Svein Aadland

Electrification and Emission Reduction for Aquaculture Vessels; Case Study of a Wellboat

Master's thesis in Marine Technology
Supervisor: Mehdi Zadeh
Co-supervisor: Bjørn Egil Asbjørnslett
June 2021

Master's thesis

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Abstract

The world society is facing significant climate change as one of the biggest challenges of our time. Climate change has provided an increased focus on reducing the world's greenhouse gas emissions and is also on top of the UN Association's agenda. The shipping industry accounts for 90% of world transport goods and is an essential part of the world economy. With responsibility for such a large part of the world's trade, it follows a high emission caused by fossil fuel. The aquaculture industry in Norway can contribute to the green shift by electrification of fish farm locations, battery usage on vessels, and infrastructure development. Research shows that 80% of today's aquaculture sites can be electrified profitably if energy savings are included in the calculation. In addition, electrified locations create new opportunities for electric-powered aquaculture vessels.

This thesis aims to look at the possibility of emission reduction through electrification of aquaculture vessels with the main focus on wellboats. A literature study has been carried out on various Energy Storage Systems (ESS), with a particular focus on batteries. A literature study on wellboats was also necessary to understand what requirements the propulsion system must satisfy in such a complex vessel as a wellboat. Through literature searches on wellboats, the auxiliary systems proved to be highly energy demanding. Battery implementation in vessels like this proved to be more challenging than expected. As the vessels have unpredictable sailing patterns and energy-intensive operations, fully electrical operation work without a shore-side power connection might look challenging. Battery use for load leveling, peak shaving, or as a non-spinning reserve can contribute to reduced fuel consumption. Due to high consumption in both port and at the fish farms, a plug-in hybrid solution with the possibility of charging the battery and carrying out operational work with a shore power connection will be the potential best solution.

Through a load profile estimation based on speed and position data from AIS and assumptions for auxiliary loads based on data from a supplier of the fish pumping, circulation, and handling equipment, a representative and credible load profile for a typical wellboat is made. The load profile provided a good overview of the vessel's load and made the basis for a case study. In the case study, three different scenarios are tested, a conventional solution, a battery hybrid solution for peak shaving operations, and a battery hybrid solution for load leveling. The battery solution for peak shaving provided an unrealistic-sized battery for the vessel, and the load-leveling scenario provided a minimal fuel saving. Eventually, constant load assumed for the auxiliary load, resulting in no fluctuations disregard when there are changes in the ship's speed. Therefore the battery is only used during transit or maneuvering, making it less profitable than it probably would be. Although the case study shows that the solution does not reduce the vessel's emissions significantly and therefore does not appear profitable, the impact of the reduced wear on engine systems should also be taken into account on the benefit side.

Sammendrag

Verden står ovenfor betydelige klimaendringer som en av vår tids største utfordringer. Klimaendringer har gitt et økt fokus på å redusere verdens klimagassutslipp og er også på toppen av FNs agenda. Skipsfartsindustrien står for 90% av verdens transport varer og er en viktig del av verdensøkonomien. Med ansvar for en så stor del av verdens handelen følger den et høyt utslipp forårsaket av fossilt brensel. Akvakulturindustrien i Norge kan bidra til det grønne skiftet ved elektrifisering av oppdrettsanlegg, batteribruk på fartøy og infrastrukturutvikling. Forskning viser at 80% av dagens oppdrettsanlegg kan elektrifiseres lønnsomt hvis energibesparelser er inkludert i beregningen. I tillegg skaper elektrifiserte lokasjoner nye muligheter for el-drevne havbruksfartøyer.

Denne oppgaven tar sikte på å se på muligheten for utslippsreduksjon gjennom elektrifisering av akvakulturfartøy med hovedfokus på brønnbåter. En litteraturstudie har blitt utført på forskjellige energilagringssystemer, med særlig fokus på batterier. En litteraturstudie på brønnbåter var også nødvendig for å forstå hvilke krav fremdriftssystemet må tilfredsstille i et så komplekst fartøy som en brønnbåt. Gjennom litteratursøk på brønnbåter viste hjelpesystemene seg å være svært energikrevende. Batteri implementering i fartøy som dette viste seg å være mer utfordrende enn forventet. Ettersom fartøyene har uforutsigbare seilingsmønstre og energiintensive operasjoner, kan helt elektrisk operasjonsarbeid uten landtilkobling se utfordrende ut. Bruk av batteri til lastutjevning, kutting av effekttopper eller som en reserve, kan bidra til redusert drivstofforbruk. På grunn av høyt forbruk i både havn og ved oppdrettsanlegg, vil en plug-in hybrid-løsning med mulighet for å lade batteriet og utføre operativt arbeid med landstrømforbindelse være den potensielt beste løsningen. Gjennom en lastprofilestimering basert på hastighets- og posisjonsdata fra AIS og antagelser på hjelpe systemenes last basert på data fra en leverandør av fiskepumpe-, sirkulasjons- og håndteringsutstyr, et det laget en representativ og troverdig lastprofil for en typisk brønnbåt. Lastprofilen ga en god oversikt over fartøyets last og la grunnlaget for casestudien.

Casestudien så på tre forskjellige scenarier, en konvensjonell løsning, en batteri hybrid løsning for kutting av effekttopper og en batteri hybrid løsning for lastutjevning. Batteriløsningen for kutting av effekttopper ga et urealistisk stort batteri, og lastutjevnings scenariet ga en lav minimal drivstoffbesparelse. Ettersom konstant belastning for hjelpe systemene er antatt, noe som resulterer i at ingen svingninger fremtrer uten endringer i skipets hastighet. Derfor brukes batteriet bare under transport eller manøvrering, noe som gjør det mindre lønnsomt enn det sannsynligvis vil være. Selv om casestudien viser at løsningene med batteri ikke reduserer fartøyets utslipp vesentlig og derfor heller ikke vises å være lønnsomme, bør effekten av redusert slitasje på motorsystemene også tas i betraktning på fordelesiden.

Preface

This master thesis is written at the Norwegian University of Science and Technology (NTNU) at the Department of Marine Technology. The thesis is written by Svein Aadland in the spring semester of 2021 and marks the final part of my Master of Science degree. Associate Prof. Mehdi Zadeh has been the supervisor.

Writing the Master's thesis has been both challenging and educational. Good guidance has been essential to complete the Master's thesis, and I would therefore like to use this as an opportunity to thank my supervisor Mehdi Zadeh and my Co-supervisor, Bjørn Egil Asbjørnslett, for good guidance. Mehdi Zadeh has been a good discussion partner, and his advice has been valuable in the process of writing this thesis. I would also like to thank Ph.D. student Daeseong Park for his invaluable help. His help has been essential to the outcome of the thesis.

Trondheim, June 10, 2021

Svein Aadland

Svein Aadland

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List of Abbreviations

AC	=	Alternating Current
AIS	=	Automatic Identification System
CO_2	=	Carbon Dioxide
DC	=	Direct Current
DNV	=	Det Norske Veritas
ECA	=	Emission Control Areas
ESS	=	Energy Storage System
EEDI	=	Energy Efficiency Design Index
FOC	=	Fuel Oil Consumption
Genset	=	Generator set
GHG	=	Greenhouse Gas
GPS	=	Global Positioning System
IMO	=	International Maritime Organization
LOA	=	Length Overall
MARPOL	=	Marine Pollution
NIS	=	Norsk internasjonalt skipsregister
NOR	=	Norsk ordinært skipsregister
NO_x	=	Nitrogen oxide
OPEX	=	Operating expenses
OSV	=	Offshore Supply Vessel
O_2	=	Dioxygen
pH	=	pondus Hydrogenii
PSV	=	Platform Supply Vessel
PTI	=	Power Take In
PTO	=	Power Take Out
RPM	=	Revolutions Per Minute
RSW	=	Refrigerated Sea Water
SCR	=	Selective Catalytic Reduction
SFOC	=	Specific Fuel Oil Consumption
SO_x	=	Sulfur oxide
UN	=	United Nations
UV	=	Ultraviolet
VLCC	=	Very Large Crude Carrier
VLCV	=	Very Large Container Vessel
VSD	=	Variable Speed Drive

Chapter 1

Introduction

1.1 Background

Shipping accounts for the transportation of 90% of the world's trade, which makes shipping a significant part of the world economy [23]. World shipping still accounts for 1,076 million tonnes of $CO2$ equivalents, an emission that is equal to 2.89% of the world's Greenhouse Gas emissions (GHG). Statistically, shipping is the least environmentally damaging mode of transport when its productive value is considered. However, IMO is working towards the industry's vision to eliminate or reduce the adverse environmental impacts from ships to the barest minimum [24]. Eventually, the world society is facing significant climate change as a reaction to GHG emissions. Currently, the focus is on reducing GHG emissions to limit global warming to well below 2 degrees celsius due to the Paris Agreement's goal [42]. As a result of stricter rules and regulations and the increasing focus on stopping global warming, the demand for more environmentally friendly solutions for shipping is increasing.

The aquaculture industry in Norway can contribute to the green shift by further electrification of the vessels and infrastructure in the industry. The solutions exist today and include shore power to the aquaculture sites, battery storage onboard, and charging of all-electric and hybrid-electric vessels. In addition to reduced environmental and climate footprint offers electric operation benefits such as reduced noise from engines and lower operating and maintenance costs [2]. In a study conducted by DNV back in 2018, they point out that as much as 80 percent of today's locations can be electrified profitably when energy savings are included in the calculation [9]. Furthermore, with shore power connection, the opportunities for electric-powered aquaculture vessels increases.

Today, there are 1,325 fish farms in operation in Norway, where 1,130 produce food fish [9]. According to ABB and Bellona [2], the fish farms, together with boats connected to the various farms, have a calculated emission of 453,672 tons of $CO2$ per year. In this calculation, vessels related to the aquaculture industry make up 224,000 tons of the $CO2$ emitted by the industry. Therefore, if the industry is to achieve the UN's sustainability goals [58] related to Climate Action and Life Below Water, and at the same time provide for increasing population growth and an increasing need for food worldwide, the industry will have to look for more environmentally friendly solutions. Furthermore, as the electrification of the aquaculture locations is an ongoing process, a natural continuation will be to look at the opportunities this provides for the vessels that carry out the operations at the facilities and how the operation profile of the most energy-intensive vessels can be electrified with the goal of achieving a more environmentally friendly production.

The marine power system traditionally consists of diesel engines and generators, but other innovative and possible solutions have emerged in recent years. Batteries, fuel cells, and supercapacitors have proven to be good examples of solutions that can contribute to a change in the shipping industry. Battery solutions primarily have found their place in the market, and there has been an increase in battery installations on vessels the recent years [37]. The automotive industry abounds in electric cars and is the main contributor to batteries' development as an energy carrier. Using a battery as an energy carrier in vehicles has been revolutionary, which has led several manufacturers to start phasing out fossil cars for the benefit of investing in electric cars [18]. The automotive industry's infrastructure and current charging capabilities make electric vehicles almost as flexible as fossil-powered cars, and the charging infrastructure is constantly evolving. The future of shipping also lies in renewable energy sources, and new solutions have to be considered to reduce emissions to a respectable level. Like the automotive industry, battery use can be a solution to the problem, but the maritime industry's challenges related to electrification are extensive. In general, replacing fossil fuels is a big challenge in the marine industry since mobility adds an extra dimension to the problem. Finding good alternatives to fossil fuels is challenging since a vessel must depend on its own onboard infrastructure while sailing or operating out at the ocean. Based on today's battery technology, the power density of the available solutions is not able to fully exchange the fossil fuel solution on the most demanding applications, i.e., long-distance and heavy-load vessel applications such as VLCC's and VLCV's. Although not all types of vessels can have a full-electric operation profile, it is still possible to reduce fuel consumption and the vessel's emissions using batteries, which is a step in the right direction against zero emissions.

1.2 Rules and regulations towards greener shipping

Climate change is one of the major challenges of our time. As a significant contributor to GHG emissions, shipping has a responsibility to help ensure sustainable development and reduce greenhouse gas emissions. In this chapter, national-, and international rules and regulations will be described to create knowledge of the current rules and regulations and the goals that will influence the industry to act more sustainably. In addition, national measures from The Norwegian Environmental Agency for aquaculture are described as these regulations are central when assessing the electrification potential of aquaculture vessels.

1.2.1 MARPOL Annex VI

MARPOL 73/78 is one of the most important international conventions on the marine environment. It was designed to reduce pollution at sea, from dumping of environmental waste to emissions from ships. The Convention aims to safeguard the marine environment by eliminating pollution by oil or other harmful substances and minimizing such discharges by accident. The MARPOL regulations consist of six annexes, where Annex VI is directed towards preventing air pollution from ships. The Annex entered into force 19 May 2005 and set the limit for global SOx, and NOx emissions from ships' exhaust [22]. In addition to this, certain ECA areas are defined, where stricter regulations apply. Figure 1.1 shows the certain ECA areas marked in red and the potential future ECA areas in yellow [51].

In MARPOL Annex VI, the legal limit for sulfur content in marine fuel was reduced to 3.5% from 1 January 2012 and further reduced to 0.5% from 1 January 2020. In addition to this, there are several Emission Control Areas (ECA), where the limits for legal emissions are even lower. These areas include the Baltic Sea, the North Sea, and along the coast of Canada and the United States. In the future, it is also possible that the ECA areas will be expanded to Japan, Singapore, the Mediterranean, and along the entire Norwegian coast. In January 2015, requirements were introduced for a maximum of 0.1% sulfur content in marine fuels within the ECA areas [53]. In addition, there are requirements for reduced emissions of nitrogen oxides in the ECA areas in North America [51].

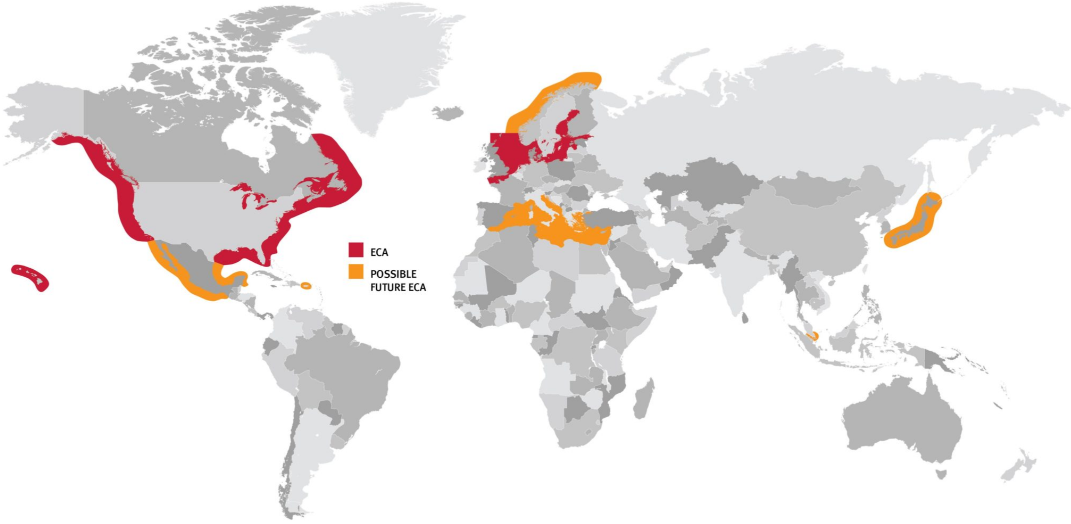


Figure 1.1: ECA areas [51]

Energy Efficiency Design Index

In addition to regulations for air pollution, an Energy Efficiency Design Index (EEDI) has also been established for new ships to follow. The EEDI is referred to by the IMO as the most crucial technical measurement that promotes the use of more energy-efficient equipment and engines aboard new ships [21]. EEDI describes the rate of impact to the environment against Benefit for society. Therefore, EEDI can be described as in Equation 1.1 as the rate of impact to the environment against Benefit for society. In other words, CO2 emission is divided by transport work [26].

$$EEDI = \frac{\text{Impact to the environment}}{\text{Benefit for society}} = \frac{CO_2 \text{ Emission}}{\text{Transport work}} \tag{1.1}$$

EEDI sets a requirement for minimum energy efficiency for different ship types and size segments within shipping. The plan is to tighten the requirements every five years to maintain the ongoing innovative and technical development of components in ship design that help minimize GHG emissions. As long as the ship satisfies the requirement for energy efficiency, the company that operates the vessel is free to choose the most cost-effective solution [21]. Today, EEDI only applies to cargo ships, container vessels, reefers, RO-RO ships, etc. The plan will apply to more ship types in the future, but since efficiency is measured in CO2 emissions per capacity-mile, the requirement must be based on something else for it to apply to other types of vessels.

