Modelling and simulation of rotary feed spreaders with application to sea cage aquaculture.* Elsevier.

Volker Quaschning. (2015, June). *Volker Quaschning*. Retrieved from Specific Carbon Dioxide Emissions of Various Fuels: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php

Winkler, D. (2017, September). Electrical Power System Modelling in Modelica – Comparing Open-Source Library Options.

Yoshio, M., Brodd, R. J., & Kozawa, A. (2009). *Lithium-ion Batteries.* New York: Springer.

Appendix A: <OpenModelica_SourceCodes> (only electronic

A zip-file with all modelica source code for models and simulation (only electronic).