1.2.2 The Norwegian Government's action plan for green shipping

In the summer of 2019, the Norwegian Government presented an action plan for green shipping. The plan shows a strategic course with possible measures and instruments to reduce greenhouse gas emissions from domestic shipping and fishing. The action plan for green shipping includes several points that describe how the Government will facilitate a green change in shipping [50][37]. Essential points in the Government's plan for greener shipping are listed below:

- Have the ambition to halve greenhouse gas emissions from domestic shipping and fishing by 2030
- Stimulate zero and low emission solutions in all vessel categories
- Stimulate further environmental friendly growth and competitiveness in the Norwegian maritime industry and facilitate increased exports of low- and zero-emission technology in the marine sector
- Assess an environmental benefit scheme for zero- and low-emission vessels in NIS and NOR
- Contribute to the International Maritime Organization (IMO)'s work to reduce greenhouse gas emissions

Electrification and hybridization of the marine sector are presented in the Government's action plan as key instruments for achieving the goal of an emission-free industry.

1.2.3 Measures from The Norwegian Environment Agency for aquaculture

Cage-based aquaculture uses nature and the Norwegian fjords as a production site and depends on a good environmental condition. To achieve sustainability goal 14 (life underwater), must the aquaculture industry's environmental impact be monitored and kept within the limits of what is assumed to be acceptable. Infection pressure, pollution, and the impacts on ecosystems cannot be greater than given tolerance limits, and a prerequisite for further development of the industry must be to facilitate excellent and long-term solutions to the environmental challenges [49]. The Norwegian Environment Agency has set up some measures to electrify the aquaculture industry. In addition, they have set up three actions that can help reduce emissions to the aquaculture industry [36].

1. Electrification of sites (feed rafts and cages). Most diesel is used on feed rafts, for example, for machinery for feeding fish. Diesel generators with a low degree of utilization can be replaced by shore power or local electricity production.

2. Diesel-powered engines can be replaced with battery-electric operating systems on the vessels.

3. Electrified feed rafts can act as the site's energy center and allow electric vessels to be supplied with electricity at the cages.

1.3 State-of-the-art

The battery market is growing, the battery price decreases and the battery solution is getting better and better. Several industries resort to electrification as it can be an environmentally friendly, energy-efficient, and at the same time, economically sustainable solution. According to DNV [9], the aquaculture industry is in the process of changing the power supply from diesel generators to shore power. It is estimated that about 50 percent of all facilities are connected to shore power today. This is a process that will continue over time. Aquaculture locations connected to shore power increase the opportunity for a more environmentally friendly and sustainable use of vessels serving the industry.

Provided that the sites have adapted facilities for operating the vessels fully electric, a few challenges are related to determining which solution will be the best according to the vessel's operational profile. Sailing distances, length of operation, and charging efficiency are factors that are decisive in an assessment of the choice of propulsion. Further in this section, some existing electric aquaculture vessel design solutions are presented.

1.3.1 Elfrida

Elfrida is an electric small service vessel developed by Siemens and Ørnli Slipp in 2017 for Salmar Farming. In 2017 this was the world's first electric vessel build for the aquaculture industry. The vessel work at Kattholmen facility, located about 50 minutes from shore with a speed of 8.5 knots [55]. The vessel has a battery capacity of 180 kWh and a diesel generator with a 150 kW effect. Elfrida is mainly working fully electric, but the diesel generator assists if the battery is not sufficient. Roger Bakken, Executive Vice President for aquaculture in Salmar, says that the vessel has worked well and about 80 - 90% of Elfrida's operation runs fully electric [30]. The project has received NOK 2 million from Enova and has functioned as an experiment for the aquaculture industry, where several companies are switching from diesel generators to shore power at the locations. Elfrida is presented in Figure 1.2.

Figure 1.2: Elfrida - Electric service vessel for Aquaculture [59]

1.3.2 GMV Zero

Grovfjord Mekaniske Verksted (GMV) will, in June 2021, deliver a fully electric catamaran designed for aquaculture service operations to their customer Wilsgård Fiskeoppdrett AS. The electric service vessel, GMV zero, has a battery capacity of $350kWh$ resulting in a range of over 32 nautical miles at 8 knots and will reduce the environmental footprint with 900 kilograms of NOx gas and 90 tonnes of CO2 in one year [1]. GMV zero's main dimensions are $13.97 \times 7.6 \times 2.40$ meters, and the vessel is designed to travel six nautical miles from the home base to the location, work for a whole day and return to the base station without charging. The vessel also has the opportunity to charge on-site. In addition to the environmental benefits, the vessel will save between 300,000 - 500,000 NOK in annual fuel costs compared to a traditional diesel-powered vessel. GMV zero is an important grant to Wildsgård's green plan, which deals with the electrification of sites, operation of green licenses, and electrification of service vessels. In Figure 1.3 GMV zero is depicted in an operation situation.

Figure 1.3: GMV Zero - Electric service catamaran for Aquaculture [31]

1.3.3 Ro Vision

Ro Vision is the world's first hybrid wellboat and is operated by the wellboat company Rostein [54]. Ro Vision already has a contract with the Norwegian salmon farmer Salmar. The vessel has a storage tanks (wells) capacity of 3,900 cubic meters and an overall length of 84.2 meters. Typically wellboats in this size range have four Gensets, but in Ro Vision, one of the Gensets of 1,300 kW has been replaced with a 600 kW battery pack. The battery pack can also be charged through a shore power connection. The battery onboard is intended for peak shaving operations and assists in situations where the vessel has a high energy requirement for shorter periods. Rostein's vice president Glen Bradley says - *"When we are in operation, energy consumption varies a lot, and then we can save and run an extra motor that has little to do by draining the battery instead of having enough energy to take the peaks. At the same time, in situations where we have an overproduction of energy, we can use it to recharge the batteries"*[54]. He also explains that the battery is used in situations where the wellboat navigates close to the fish cages, the battery is used as a redundancy if something happens to the engines or the engine has a breakdown. Usually, wellboats in this size range have to run two engines for redundancy power and states that this is a waste of energy. In addition to the battery pack, the vessel has a catalytic reduction (SCR) system to reduce NOx emissions from diesel engines. According to Bradley, this is just the beginning of Rostein's green shift, but he also noted that the wellboat industry still has a long way to go before the industry can call itself green, but this is a step in the right direction. Figure 1.4 shows the hybrid electric wellboat Ro Vision.

Figure 1.4: Ro Vision - Hybrid battery electric Wellboat [54]

1.3.4 Gåsø Høvding

In January 2021, the world's largest wellboat, Gåsø Høvding, was launched at the Sefine Shipyard in Turkey and will arrive in Norway in autumn, the same year. The vessel has a total well capacity of 7,500 cubic meters, and with a long-term contract for transportation and de-lice fish for a breeder, it is put straight to work when it arrives in Norway [14]. The unique thing about this vessel is that it is unnaturally wide compared to ordinary wellboats. In addition, the vessel is equipped with pumps onboard that use the negative pressure in the transport tanks to pump the fish onboard instead of using vacuum pumps. Gåsø Høvding also gets a 540 kWh battery pack that will be used for peak shaving and redundancy if the diesel engines have problems. Together with the customer, it is also planned that the vessel will be able to have a power supply from shore during unloading at the slaughterhouse. As the vessel can lie between one and three days to the quay to unload, this will provide a significant environmental benefit. Figure 1.5 shows the towing operation from the shipyard to Norway.

Figure 1.5: Gåsø Høvding - World's largest wellboat [16]

1.4 Research Question and objectives

The main research question in this thesis is:

”*How can hybrid power system and batteries be feasible and viable for sustainable operation of aquaculture vessels?*”

This thesis is partly an extension of the work from the specialization project conducted in autumn 2020. The main objective of the project thesis was to do a literature review on electrification of the aquaculture industry, creating an understanding of the industry and what developments are needed to create a change in the industry. In addition, AIS data and the use of AIS were investigated, and a tool for processing AIS data was created.

The objectives for the master thesis are:

- Investigate different Energy Storage Systems (ESS) and hybrid power systems for ships
- Conduct a technical investigation of typical propulsion systems and auxiliary equipment used in wellboats to understand the impact of the different components on the vessel’s energy consumption
- Perform load profile characterization of different marine vessels
- Perform load profile estimation for a typical wellboat using AIS data.
- Feasibility and Case study on the studied wellboat. The study should contain a representative load profile for the wellboats that can be used in cost analysis.

The main contribution for this master thesis is to look for a more environmental solution for aquaculture wellboats in the light of an operational profile, and load profile estimated from AIS-data.

1.5 Structure of the thesis

The structure of the remaining part of the thesis, together with a description of the content of each chapter, is presented below.

Chapter 2 - Hybrid power systems and electrification

Chapter 2 introduces different ESS and their applications onboard ships, with the main focus on the battery as a storage system. A review of Hybrid battery propulsion systems is also presented before electrification of aquaculture vessels is reviewed. This chapter aims to understand different hybrid-electric propulsion systems and the aquaculture vessel system requirements.

Chapter 3 - Characterization and Estimation of Vessel Load

Chapter 3 is divided into two, where the first part characterizes load profiles from several vessels to create knowledge of essential factors and theory for load profiles. In the second part, the method for load profile estimation from AIS data is presented.

Chapter 4 - Hybrid power system and emission reduction potential for a wellboat

Chapter 4 aims to discuss the emission reduction potential for commercial wellboat in light of the estimated load profile from Chapter 2.

Chapter 5 - Case study - Wellboat

Chapter 5 presents the case study conducted for a typical wellboat with the main focus on fuel savings implementing batteries in the vessel's topology.

Chapter 6 - Discussion

In chapter 6, the findings and the results for the thesis are discussed. Weaknesses and potential for improvement and thoughts about the results are described here.

Case study: Wellboat; feasibility and economic viability

Chapter 7 contains the conclusion of this master thesis before finally proposals for future work related to the topic are presented.

Chapter 2

Hybrid power systems and electrification

2.1 Energy Storage Systems (ESS)

Today, there are several types of energy storage systems, all with their advantages and disadvantages. Examples of typical energy storage systems can be batteries, supercapacitors, or flywheels. First, however, it is essential to understand these system's space needs, power density, and effect capability. The weight can also vary significantly, something that must be considered when designing the ship's power system. In addition to the vessel's available space and weight limitation, the vessel's operating profile and regulations for safety and requirements are of great importance for choosing an appropriate energy storage system for a ship [39].

An ESS system can replace conventional diesel engines, either as a fully electric system or a hybrid system. In a fully electric system, all emissions are equal to zero if we disregard the emissions from the production of the ESS system. On the other hand, in a hybrid electrical system, fuel savings and emission reductions will be achieved, and the system's efficiency will thus be higher. According to Corvus Energy, fuel savings and CO2 reduction are commonly achieved in a hybrid system between 15 and 25 percent and NOx reduction between 30 to 40 percent. In addition to the fuel savings and the emission reduction, an installed ESS can reduce noise and vibrations for the crew's comfort [10]. Standard operation modes for a hybrid system such as peak shaving, load leveling, spinning reserve and Zero-emission mode are described in more detail before different energy storage systems are looked at more closely.

Peak shaving

Peak shaving describes itself quite well, just by name. In peak shaving operations, the ESS ”shave” the load peaks so that the generator sets can be operated on a more optimal load [11]. Peak load is a sensitive factor for the vessel's electrical grid as they represent the highest energy demand during the operation time. However, the peak load also represents disadvantages such as increased fuel consumption and emissions, so by cutting peak loads, the vessel can achieve savings on fuel and emissions as well as maintenance costs [57].

Load leveling

Load leveling is a method or operational mode for reducing the large fluctuations occurring in the vessel's electrical demand [52]. This can be done, for example, by storing excess energy during periods when the vessel's energy demands are low and then using during periods when the energy demands are high. Load leveling operations can save the system from fluctuating loads, which can reduce the system's need for maintenance. In addition, when the load is leveled at an optimal load condition, the Genset fuel economy, and emissions can be improved compared to a conventional solution [11].

Spinning

Spinning reserve or operating reserve is engines running as a reserve in case of sudden reduction or loss of power. Using ESS to fulfill the vessel's requirement for redundant power enables fewer running engines, which in turn leads to reduced fuel consumption, emissions and engine running hours, and maintenance costs [3].

Zero-emission

The zero-emission mode makes it possible to turn off all generators so that no fuel is burned, and therefore the emission equal to zero. In zero-emission mode, all propulsion is driven by the ESS on board the ship. In addition to eliminating emissions and fuel consumption, the power system makes no noise, pleasing the crew [11].

2.1.1 Flywheel

Flywheels are mechanical rotating wheels that can be accelerated up to very high speeds for the purpose of absorbing energy in the form of rotational energy. The energy can later be recovered by reducing the rotational speed. To increase and decrease the rotational speed, it is common to use an electric machine that alternately acts as an electric motor and generator. A flywheel will thus be able to function as a battery where energy is stored as mechanical energy (rotational energy) [41]. To express the energy stored in a high-speed flywheel the following equation is used:

$$E = \frac{1}{2} I \omega^2 \tag{2.1}$$

where $I = \int r^2 \, \mathrm{d}m \left(\mathrm{kg} \cdot \mathrm{m}^2 \right)$ represents the flywheels moment of inertia, and $\omega(rad/s)$ is the fly wheels angular speed.

In advanced flywheels, the rotational speed can operate at speeds from 20,000 to over 50,000 rpm (rotations per minute). The energy loss due to friction can be significantly reduced by using a vacuum chamber and a rotor that is clamped by means of magnetic levitation. Compared to other batteries, flywheels have a very long life time with small maintenance requirements and without any practical limit to how many charging cycles (charging/discharging) can be carried out. The energy density can reach over 100 Wh/kg and the maximum output, stated in kW, can be very high compared to other battery types. However, the amount of energy that can be stored is a strong limiting factor. The storage capacity varies but is rarely over 100 kWh [20].

2.1.2 Super-capacitor

Supercapacitors, also known as ultracapacitors and electrochemical double-layer capacitors, are using the capacitance effect to store energy. The supercapacitors are capacitors with very high capacitance and low voltage limits [61]. Supercapacitors consist of two metal plates that are coated in a high carbon surface area. Since the capacitance is proportional to the area of the plates, this allows the supercapacitor to store significant energy as an electric field. Supercapacitors have a high discharge rate, making them more suited for applications where higher power is required for a short time duration. Their charging rate is equally fast and they have a much higher life cycle than batteries, usually up to a million cycles [41].

On the other hand, their cost per watt-hour is much higher than batteries. Due to their low specific energy density but very high specific power, they work best in combination with batteries to complement each other to provide overall good system performance. Both supercapacitors and batteries operates on DC.

2.1.3 Battery

Batteries are under the chemical energy classification. Batteries provide electricity through an electrochemical oxidation-reduction reaction. Today, the most common and cost effective type of battery that is used is the lead-acid battery. However, lately, there has been a growing interest in batteries with higher energy densities such as Nickel Metal Hybrid (NiMH), lithium-ion (Li-ion), and sodium-sulfur (NaS) due to a steady increase in hybrid and electric systems for ships. The main limitation of battery technology is the finite life cycle, which can also be affected by discharge depth. NiMH and Li-ion batteries can provide an increased lifetime for a higher cost. Each battery technology has its own sets of advantages and disadvantages, as shown in Table 2.1 [41].

Table 2.1: Comparison of different battery technologies [41]

Type of battery	Advantages	Disadvantages
Lead Acid	Inexpensive Lead is easily recyclable Low self-discharge (2–5% per month)	Shorty cycle-life (around 1,500 cycles) Cycle life is affected by depth of charge Low energy density (about 30–50 kWh/kg)
Nickel Cadmium	High energy density (50–75 kWh/kg) High cycle count (1,500–3,000 cycles)	High degradation High cost Toxicity of cadmium metal
Sodium Sulphur	High energy density (150–240 kWh/kg) No self-discharge No degradation for deep charge High efficiency (75–90%)	Temperature of battery is kept between 300 °C to 350 °C
Lithium-ion	Very high efficiency (90–97%) Very low self-discharge (1–3% per month) Low maintenance	Very high cost Life cycle reduces by deep discharge Need special overcharge protection circuit

As described in Table 2.1, performance naturally comes with a high cost. Therefore, lithium-ion batteries are the most expensive batteries but still currently the batteries that are best suited for use as an energy storage device on ships due to the performance demand, either focusing on high energy or high power. For vessel applications, a combination of high energy and high power is often preferable. The power density is also high in these types of batteries, making the weight of the battery more suitable for use in vessels. Batteries operate on direct current (DC) and require power converters to be connected to the ship's grid. The type of converter will depend on the type of bus used: AC or DC.

Battery as a source of energy in maritime sector

Battery technology is a well-known technology that is constantly evolving. The automotive industry abounds in electric cars and contributes to battery development and battery as an energy carrier. Battery as an energy source in the maritime sector is less common but has increased considerably in recent years. According to the Maritime Battery Forum presented by DNV, it was in November 2019, 185 vessels using a battery as an energy source to perform various operations onboard the ship. Of these vessels were 67 operating in Norway. In addition to the ships operating with batteries, there are 185 new vessels under construction, and this number is also expected to rise. Figure 2.1 is showing the number of ships using batteries somehow as a source of energy, from 1998 - 2026. The blue column is vessels in operation, and the orange column is vessels under construction [37].

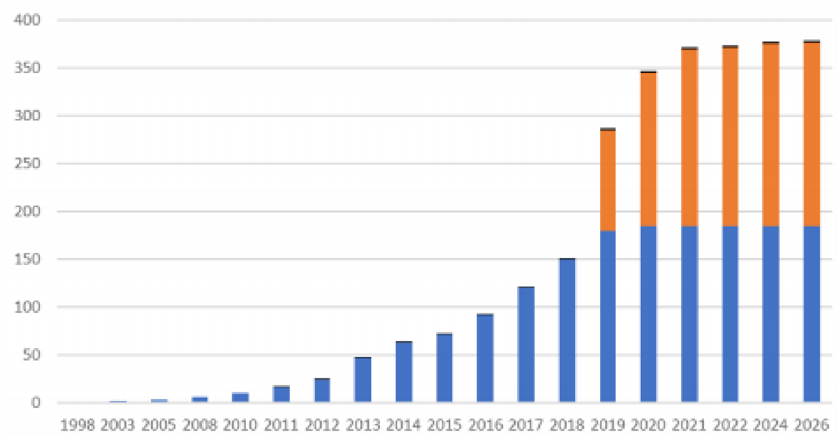


Figure 2.1: Number of ships with batteries in operation and under construction, per November 2019 [37]

Some vessels use battery as their primary source of energy (pure electric system), or the more common way to use batteries is in combination with diesel generators (hybrid system). Batteries can, in several ways, help to reduce climate emissions using them as an energy carrier. In the Klimakur 2030 report, various applications for battery usage are described. The applications are listed below [37].

- **Propulsion** - Vessels using battery as propulsion.
- **Redundancy** - The batteries are used as redundancy for generators. There will be less need to have generators running as a spinning reserve. The batteries can also be used as a general reserve by emergencies.
- **Peak shaving** - Energy from the batteries is used for peak shaving of the engine's power peaks. The battery becomes a buffer and balances the power from the motors.
- **Optimization** - Batteries can help optimize the generators, which can reduce maintenance, also called load leveling and load smoothing.
- **Regenerative effect** - Recovering energy from lifting operations using cranes or other operations.

Battery market and pricing

The battery market is growing, and the automotive industry is one of the contributors pushing the market. There are several major players worldwide, and the latest news is that Equinor, in collaboration with

Hydro and Panasonic, will investigate the possibility of the European battery business. Equinor writes on their website that they believe that battery storage will play an increasingly important role in the work of leading energy systems towards the goal of net zero-emission. They also state that they expect battery production to grow rapidly as a solution to climate change[13].

Today the annual lithium-ion battery market is worth between \$20 billion - \$30 billion. James Frith is senior energy storage analyst for Bloomberg NEF, said in 2019: *"According to our forecasts, by 2030 the battery market will be worth \$116 billion annually, and this doesn't include investment in the supply chain. However, as cell and pack prices are falling, purchasers will get more value for their money than they do today."* Battery cost can further be reduced in the years to come by reducing the manufacturing capital expenditures, new pack designs, and a change in the supply chains[19]. If batteries become cheaper, it can be expected that more sectors will electrify. The projection of the battery marked value is shown in Figure 2.2.

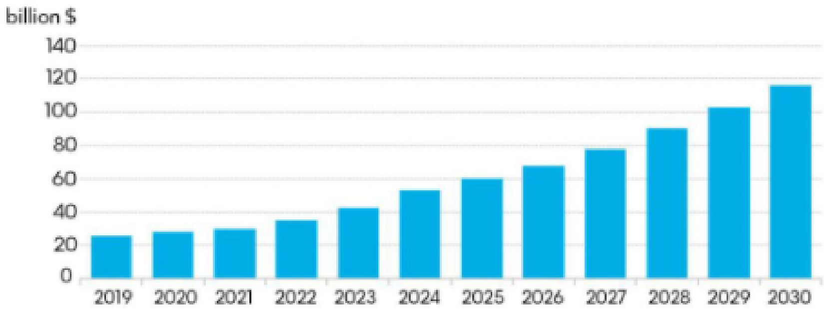


Figure 2.2: Projection of the battery marked value [19]

In 2010 was the battery price between \$1,100 - \$1,000 per kilowatt-hour. Since this, the price has fallen by around 90 percent, and it is predicted to fall even more in the years to come [19][35]. Figure 2.3 refers to the battery price from 2010 to 2018 and the projected price for the years until 2030.

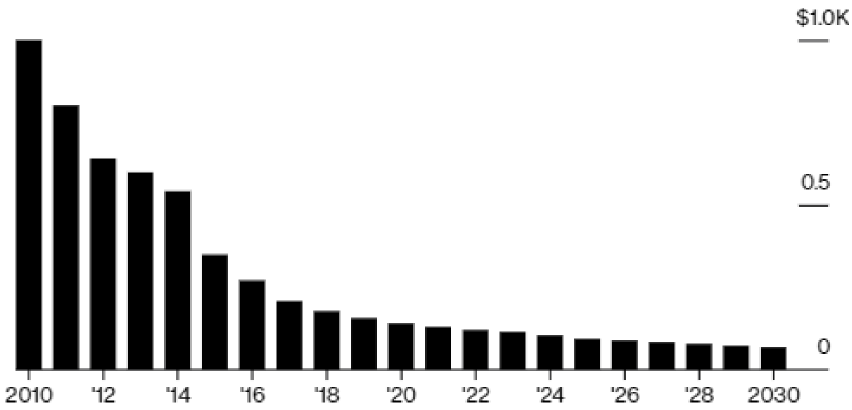


Figure 2.3: Historical battery price and projections [35]

2.2 Review of battery hybrid marine propulsion systems

This chapter describes different existing power systems with integrated batteries. The review of the different systems is based on a publication from DNV - In focus - The future is hybrid [8]. The power systems review explains what battery and hybrid solutions exist today and what benefits these solutions can provide. This review also forms an understanding that can be useful when the possibility of electrification of aquaculture vessels is to be looked at more closely. Figure 2.4 describes the different symbols used in the description of the power systems.

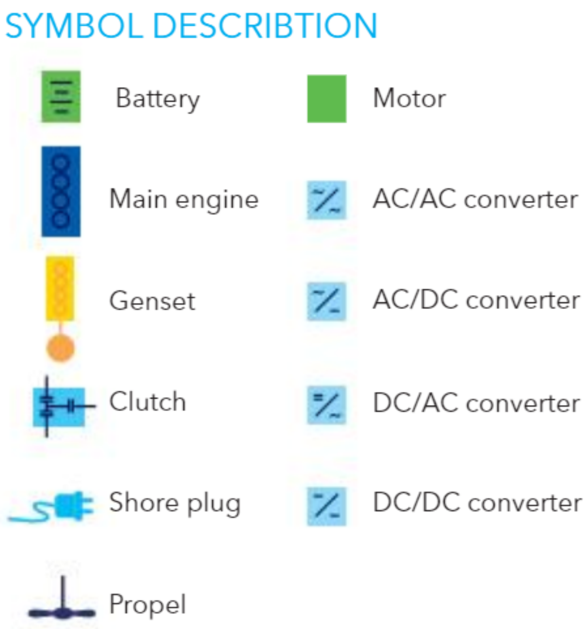


Figure 2.4: Symbol description [8]

Mechanical propulsion with battery hybrid electrical power plant

A system using mechanical propulsion with a battery hybrid electrical power plant is a system using a traditional propulsion system but a battery in the electrical system. In this type of system, the battery will be effective in the use of smoothing the electrical loads and at the same time helping to handle large load steps. By reducing the large load steps, it might be possible to reduce the number of auxiliary engines. The battery can also be used to harvest energy in cases where the load can regenerate power, such as during crane operations. Figure 2.5 shows a mechanical propulsion system with battery hybrid electrical power plant [8].

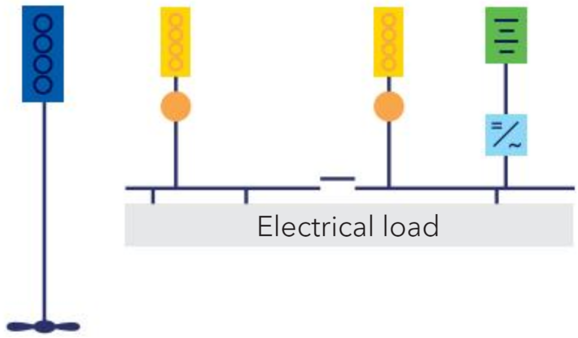


Figure 2.5: Mechanical propulsion with battery hybrid electrical power plant [8]

Hybrid battery propulsion

In a Hybrid battery propulsion system, the batteries are integrated into a power system for electrical propulsion. In this kind of system, the batteries will provide power to the propulsion of the ship. By using such a system, it is possible to either run on pure battery power, only power from the generator sets, or in parallel operation using both batteries and generators to power the ship. In a hybrid battery propulsion system, the battery will also smooth the load variations on the generator sets, called peak shaving. A hybrid battery power system comes with benefits as reduced noise and vibration on the ship, as the battery will smooth the load. With a hybrid battery propulsion system, it is possible to facilitate zero-emission operation when entering a harbor. Figure 2.6 shows a hybrid battery propulsion system [8].

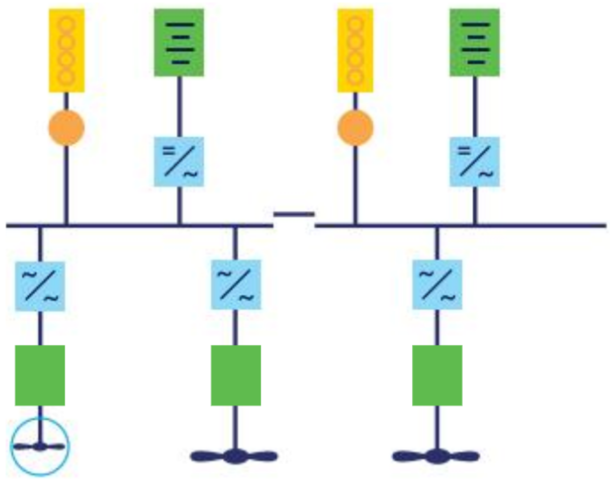


Figure 2.6: Hybrid battery propulsion [8]

Hybrid battery propulsion, with distributed batteries

In a hybrid battery propulsion system with distributed batteries, the efficiency is the main difference from a standard Hybrid battery propulsion system. A standard Hybrid battery propulsion system has several power converters, where each of these converters represents a power loss of approximately 2 percent. However, by distributing the batteries into the propulsion converters, the number of power converters can be reduced, resulting in further reduced loss of power.

Another benefit of a hybrid battery propulsion system with distributed batteries is that each propulsion unit is independent of a common energy source. This might be a smart solution in vessels requiring a highly reliable propulsion thrust, such as redundant dynamic positioning vessels. Figure 2.7 shows a hybrid battery propulsion system with distributed batteries [8].

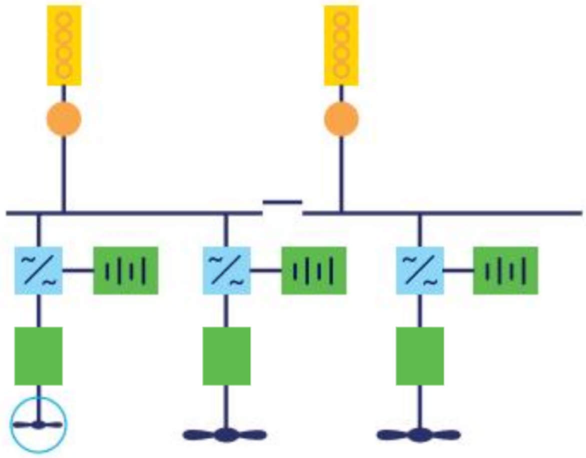


Figure 2.7: Hybrid battery propulsion, with distributed batteries [8]

Hybrid battery, electrical, mechanical propulsion, and DC distribution

In Figure 2.8 a hybrid system with plug-in possibilities and DC distribution is shown. The system has an electrical/mechanical hybrid solution for propulsion. By using a DC-distributed system, the speed of the prime movers for the generators can be adjusted to the load-dependent optimum fuel level. This means that fuel consumption is reduced and the environmental footprint is minimized. This electrical/mechanical hybrid solution allows the main engine to generate electricity, also called (Power Take Out (PTO)). The generator sets and batteries can also produce propulsion power, also called (Power Take In (PTI)). A boost mode is possible (additional thrust power) when the main engine and PTI motor are running in parallel [8].

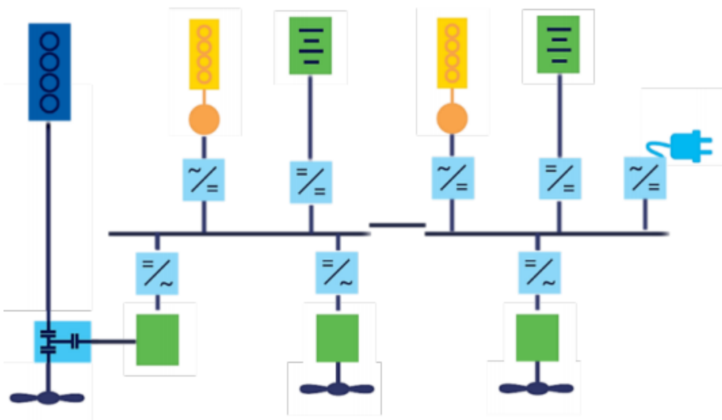


Figure 2.8: Hybrid battery, electrical, mechanical propulsion and DC distribution [8]

Battery propulsion

Figure 2.1 shows a fully electric power system where the battery is the only energy carrier. The battery is charged through an AC/DC converter that is either located on the vessel or the charging station. The system contains two independent battery systems delivering power to the thrusters [8]. A fully electric propulsion system with only batteries as an energy source can be complicated in several cases, as such a solution is very dependent on the charging possibilities and the infrastructure. This type of solution does, therefore, not fit every type of vessel and its operational profile.

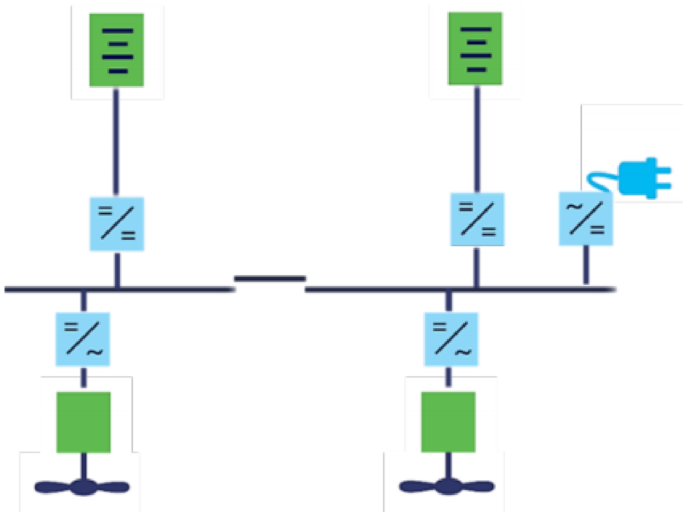


Figure 2.9: Battery electric propulsion system [8]

2.3 Electrification of aquaculture vessels

Electrification of aquaculture vessels entails a general energy efficiency of the vessel in combination with the battery being used for propulsion or supplying other auxiliary systems aboard. Aquaculture vessels can be well suited for electrification, as some of them often run short distances locally. The size and the need for engine size and the operational profile for the vessel are factors that determine if the vessel is suited for an electric solution. Charging on the feed barges or the fish cages might be necessary for some vessels if electric-powered propulsion should be a good solution [36].

According to the Norwegian Environment Agency is shore power necessary measures in combination with battery packages, whether the vessels can be electrified and at the same time be environmentally friendly. The vessels can be fully electric or hybrid solutions. This depends on where the site is located, access to power and type of operations, and sailing distance. When the feed barge is connected to shore power, it is possible to supply power to the edge of the fish cages. High energy demanded operations carried out while the vessel is anchored to the cages may be possible to conduct while connected to shore power. It is estimated that a contribution like this can reduce 75 percent of the fuel consumption related to service vessels serving the industry [36].

Hybrid vessels using the battery for peak-shaving are becoming more common. Electric equipment as cranes, winch, or other equipment used for operation in aquaculture is a current measure that helps to increase the degree of hybridization. They will provide more optimal utilization of the batteries [37]. The aquaculture industry is substituted by services delivered by wellboats and cargo ships. There are some barriers associated with the electrification of wellboats, and cargo ships, as these are vessels with a high power requirement. These types of vessels often have unpredictable working days and complex sailing patterns. It might, therefore, in some cases, be challenging to convert from diesel to electric power systems easily. However, emissions to these vessels can be reduced through speed optimization, route planning, and hybridization with battery packs and shore power connection [36]. This can provide benefits such as reduced emissions during transit and operation, reduced operational costs, better working environment for employees on board through reduced engine noise and vibration.

2.3.1 Electrification of location

Electrification of aquaculture locations requires shore power if it should be energy and environmentally friendly. Shore power to the aquaculture site can be developed through submarine cables from shore to the feed barges and then further out to the fish cages. Electrification of the locations can have an environmental effect and a cost-saving associated with reduced diesel consumption. The Norwegian Environment Agency has estimated that an average aquaculture location uses 70,000 liters during operation time, corresponding to approximately one and a half years. However, electrification of the aquaculture sites is essential in the development of electrified vessels serving the industry [36]. Electrified locations can make it possible to carry out operations with shore-side connections. The operation is the most energy-intensive work for individual vessels and can therefore be profitable and more environmentally friendly with shore power connection.

2.4 Wellboats

Wellboats, also known as Live fish Carriers, is a special vessel used to transport live fish to and from the location. Such vessels mainly transport smolt to the aquaculture facilities or transport ready-to-slaughter fish to the slaughterhouse, but in recent years, these vessels have become more and more complex, as they are used for other types of operations than just transporting fish [34]. Wellboats are also often used to treat diseased fish or in de-lice operations. The vessel has several wells where fresh seawater circulates with the vessel's speed, or the water is recycled using a pump system [27]. Wellboats are also used to transport fish in bulk. Part of the coastal fishing fleet collects the fish they catch in cages or rods because they do not have the carrying capacity to feed it themselves. If necessary, a wellboat is hired to transport the fish to the packing or redistribution. During transport, the fish is cooled down by the boat's RSW system. The fish can also be mixed with ice, but this is less common today, preferably in the summer when temperatures are high [60].

In order to understand the scope of electrification of the wellboat's operation profiles, it will be essential to understand the vessel's work tasks and which systems are used at any given time. Five main tasks carried out by the live fish carrier are listed below:

- **Smolt transportation** - *From smolt hatcheries to aquaculture location*
- **Harvest transportation** - *From aquaculture location to slaughter house*
- **De-lice operations** - *Carried out on site at aquaculture location*
- **Size sorting of fish** - *Carried out on site at aquaculture location*
- **Handling of diseases** - *Carried out on site at aquaculture location*

Each of these operations requires different types of auxiliary equipment to conduct the specific tasks. As the vessel's auxiliary components are power-consuming and can dominate the vessel's power demand, it is crucial to get acquainted with the main auxiliary features and the consumption of the features. Figure 2.10 shows a typical wellboat and description of the components by name and their position in the vessel.

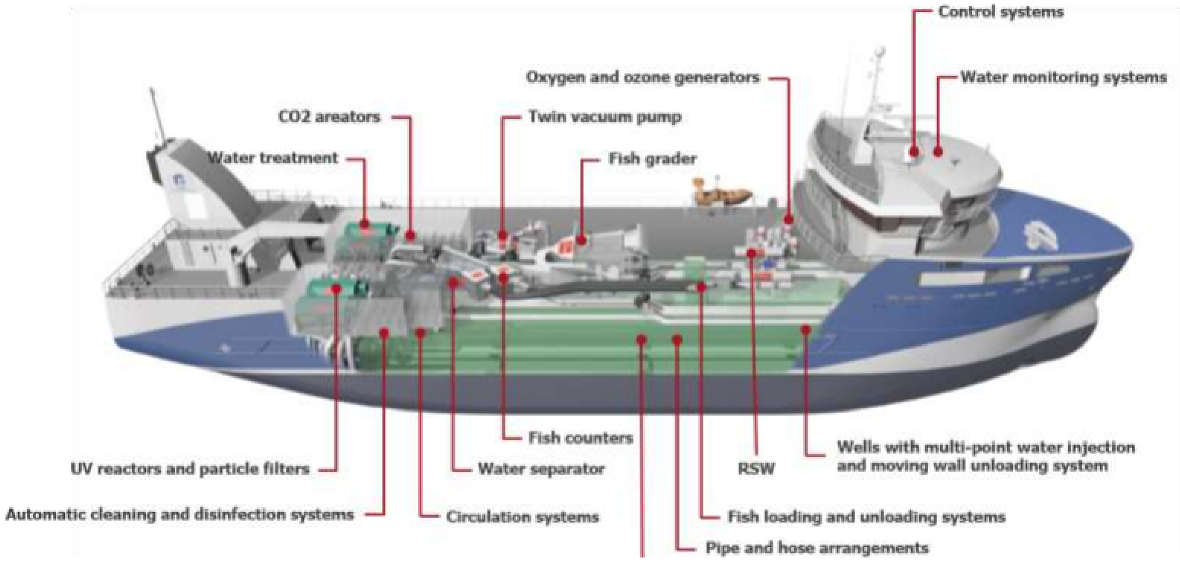


Figure 2.10: Wellboat system design illustration - 1 [7]

The machinery of the vessel is placed in the back of the vessel like shown in Figure 2.10. The component and machinery are described in more detail in the section for electrification of auxiliary systems and electric propulsion systems.

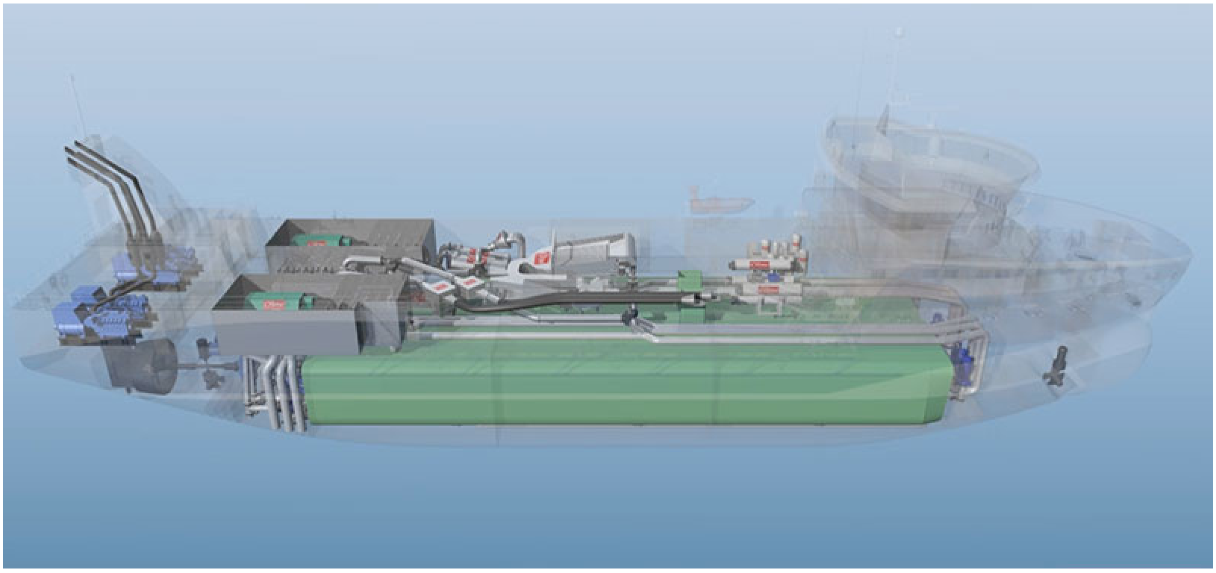


Figure 2.11: Wellboat system design illustration - 2 [43]

2.4.1 Electrification of auxiliary system

Live fish pumps

Live fish pumps are used for loading and unloading live fish. These pumps come in several sizes, and the pumps' effect should be designed in the order of magnitude of the vessel's wells. According to Samson Pumps, delivering pumps for live fish pumping, these pumps come in a size range of 310 m^3/h - 1,100 m^3/h. The size of these pumps will, of course, be crucial to the electrical power consumption of the pumps [48]. The RPM of the pump is directly related to the pump's electrical power consumption. In addition, the transportation height of the mass is also crucial to the pump's electric power consumption. The pump's electrical power consumption is dependent on the size of the vessel's tanks, the pump's capacity, and the length of the pump's operation.

RSW systems

A Refrigerated SeaWater System or RSW system is used for water cooling in the vessels wells. The RSW system makes it possible to cool the fish to a temperature where it can be in the storage tanks for a longer period without significantly reducing the quality. RSW systems recirculates seawater through pumps and a chilling system. The refrigeration system cools down the seawater before it flows into the bottom of the tanks and is evenly distributed [56].

According to PTG [46] they deliver RSW systems in size range of 50 - 2,500 kW. For reference, they delivered an RSW system to Scotland's Migdale Transport Ltd. with a capacity of 1,100 kW for a cargo capacity of 1,500 cubic meters [47]. The RSW system is mainly operated during the whole day. Therefore, the RSW system is one of the main contributors to the wellboats consumption.

Circulation & Water treatment system

The circulatory system ensures good fishing welfare and sustainable handling of the fish during transport. A circulation and water treatment system aim to maintain fresh, oxygenated water inside the storage tanks during transportation. The water quality inside the storage tanks is monitored to keep the given requirements of oxygen content (O2), carbon dioxide content (CO2), and the pH value or acidity of the water [38]. The circulation pumps circulate seawater for as long as there are fish in the storage tanks. The capacity of the pumps will vary with the cargo capacity of the vessel.

2.4.2 Electric propulsion system

Based on the brief review on hybrid power systems conducted previously in this chapter and considering the auxiliary systems onboard typical wellboats, a suggested hybrid solution for this type of vessel is to be discussed. As described earlier, the ship propulsion system could either be an alternating current (AC) system or a direct current (DC) system. AC systems have for a long time been dominant in the marine industry, but in recent years DC systems have received attention as a promising solution for hybrid power systems with their power stability, potential economic and environmental benefits [29]. Examples of AC and DC systems and their functionality, advantages, and disadvantages are described below.

Electrical propulsion system with AC grid

Figure 2.12 shows a typical electric propulsion system with an AC grid. The AC electric propulsion system does not have any main engine to supply power to the propulsion, instead, the system consists of a set of diesel Gensets (1) supplying power to the AC grid. The diesel generators have to run at a fixed speed to obtain the required frequency for the AC grid. The propulsion motors (5), auxiliary loads, and motors (6) are connected to the AC grid, and the voltage and frequency for the different loads are regulated by transformers (3) and frequency converters (4) to achieve the required operating parameters for the different loads. The number of Gensets running at the same time can be controlled, for optimal system efficiency, depending on the load required. This Genset running control is resulting in each engine running on optimal load [17].

An AC electric propulsion system is considered a fuel-efficient solution for vessels where the hotel load and loads from auxiliary systems are a significant part of the required propulsion power. For vessels with several activities that characterize the operating profile, the AC grid system can be a suitable solution because the Genset power can be used for both propulsion and auxiliary systems [17]. In the case where electrification of wellboat is to be considered, and it has become known that several types of auxiliary systems characterize the operation profile of these vessels with a high consumption factor, this type of solution is well suited.

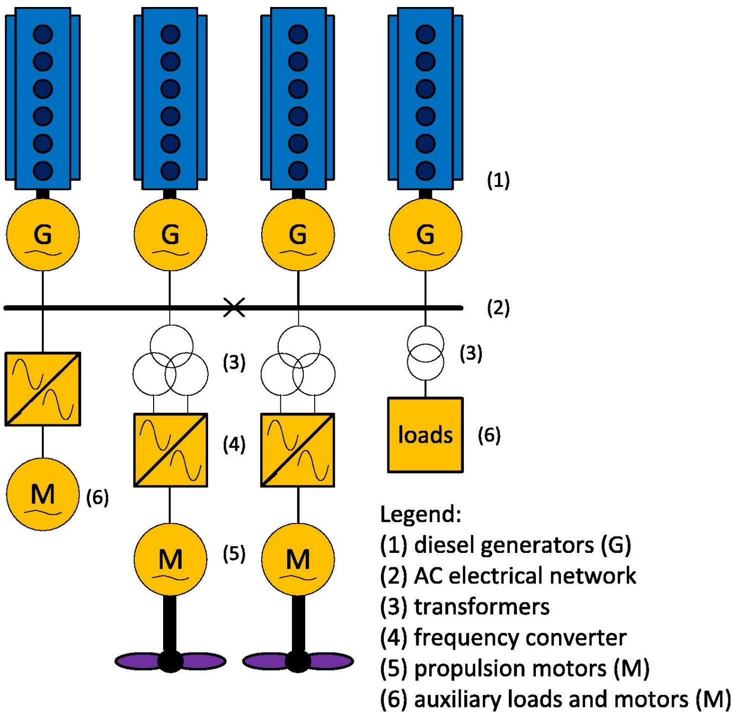


Figure 2.12: Electrical propulsion system with AC grid [17]

Hybrid Electrical propulsion system with AC grid

Figure 2.13 shows an electrical propulsion system with a hybrid power supply. This is a solution for implementing batteries in an AC grid system through a DC/AC converter. This solution can be well suited if considering a retrofit of an existing solution with an AC grid. The principle of this solution is to use batteries to store excess energy produced by the Gensets and then later use the power when the system's energy demand is high. The battery also makes it possible to switch off the Gensets while operating at no load or during low load operations [17]. Such a system also makes it possible to reduce fuel consumption by distributing power from the battery to the system so that the Genset can be operated at optimal SFOC at any time. In addition, load-leveling, peak shaving, and battery use for redundant power are possible with this solution.

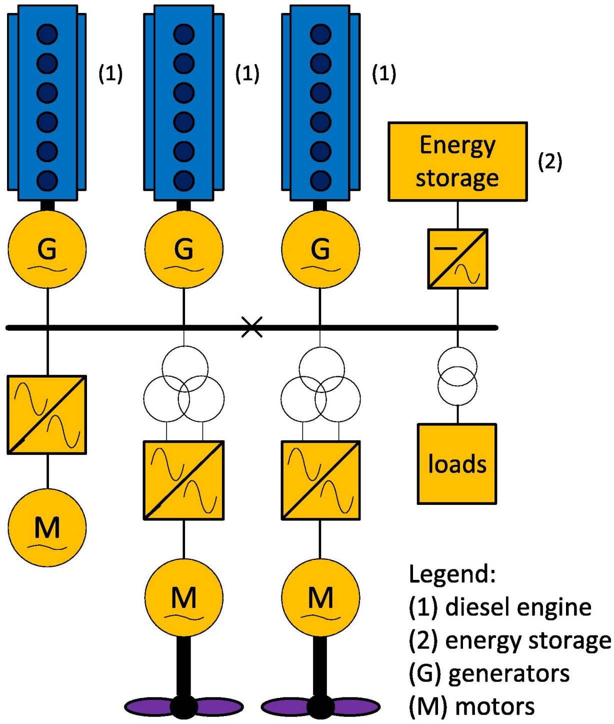


Figure 2.13: Electrical propulsion with battery power supply [17]

Hybrid electrical Propulsion system with DC grid

Figure 2.14 shows a typical DC electrical propulsion system with three Gensets and one ESS installed. Compared to the electrical propulsion system with the AC grid, where the diesel generators have to run at a fixed speed, the diesel generators for electrical propulsion systems with DC power supply can run at variable speed. The advantage of this is that the fuel consumption for engines running at variable speed is lower than for engines running at a fixed speed in part load [17]. The diesel generators are all connected to the DC grid through voltage rectifiers, rectifying the AC voltage produced by the generators to DC. The DC energy source, for example, a battery, can easily be connected to the DC network through a bidirectional DC/DC converter. This converter can either supply power to the DC network or charge the battery with excessive power from the diesel generators. To obtain the required frequency and voltage for the different loads, power electronic devices like DC/AC converter are used.

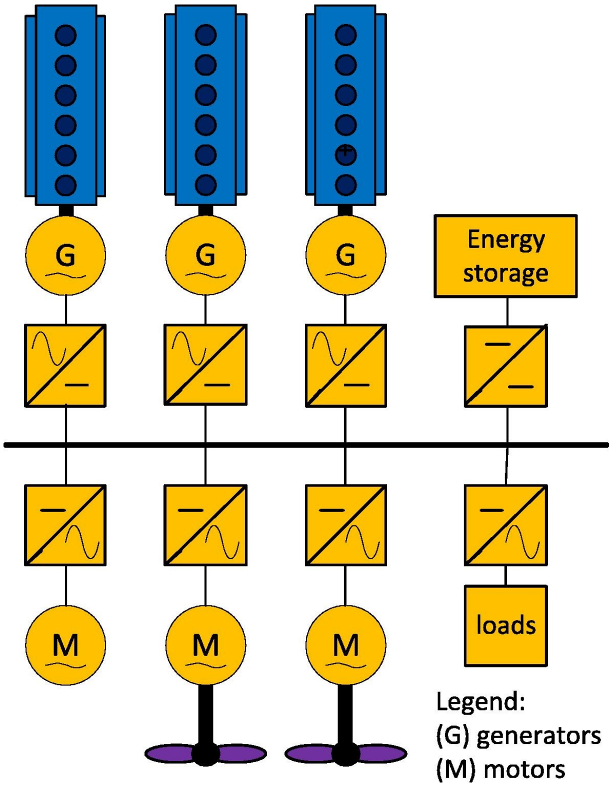


Figure 2.14: DC electrical propulsion system [17]

2.4.3 Integration of energy storage system

When designing a new vessel, both the AC grid and the DC grid propulsion system should be evaluated. As we know battery operates on DC, so integration of battery or other ESS can more easily be implemented [17]. Most of the existing wellboats use an AC grid system. A retrofitting of existing machinery to implement ESS is possible. The best solution would be to keep the system's AC grid. Since conversion to DC most likely will be extensive and expensive. Another essential factor when integrating ESS into a system is that each component and converter represents a loss of energy. Therefore the number of power converters should be kept to a minimum, as each represents a loss of energy of approximately 2% [8].

Chapter 3

Characterization and Estimation of Vessel Load

A load profile represents the variation in load in a system relative to time. The load profile will therefore correspond to the system's energy demand at a given time and will consequently be an essential factor when the possibilities for electrification of a vessel are to be studied. This chapter is divided into two. The first chapter refers to important factors and theory for load profiles from different vessels presented and characterized based on the theory. The second part of the chapter deals with a load profile estimation of a wellboat based on AIS data. Assumptions and calculations made are explained and justified along the way. The final result from the estimation is finally characterized in the same way as the examples in the first part of the chapter.

3.1 Load profile characterization of marine vessels

In this section, a simple load profile will be explained and characterized to understand key factors in load profiles. The key elements will be explained and illustrated using a simple load profile. Further, different vessels are considered to look at different ships and the energy demand throughout a period of operation. For data processing, sorting, calculations, and production of results, Python with Jupyter Notebook is used.

Baseload

The baseload or hotel load represents the electrical load caused by all systems on the vessel except propulsion or auxiliary systems load. The system's baseload can also be defined as the minimum amount of electrical demand needed over the given time. Baseload is a continuous load, and the load requirements do not change much over time. [12]. Typical hotel loads can be electric loads from kitchens, cabins, or other facilities onboard a vessel.

Peak load

Peak load is best explained as the electrical grid's highest energy demand in a period of time. Peak load is also known as peak demand or peak load contribution. Eventually, the peak load represents the maximum energy demand in a system in the given period. The peak load periods are typically short [12].

Average load

Average load is defined as the average of all loads that occur in a system in a period of time. For example, the average load for a vessel can be calculated for one operation or one year of operations. For calculating the average load Equation 3.1 can be used.

$$A_{load} = \frac{\text{Total energy used [kWh]}}{\text{Time [h]}} \tag{3.1}$$

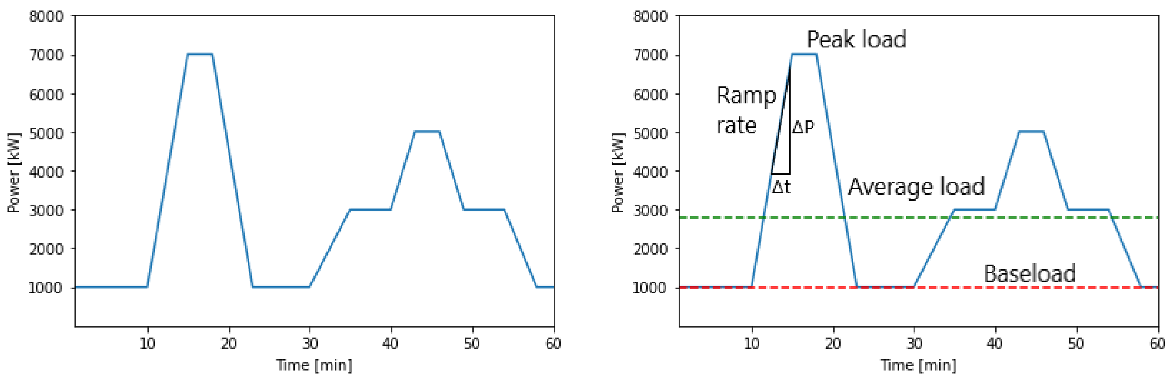
Ramp rate

Ramp rate is the rate of increase or change in energy per time. When we talk about load profiles, we look for the steepest climb to define the load profile's max ramp rate. The ramp rate is calculated considering the change in power divided by the change in time. Equation 3.2 shows the equation calculating ramp rate.

$$R_r(t) = \frac{\Delta P}{\Delta t} \tag{3.2}$$

3.1.1 Simple load profile

A simple load profile is made and should be characterized using the terms described in the section above. The load profile is represented in Figure 3.1. The load profile is inspired by different vessels so that the values should be somehow representative. For example, the load profile could represent one hour of operation for a typical offshore service vessel or another vessel in the same size range very simplified. The load profile creates an understandable and descriptive model that describes the essential factors in a vessel's load profile.



(a) Simple load profile

(b) Simple load profile characterized

Figure 3.1: Simple load profile characterization

Figure 3.1a represents a varying load profile through a time window of 60 minutes. In Figure 3.1b, the load profile is presented with named factors. The figure shows the load profile base load at 1,000 kW and the peak load of 7,000 kW. The ramp rate is quite low due to the clarity of the description in the graph. The load profile's characterization id presented in Table 3.1.

Table 3.1: Load profile characteristics for simple load profile

Parameters	Value	Unit
Peak load	7,000	$[kW]$
Average load	2,800	$[kW]$
Hotel load	1,000	$[kW]$
Max ramp rate	20	$[kW/s]$

This simple load profile characterization forms a basis for further characterization of load profiles on different vessels. The concepts and the method will be necessary even if the load profiles become complex. Furthermore, load profiles from a ferry, PSV, seismic vessels, and wellboat are closer looked into and characterized.

3.1.2 Ferry

A ferry is a passenger vessel specially designed for the transport of cars or other vehicles. The ferry's operation profile is relatively simple as the ferry follows a strict timetable due to the car traffic depends on it. The ferry load profile will therefore be repetitive and monotonous.

In this example, a load profile for a random ferry illustrated in figure 3.2 is used. The load profile represents 24 hours of operation. This load profile will be the starting point when the ferry operational modes and the crucial features shaping the load profile shall be identified.

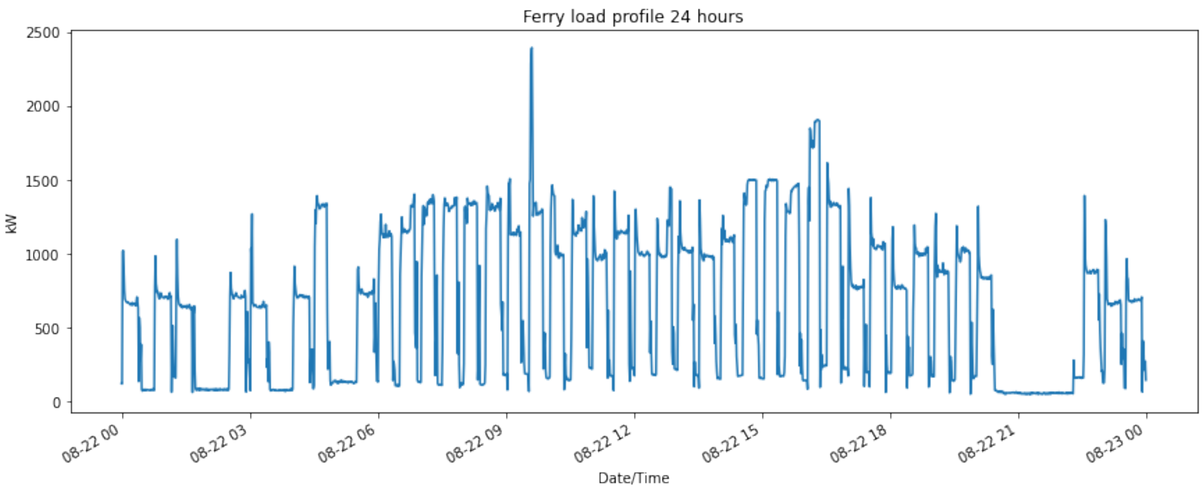


Figure 3.2: Load profile for a typical ferry

When the load profile is characterized, it is assumed that the low constant load at average 180 KW, which occurs several times during the 24 hours presented in the load profile above, is the vessel's baseload or hotel load. The average load, peak load, and ramp rate for the load profile are presented in Table 3.2. The ferry's peak load was found to be 2,404 kW, and the vessel's maximum ramp rate was found to be 43 kW/s. The ferry also had an average load of 678 kW during the 24 hours.

Table 3.2: Load profile characteristics for the ferry

Parameters	Value	Unit
Peak load	2,404	$[kW]$
Average load	678	$[kW]$
Hotel load	180	$[kW]$
Max ramp rate	43	$[kW/s]$

The ferry load profile is quite simple to understand, and it corresponds pretty well to how a ferry's operation profile is structured. The vessel's operation profile consists of unloading and loading cars, maneuvering, and transit. A histogram was made to look at the vessel's time use at different loads during the 24 hours and is presented in Figure 3.3. Each bar represents an increase of 90 kW. The histogram shows that the ferry spends a lot of time at the quay but most of the time in transit at around half load. Very little time of the period is spent in the high load phase.

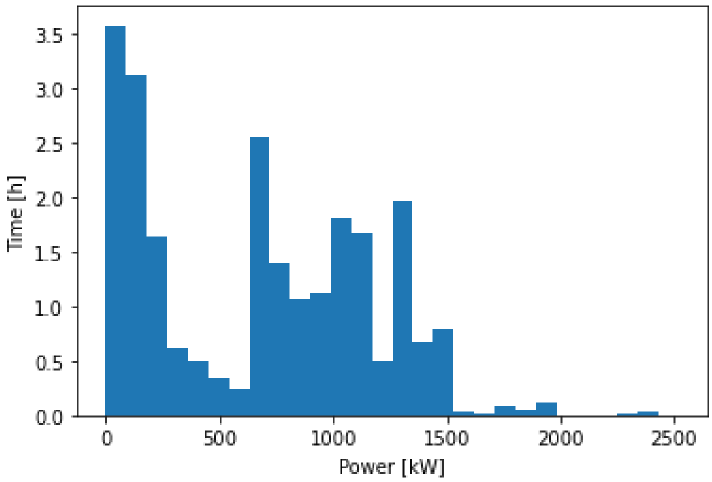


Figure 3.3: Load histogram for typical ferry

3.1.3 Platform Supply Vessel (PSV)

Platform supply vessels or PSVs are a type of offshore vessel mainly used for transiting essential equipment and additional human resources to reinforce high sea operations. At its broadest and most literal of implications, a platform support vessel is a much-needed support ship. Synonymously referred to as Offshore Supply Vessels (OSVs), platform supply vessels help sustain the construction and maintenance projects demands, thus fulfilling a vital necessity like operations at the high seas [40]. PSVs are typically in size range from 50 to 100 meters in length and designed to perform one or more operations types.

In this example, load data for a typical PSV vessel is used for the characterization. Figure 3.4 shows the load profile for the PSV vessel. The load profile represents two months of operation, and the load appears to vary greatly throughout the period.

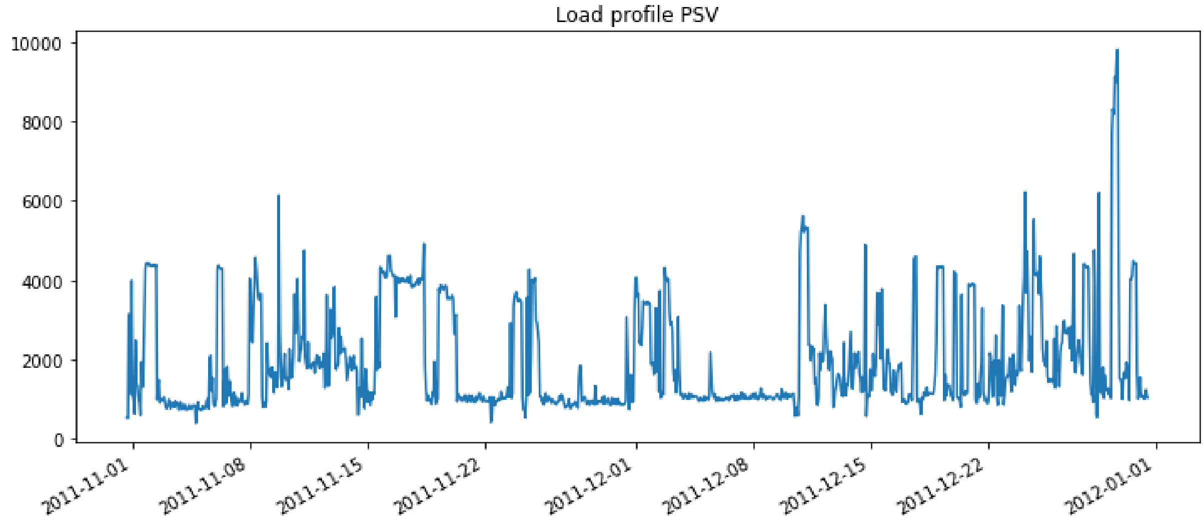


Figure 3.4: Load profile for a typical PSV

Using the load data combined with vessel speed, the different features for the load profile description were found. Hotel load is assumed based on average load when the vessel's speed was equal to zero. The Hotel load was found to be 950 kW. The PSV vessel's peak load was 11,836 kW, and an average load was found to be 1,917 kW for the entire period. Furthermore, the maximum ramp rate was calculated to be 126 kW/s. Table 3.3 shows the results for the characterization of the load profile for the PSV.

Table 3.3: Load profile characteristics for PSV

Parameters	Value	Unit
Peak load	11,836	$[kW]$
Average load	1,917	$[kW]$
Hotel load	950	$[kW]$
Max ramp rate	126	$[kW/s]$

The load data was plotted in a histogram to find out more about the PSV vessel's load profile. The histogram shows the vessel's time use in different power phases. Each bar represents an increase of 250 kW. The histogram shows that the vessel spends the most time in low load operations and medium-low load operations.

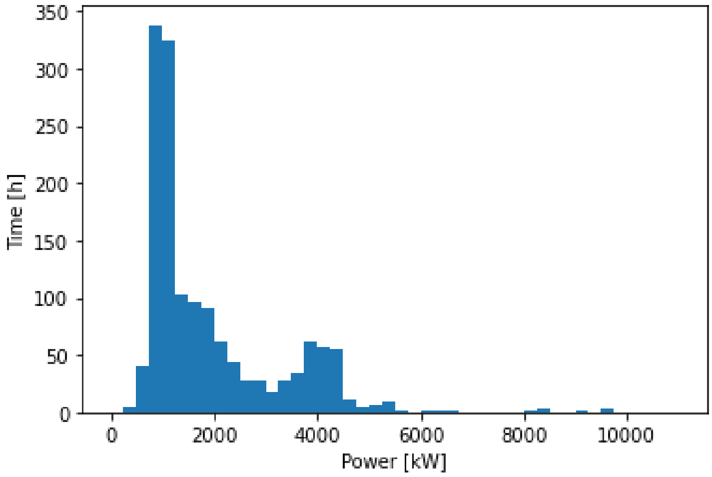


Figure 3.5: Load histogram for a typical PSV

3.1.4 Seismic vessel

Seismic vessels are ships that are mainly used for the purpose of seismic surveys in the open oceans and deep sea. A seismic vessel is used as a survey vessel to pinpoint and locate the best possible oil drilling area in the middle of the oceans. In this way, seismic vessels can be an essential resource in finding the best possible subsea location for oil drilling. As an incorrect choice of location can lead to dangerous and threatening consequences for the marine ecosystem, the use of seismologic vessels will prevent such mistakes. Seismic vessels also have additional benefits to being vessels that survey underwater seismology. The vessels can also be used to map the sea bottom and study the geology of the ocean [44].

For the characterization, a load profile for a typical seismic vessel is used and shown in Figure 3.6. The load profile for the seismic vessel represents a period of three months. The load profile appears to contain some fluctuation in the load and a longer period without operation where the load is lowest.

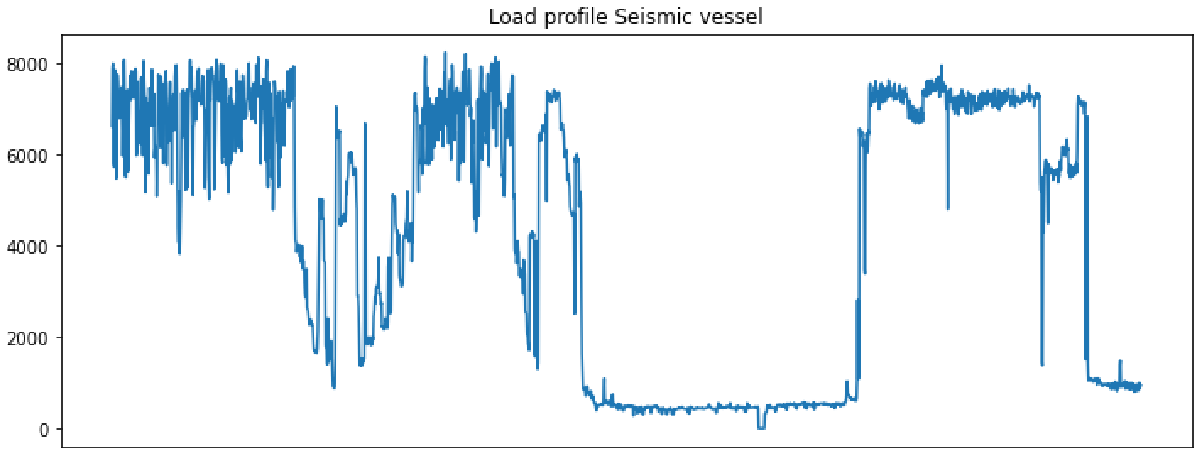


Figure 3.6: Load profile Seismic vessel

The load profile was further characterized, and the vessel's hotel load was assumed to be an average of the low loads when the ship may appear to be at the quay without an assignment. The hotel load was based on that assumed to be 550 kW. The peak load was found to be 9,432 kW and the average load for the period was 4,344 kW. The maximum ramp rate was calculated to be 133 kW/s. The results for the characterization is presented in Table 3.4.

Table 3.4: Load profile characteristics for Seismic vessel

Parameters	**Value**	**Unit**
Peak load	9,432	$[kW]$
Average load	4,344	$[kW]$
Hotel load	550	$[kW]$
Max ramp rate	133	$[kW/s]$

After the characterization of the load profile, the data was plotted in a histogram to take a closer look at the time spent in the various power phases. The histogram is presented in Figure 3.7, and each bar in the histogram represents an increase in power of 250 kW. The vessel appears from the histogram to spend some time in low load operation, and this may be as the vessel, according to Figure 3.6 appears to have a longer period without a mission. However, the ship seems to spend most of its time in medium-high to high load operations.

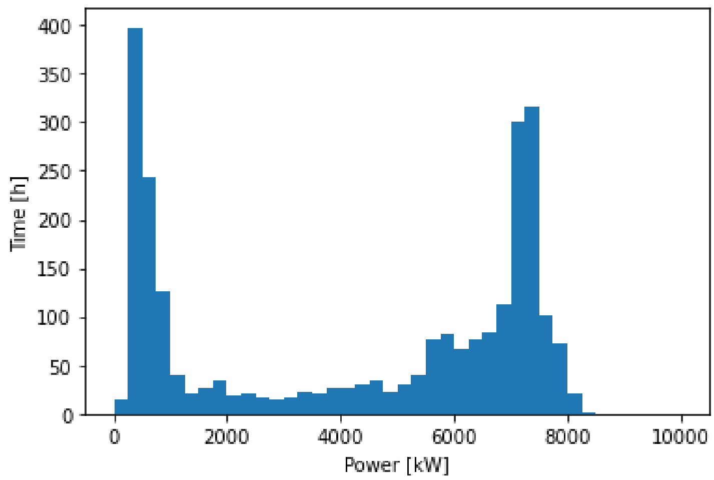


Figure 3.7: Load histogram for a typical seismic vessel

3.2 Load profile estimation for wellboat

In this section the methodology for load profile estimation for a typical wellboat is presented. The load profile estimation is based on historical AIS data from a specific wellboat. A short description of the AIS data file, and AIS is included to to describe how this type of data is logged, and later can be used for various purposes.

3.2.1 AIS Data file

Accessing load profiles on wellboats proved to be more difficult than expected. This is because the market is characterized by high competition between the ship designers, intending to deliver the most energy-efficient design. So to generate a load profile for a typical wellboat, speed-data from an AIS data file was used.

An agreement with NTNU was signed to access AIS data from the Norwegian Coastal Administration. One of the points in this agreement states that the person undertakes to treat individual ships' identity as confidential information, which means that individual ships' identity shall not appear in published or otherwise externally communicated information. Although the ship's identity must be kept secret, tables describing key data are made to describe the size and other crucial data for the vessel used further in the thesis.

3.2.2 Automatic Identification System (AIS)

AIS stands for Automatic Identification System and was introduced by United Nations Maritime Organization to increase the safety of ships and the environment. Using AIS, regulations and monitoring of ship traffic are improved. AIS transponders on board ships send out information about the ship's identity, position, speed, and course. This information is captured by the Norwegian Coastal Administration's land-based AIS chain, AIS Norway, which consists of 50 base stations along the coast, and by the AIS satellites, AISSat-1 and AISSat-2 [32]. AIS-data can be useful in many areas, as the information sent by the transponders is very detailed. AIS has today a wide range of applications. Today AIS is used to show information about vessels in real-time and has great utility in civil maritime traffic monitoring, but also in connection with several other government tasks [32]. For example, the oil industry uses it to get an overview of ship traffic around a reported oil spill. Access to real-time AIS data can anyone get via internet sites like BarentsWatch, but an application must be submitted to search in historical AIS data. In the application, the purpose of the application must be specified. This data is mainly shared with public authorities and ports, but others can also apply for access. Using AIS from a typical wellboat for aquaculture makes it possible to get an overview of the operation profile for the type of vessel. The speed profile and the routes can be monitored using programming tools like Python and position data and speed data from the AIS file. AIS data can, in this way, be an influencing factor in the decision for an environmental propulsion system.

3.2.3 Load profile estimation

As mentioned, a load profile will be created based on the vessel's speed profile. A data file containing AIS data from four months is used as the starting point. Figure 3.8 represents the speed profile for four months of operation for a typical wellboat and creates the basis for the conversation from speed to power.

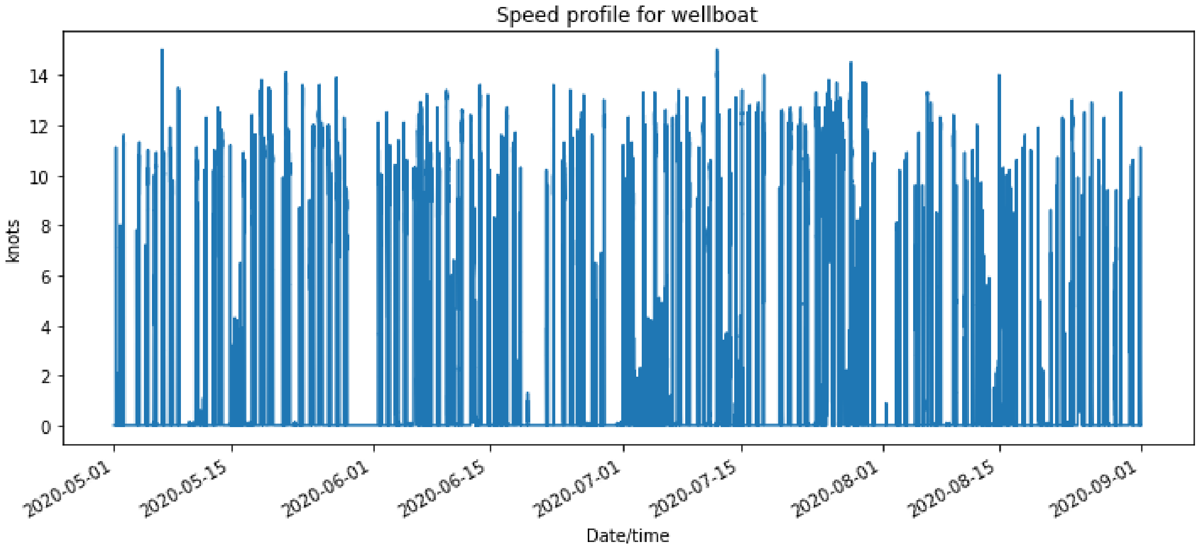


Figure 3.8: Four months speed profile for wellboat

In order to move a ship through the water at a given speed, certain power output from the engine is required. Of course, the relationship between power (P) and speed (V) depends on many factors. However, for a given ship at a given draft and trim, disregarding the influence of wind and waves, etc., the relationship most often well describes the power as [28][33]:

$$P_{prop} = c_1 \cdot v^{c_2} \tag{3.3}$$

The required power for propulsion, P_{prop} is the total installed power subtracted the hotel load, and can be expressed as:

$$P_{prop} = P_{inst} - P_{hotel} \tag{3.4}$$

where coefficient c_1 is used for power and ship velocity matching. The constant c_2 is dependent on hull form, and is assumed to be equal to 3 according to [28] where this is the constant for conventional hull forms. To find the vessel's constant c_1 from the equation 3.3 an assumption was made. First, it was assumed that the vessel's maximum engine power minus the hotel load occurs when the ship reaches the top speed, and the equation was solved for the constant:

$$c_1 = \frac{P_{prop}}{v^3} = \frac{5,820kW - 180kW}{15^3 kn} = 1.671 \tag{3.5}$$

After defining the constant for the vessel, the speed-power curve was generated and is showed in Figure 3.9. The curve represents the vessel's power demand at a given speed.

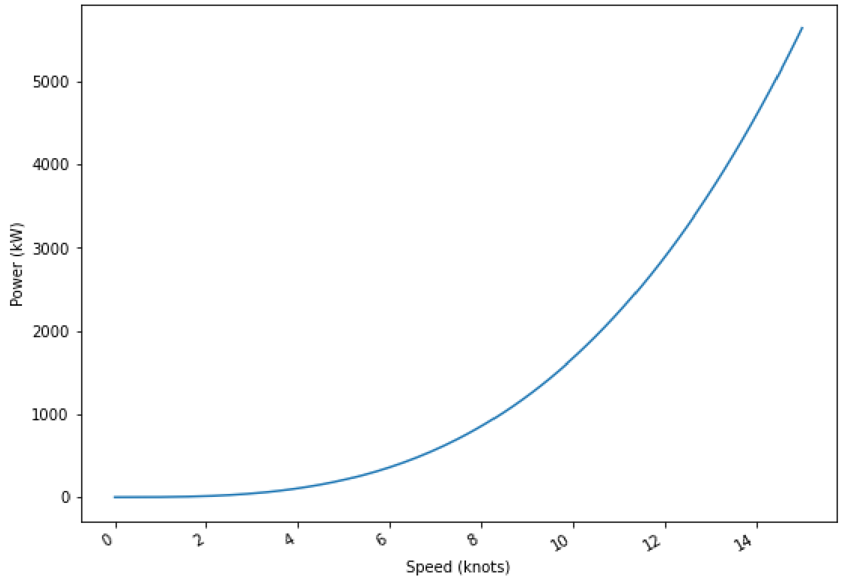


Figure 3.9: Speed-power curve for the wellboat

A propulsion power profile was estimated with the speed-power curve combined with the speed data from the AIS file. Because GPS data like AIS can give unrealistic peak acceleration values due to fluctuations in the GPS position data, the AIS data was post-processed. Duplicates in the data file were deleted, and the maximum speed was limited to 15 knots. Based on the previous load profile characterizations and research, it is assumed that the hotel load is set to a constant of 180 kW. This may be a conservative estimate since the ship's port generator is 220 kW. However, since the load profile will be used to look at the possibility of electrification, it is more correct to use an conservative estimation. The result for the wellboats load profile estimation for the whole four-month period is shown in Figure 3.10. The figure shows the sum of the propulsion load and the hotel load for the vessel.

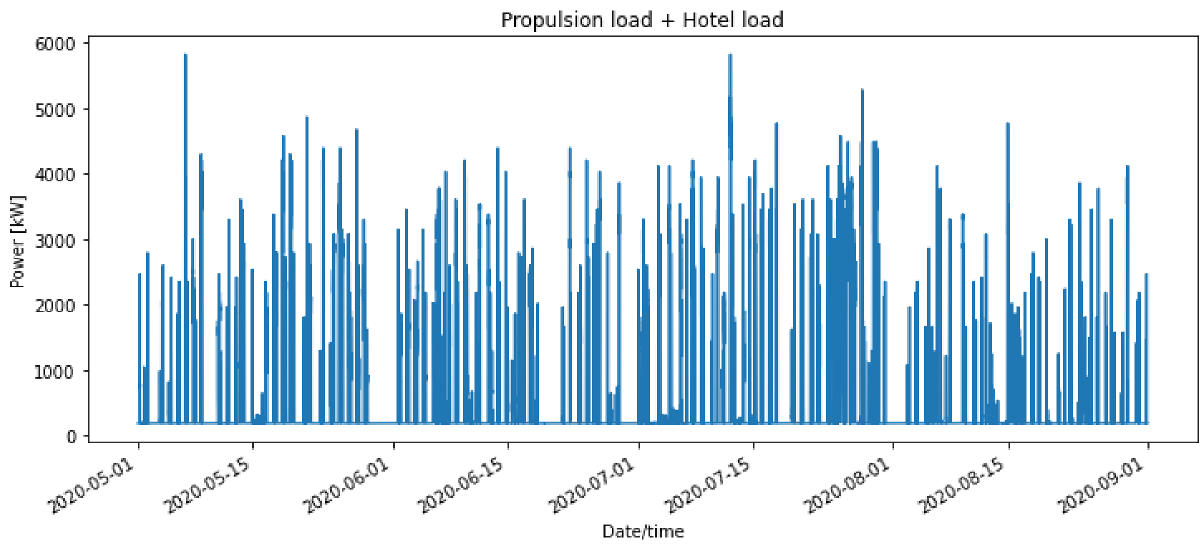


Figure 3.10: Estimated load profile for the wellboat

The load profile indicates that the vessel has shorter sailing distances and, much of the time, is used for stationary operations or waiting for assignments. This can agree reasonably well with the operation profile of a typical well boat as the operations are often carried out stationary at the facilities. The vessels, therefore, spend a lot of time lying still.

As wellboat operations are characterized by high consumption from auxiliary equipment like pumps, RSW, and circulation systems, it was chosen to look more closely at a week of operation to log the time use and position of the vessel. The logging of the vessel's position data in the representative week can be found in Appendix A. As the auxiliary loads largely control the vessel's consumption, these loads were added to the load profile based on the vessel's location. In order to make the best possible assumptions for the consumption of the auxiliary equipment, several wellboat companies and equipment manufacturers were contacted. Due to intense competition in the market, it wasn't easy to get them to provide information. However, a table was sent from Cflow [7], one of the major suppliers of fish processing equipment. This table showed an average consumption for the auxiliary equipment for a wellboat with a capacity of 3,000 - 3,500 cubic meters—the table reserved from Cflow could be found in Appendix B. Based on the vessel's position data, it was possible to see whether the vessel was at a facility, homeport, distribution port, or in transit.

Table 3.5: Assumptions auxiliary loads

Assumptions	**Value**	**Unit**
Home port	0	$[kW]$
Transit	1,184	$[kW]$
Operation	1,673	$[kW]$
Distribution port	1,571	$[kW]$

When the vessel is located at the home port, it is assumed that the vessel's consumption from auxiliary loads is equal to zero. This is because the vessel's storage tanks are empty, and it is not necessary for circulation systems, RSW, or pumps to run. During transit, the vessel's consumption is assumed to be 1,184 kW. This assumption is the average value of "transit fully loaded" and "washing in 11 knots" from the table given by Cflow. An assumption that the ship was fully loaded at all times during transit would have been conservative. Therefore a somewhat lower value is assumed. When the assumptions for the operation were made, the value for "Treatment" was used. This value represents the average consumption during a de-lice or treatment operation. It is challenging to know which procedure is being carried out at any time, but since this was the highest value and the difference between a loading and unloading process was so low, this seemed to be a reasonable assumption. For the distribution port, an average value for loading and unloading was assumed. This is because in some of the ports, the vessel docks, there are loading and unloading operation possibilities.

The assumptions for the representative week were implemented in the data file. A figure presenting the vessel's loads was made and is shown in Figure 3.11. The blue line shows the propulsion load for the vessel, the yellow line shows the auxiliary load, and the green line shows the hotel load.

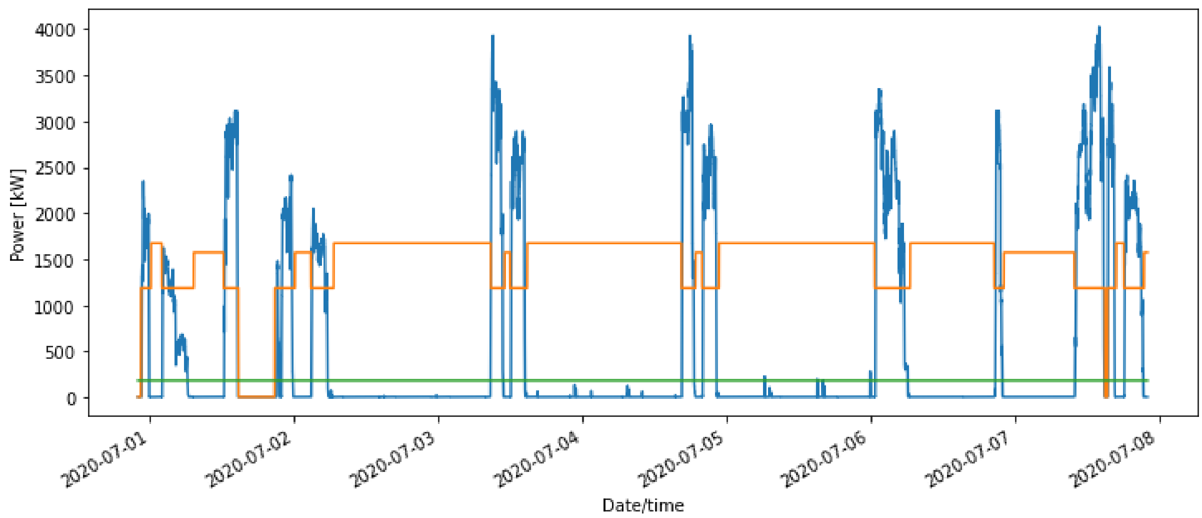


Figure 3.11: Divided Load profile - Propulsion load (blue), Auxiliary load (yellow) and Hotel load (green)

Once the vessel's propulsion load has been estimated and the most important assumptions for auxiliary loads and hotel loads have been made, the vessel's total load can be expressed as:

$$P_{total} = P_{prop} + P_{Auxiliary} + P_{Hotel} \tag{3.6}$$

Figure 3.12 present the result of the estimated load profile for one week of operation.

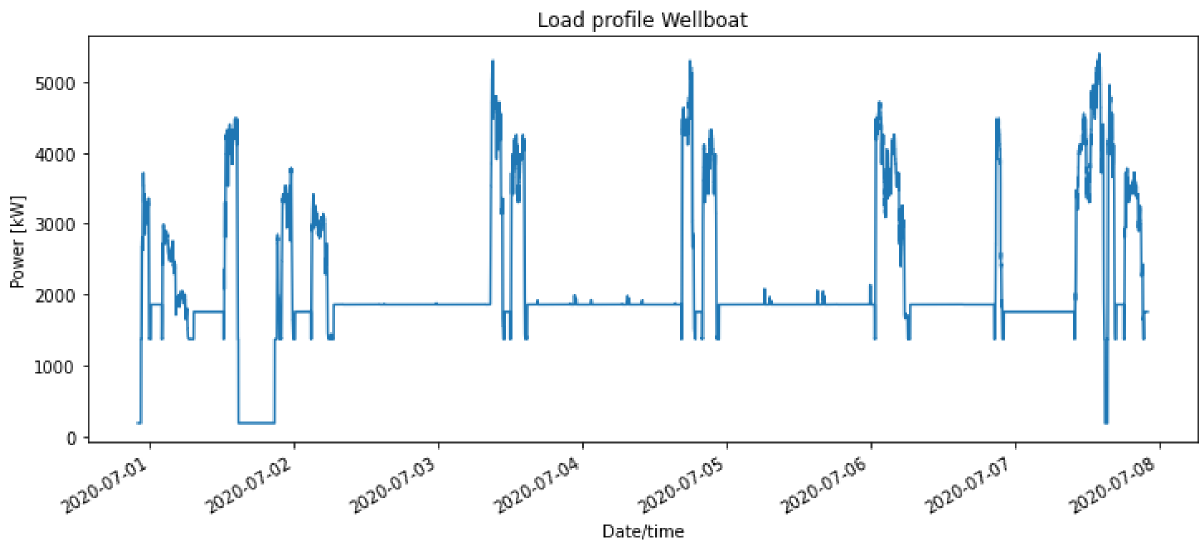


Figure 3.12: Load profile for wellboat

The estimated load profile for the wellboat was further characterized, and the result is presented in Table 3.6. As the load profile is estimated and not based on actual measures, this will introduce some uncertainties for the estimated load profile. As mentioned earlier, comparing with actual data was difficult as none of the companies wanted to share data. However, the hotel load is as described previously assumed and will therefore be a constant 180 kW.

The acceleration phase and the maneuvering phase are energy-intensive. Based on the data converted from the AIS dataset, the speed-power conversion for the acceleration phase and maximum ramp rate might be a bit misleading. Nevertheless, there is reason to assume that the ramp rate of the vessel is slightly higher than 26kW/s if we are to compare it with the other vessels. On the other hand, the retardation phase is not established as a zero-consumption phase and will compensate for most of this deviation. The vessel's average load and peak load were found to be 2,124 kW and 5,385 kW.

Table 3.6: Load profile characteristics for wellboat

Parameters	Value	Unit
Peak load	5,385	$[kW]$
Average load	2,126	$[kW]$
Hotel load	180	$[kW]$
Max ramp rate	26	$[kW/s]$

A histogram of the vessel's power use is made. Figure 3.13 shows the vessel's load histogram, each bar represents an increase of 300 kW. As expected, the vessel spends most of its time during the period in a stationary position. This is due to the vessel's operations being carried out stationary on the facilities and port as described earlier. The short period with the lowest load represents when the vessel is in the home port, and the only load is the hotel load. The biggest effects on the histogram come from operation work carried out at the facilities or during loading and offloading. The rest of the loads in the medium to high load segment represents the vessel's transit. The histogram, therefore, confirms the assumption previously made that the vessel spends the most time in operation mode.

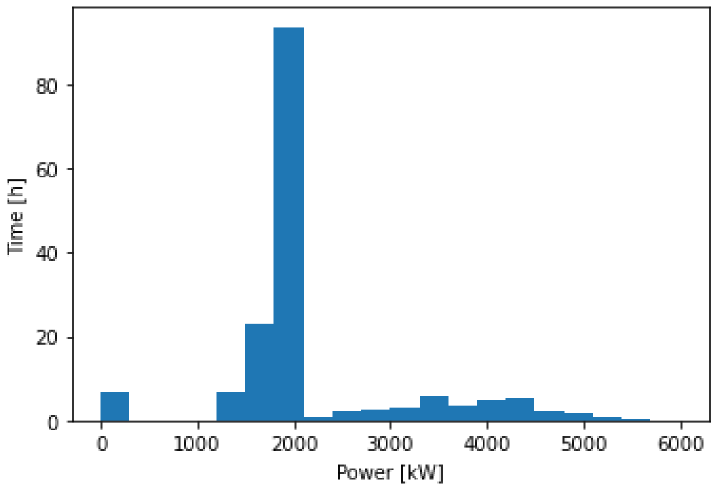


Figure 3.13: Load Histogram for the wellboat

Chapter 4

Hybrid power system and emission reduction potential for a wellboat

When installing a hybrid system or assess whether retrofitting of existing topology is to be carried out, the vessel's power demand and operational profile are central to the solution. In this Chapter, the possibilities for electrification and emission reduction are looked at more closely in light of the load profile of the wellboat. Based on the wellboat's load profile, this Chapter looks at the possibilities for emission reduction. Different energy storage systems have earlier in the thesis been described and how they can fulfill the requirements for a vessel. However, in this feasibility study, battery as ESS is considered to be the most beneficial and realistic solution, based on weight, size (power density), and general system properties.

4.1 Possibility of emission reduction

Based on the load profile created, battery use for peak shaving operations, low load operations, or load leveling will be the most appropriate reason for implementing a hybrid power system for a typical wellboat. As the vessel has an irregular operation profile and the operational work requires a high load in longer periods, the battery will be best suited for peak shaving and assistance during the system's highest power demands. Load leveling will also have an effect as the vessel's fluctuating loads are evened out, and the Genset can operate on an optimal load.

The most significant potential for reducing fuel consumption resulting in reduced GHG emissions occurs when the ship's power demand fluctuates. Maneuvering operations or the acceleration phase can be an example of fluctuating power demand. In the estimated load profile, the load only fluctuates when the vessel changes speed. It was difficult to obtain actual data on a wellboat, therefore estimates on the average load for the auxiliary components were necessary. As the estimated load is constant when the vessel has the same operational status, there are no fluctuations in the load when the vessel is in port or during active work on the facilities. Given that a system will have a fluctuating load during loading, offloading, and other operational work as the real data would have provided, an ESS system will level the load throughout the entire operational profile of the vessel.

However, in light of the estimated load profile and information provided by Cflow, the consumption during the loading and offloading operations is significant. The possibility for fuel savings by shore power connection during loading and offloading will obviously provide fuel savings. Since the electrification of aquaculture locations is becoming more common, a plug-in solution can also contribute to a reduction in consumption both when the vessel is docked and when the vessel does operational work at the cages. Plug-in at locations also provides benefits such as charging the battery between sailing and reduced generator noise during operations.

4.1.1 System efficiency

The main reason for implementing a hybrid propulsion system in a new vessel or retrofit an old ship is to increase the overall system efficiency, resulting in reduced emissions and ultimately to save operational costs. Introducing batteries as ESS in the vessel propulsion system makes it possible to drive the generators at the optimal speed for optimal fuel efficiency, resulting in a more environmentally friendly propulsion system and reduced fuel cost. The battery can also handle the fluctuating loads and help when the vessel's power demand is highest by peak shaving operations. When it comes to system efficiency, this can be expressed by Equation 4.1.

$$\eta_{\text{SYSTEM}} = \frac{\text{Energy output}}{\text{Energy input}} = \frac{\text{Work out}}{\text{Energy in}} \tag{4.1}$$

The Genset efficiency typically is 30-40% [17]. This is because much of the Genset input energy disappear out of the system as heat. When installing a battery, this efficiency can be increased.

4.2 Role of storage system

Through literature search and study of systems and power requirements for the auxiliary equipment onboard typical wellboats, it is clear that the auxiliary loads are significant. The pumps, the circulation system, and the RSW system are at times dominant. In the load profile characterization, it is clear that we find the highest loads during transit as the circulation system and RSW system are also active to maintain optimal conditions for the fish during transportation. In the characterization of the load profile, the load from the auxiliary systems and the hotel load is set to be constant based on the operational mode for the vessel. Usually, during an operation, loading, or unloading situation, the load would be fluctuating. Battery support during operation could therefore also help save emissions and reduce fuel consumption.

As battery use is best suited for use during low load operations or as a support during high peak demands, peak shaving operation will significantly reduce fuel consumption and emissions. However, as mentioned earlier, a wellboat's operations and sailing distances can vary greatly with the type of operation and aquaculture site location. Therefore, fully electric operations at the cages can be complex. Nevertheless, with today's technology and in light of the load profile estimation results, the best roles for the ESS are to supply in low load operations, load leveling, or peak shaving to remove the fluctuation in the load. In addition, the battery could be used as a non-spinning reserve and redundant power in case of emergency.

4.3 Main items for retrofitting the power and propulsion system

To consider a hybrid solution for a wellboat the existing topology need to be studied. Different power electronics and converters are needed to interface and interconnect different power producers (Gensets) with typical loads like thrusters and aux equipment connected to the distributed power bus. Various systems and configurations have been described in earlier sections and will vary depending on the energy storage technologies chosen and the type of electric grid used on the ship. For example, some technologies such as batteries and fuel cells operate on direct current (DC), while a flywheel connected to a variable frequency converter will be producing an alternating current (AC). In this case, the vessel has an AC electric grid installed. This means that an ESS battery solution will require DC/AC converters to be installed together with the battery storage system to provide correct power to the vessel power grid/bus.

4.3.1 Battery storage system

The main component for a retrofit from a conventional system to a hybrid electrical system will be the battery pack. The size of the battery package will depend on the vessel's operational profile and what the system is calculated to be used for and have of available power. For description and as an example of a typical battery package, the Corvus Orca Energy package is used. This example will give an understanding of the weight and volume of a standard battery package for ship propulsion systems. The Orca Energy is suited for applications that are in need of energy and high power. The battery package is, according to Corvus Energy [10] suited for Fishing vessels. The battery pack has a C-rate - continuous (Discharge / Charge) up to 3C for both discharging and charging. Table 4.1 presents three Orca example packs, their dimension, and weight. Figure 4.1 shows the described battery package from Corvus.

Table 4.1: Corvus Orca Energy battery pack specifications

Example Packs	Dimensions	Weight
Vertical Pack - 124 kWh	Height: 2,241 mm — Width: 865 mm — Depth 738 mm	1,628 kg
Horizontal Pack - 124 kWh	Height: 1,260 mm — Width: 1,730 mm — Depth 738 mm	1,726 kg
Tall Pack - 249 kWh	Height: 3,000 mm — Width: 1,345 mm — Depth 738 mm	3,375 kg

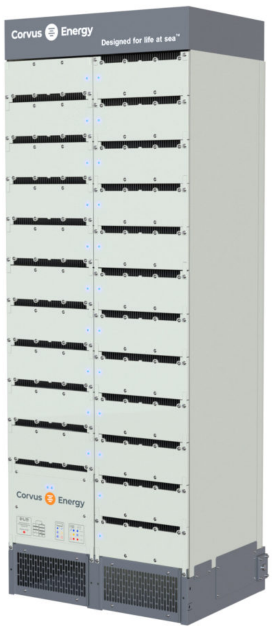


Figure 4.1: Battery package from Corvus - Orca Energy [10]

4.3.2 DC-AC Converters

In this case, the propulsion system has an AC grid. In order to be able to install batteries to the propulsion system, DC-AC converters are necessary, as batteries operate on DC. With a DC-AC converter, the battery's DC output can be converted to AC using an inverter. This switching converter is usually with thyristors, which will output a controlled AC waveform based on the switching scheme used. Figure 4.2 shows a typical DC/AC inverter used in ship propulsion.

Figure 4.2: DC/AC inverter [25]

Chapter 5

Case study: Wellboat; feasibility and economic viability

5.1 Motivation for case study

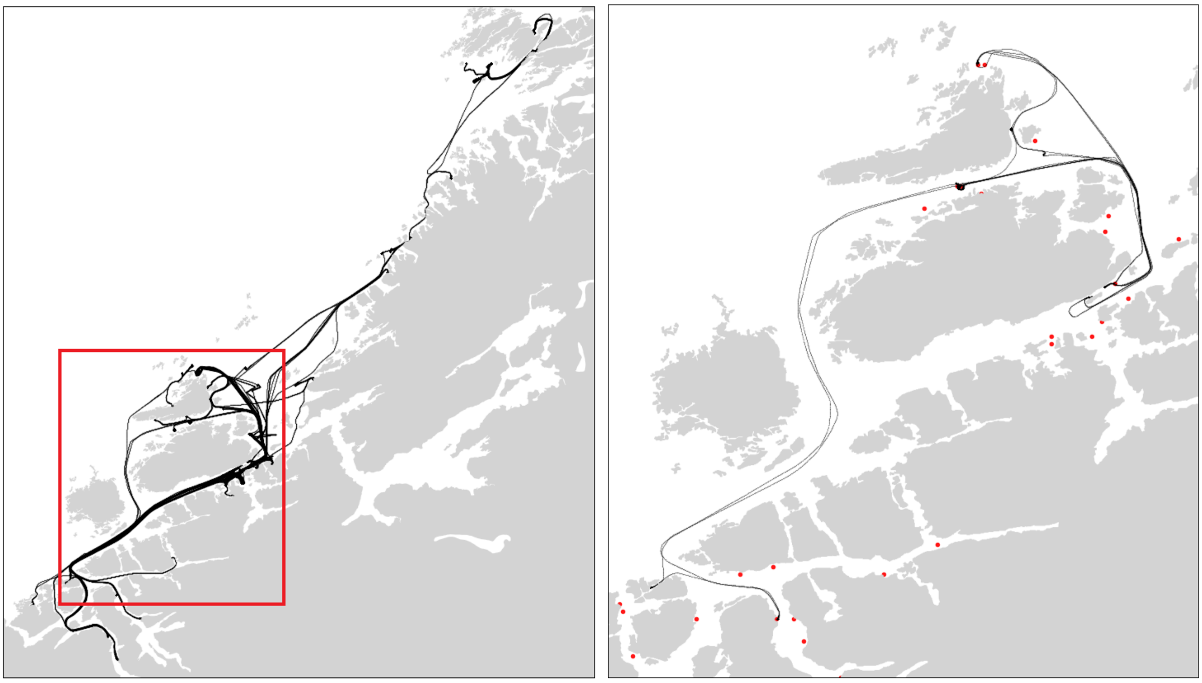
The case study is based on a typical wellboat operating in Norway. The motivation for studying wellboats and the opportunity for electrification is due to the size and importance of Norway's aquaculture industry. Large parts of the aquaculture industry also use the Norwegian fjords as production premises and contribute to the fjords' pollution. By increasing energy efficiency and identifying the vessel's operating pattern and energy use, new solutions can reduce emissions to the Norwegian fjords and the aquaculture industry's emissions.

5.2 Vessel route and operational profile

The vessel's route and operation profile are essential factors when the possibilities for electrification are to be looked at more closely. As described earlier, the AIS data file had to be processed, and a database tool had to be made for reading the CSV files from The Norwegian Coastal Administration. Python, together with Jupyter Notebook, is used to write the code. Mainly two articles written by Bjørnar Brende Smestad are used. The name of the articles is "Preparing an AIS database for analysis"[5] and "Plotting geospatial AIS data from a database using Python" [4]. The database tool mainly plots the AIS data onto a map to show the vessel's route pattern.

Today the vessel mainly operates in aquaculture locations located in the fjords of Møre and Romsdal, and Trøndelag. Figure 5.1a shows the route pattern for four months of operation plotted on the map. The representative week used in the case study is presented in 5.1b, the figure clearly shows that this area is where the vessel has the most activity in the four months. This confirms that the operation profile based on this week will be quite representative. For an overview of the aquaculture locations near the sailing route, these were also plotted as red dots on the map shown in Figure 5.1b. Geographical data for the locations were obtained from the Directorate of Fisheries [15].

Wellboats are shared between several facilities, and the sailing distances can vary. Therefore, we will see that the operation pattern is more unstructured and quite unpredictable whether we resemble the vessel with a container ship or even more simply a ferry. As the vessel's operating profile is variable and unpredictable, a full electrical solution can be excluded as such a solution will depend on the infrastructure.



(a) Vessel route pattern for 4 months

(b) Vessel route pattern for one week

Figure 5.1: Route pattern for a typical wellboat

Based on the vessel speed, the vessel's time use was sorted to create an operational profile for the wellboat. The load profile was sorted into five operational modes, Port/location, Maneuvering, Slow speed, transit, and full speed. The different operational modes have been identified as described in Table 5.1. Due to possible errors in the GPS signal, the port and location stage is assumed to be an interval from 0 - 0.2 knots.

Table 5.1: Stages defined by speed interval

Stage	Speed interval
Port or location	0 - 0.2 [kn]
Manuvering	0.2 - 3.5 [kn]
Slow speed	3.5 - 10 [kn]
Transit	10 - 14 [kn]
Full speed	14 - 15 [kn]

The speed intervals only say something about the vessel's operational speed. It is therefore difficult to know if the vessel's position is on-site doing operation or in port. Based on this, the AIS file for the representative week was reviewed to determine the vessel's location when the speed was in the range between 0 - 0.2 knots. Based on the speed intervals and the vessel position data, the vessel's operational profile was made. Figure 5.2 shows the operational profile for the typical wellboat. During the representative week, the vessel is located 29 hours in port. This time represents both homeport, slaughterhouse, and distribution port. On the other hand, the vessel spends 95 hours for operation on-site, equivalent to approximately 54% of the total time.

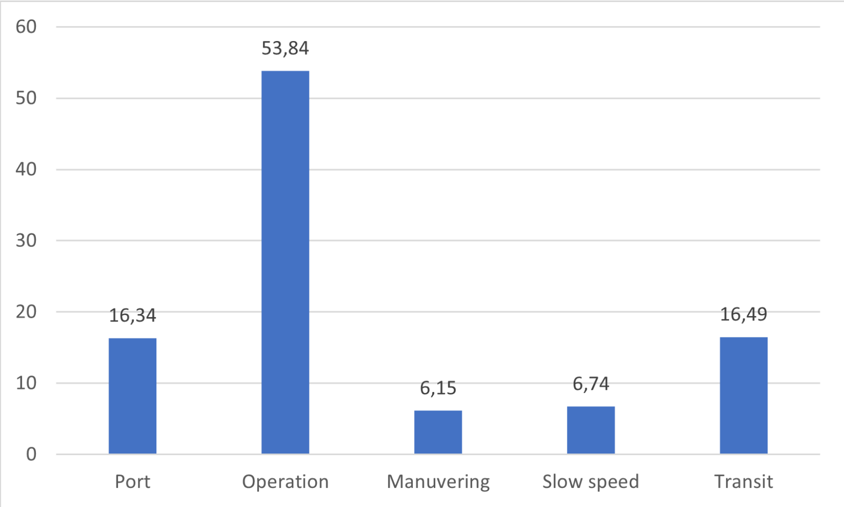


Figure 5.2: The reference vessel's operational profile

5.3 Technical background

The wellboat that is used as a reference in this case study is today outfitted with a conventional diesel-electric engine propulsion system. Although, as described earlier in Chapter 3 the load profile is based on AIS data, the ship's identities must be kept secret. However, Table 5.2 presents the vessel's dimensions and other relevant data describing the design parameters for the vessel.

Table 5.2: Main design parameters for the wellboat

Design parameters	Value	Unit
LOA	78	$[m]$
Beam	16	$[m]$
Lpp	75.03	$[m]$
Depth moulded	11	$[m]$
Top Speed	15	$[kn]$
Gross tonnage	3,566	$[t]$
Main engine	$4 \times 1,455$	$[kW]$
Net tonnage	1,070	[]
Cargo capacity	3,000	$[m^3]$
Fuel tank	264	$[m^3]$
Fresh water tank	170	$[m^3]$
Ballast	1,350	$[m^3]$
Accommodation	10	[]

The vessel is today equipped with state-of-the-art fish handling and transportation systems based on closed technology that meets current and future requirements for fish welfare in terms of circulation, oxygenation, filtration, UV, and RSW cooling. Hot and polluted seawater is filtered during loading. In addition, the vessel has an automatic washing and disinfection system for flushing and washing storage tanks and pipe systems.

5.3.1 Vessel topology

In order to look for potential emission reduction for the wellboat, the existing topology had to be studied closer. Today the vessel is equipped with a Siemens diesel-electric system, with four engines of type MTU 12V4000P83 producing 1,455 kW each. Together with one port generator having 220 kW, these main engines are connected to the AC grid. The four MTU engines serve the propeller system containing two Helseth 4TX850/300-3500 VSD, each with a power output of 1,200 kW. Rolls-Royce has supplied the steering gear for the propellers. The vessel is also equipped with a bow thruster of 600 kW and a stern thruster of 600 kW. The single line diagram for the vessel topology is presented in Figure 5.3. The topology presented in the figure is the basis for the case study and will be tested in case scenario 1.

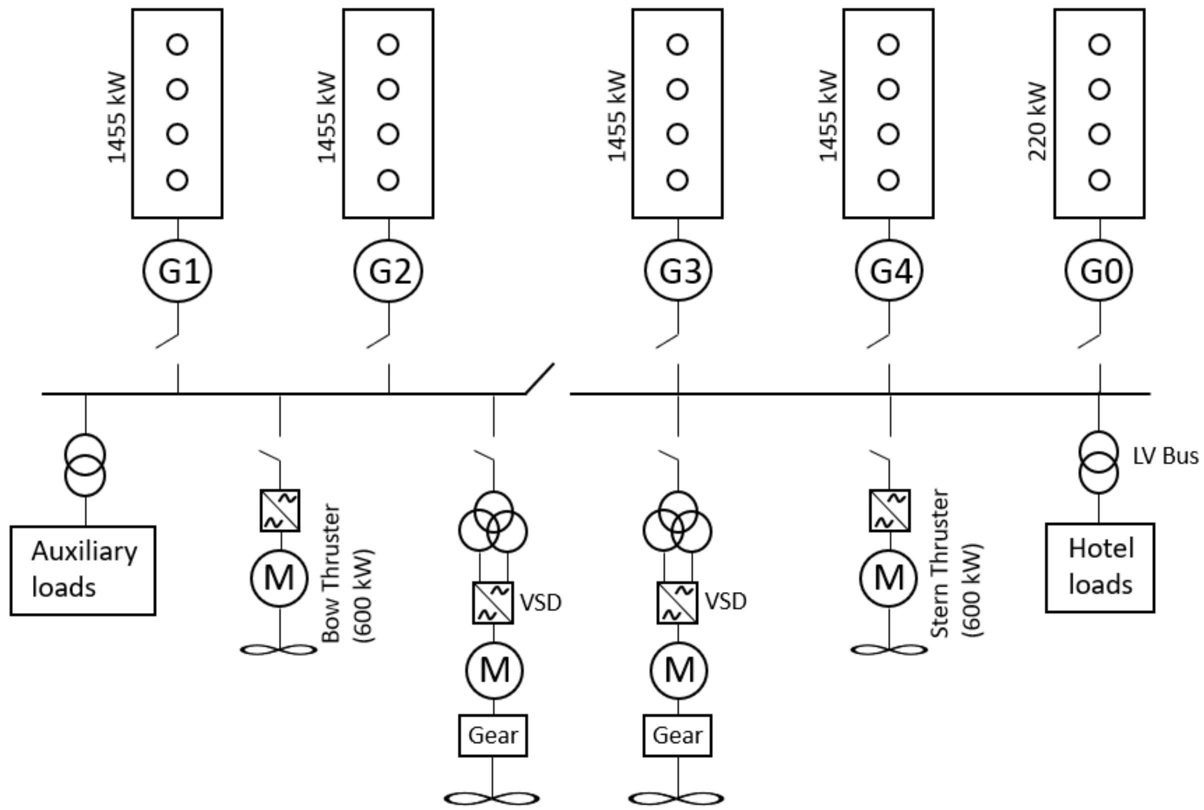


Figure 5.3: Wellboat topology

Fuel price

The diesel price used for the cost analysis is based on a conversation with Bunker oil in Ålesund [6]. As of June, the price was in the range of NOK 4.22 per liter plus an emission tax of NOK 1.58 per liter. This will then constitute a total price per liter of NOK 5.8 per liter. Diesel density is assumed to be 0.835 for converting from kg to liter.

5.4 Scenario 1 - Conventional diesel propulsion system

Case scenario one represents a conventional diesel-electric solution. This solution operates four Gensets as the existing solution. This example aims to simulate the vessel's existing solution to be able to say something about the profitability of battery implementation.

The vessel does not use all the engine-generator sets at all times. The number of generators in use at the given time is implemented in the data set. When the total load exceeds 90% of the maximum performance from one Genset, it activates two Genset. When the load further exceeds 90% of the maximum performance from two, the third Genset is activated, so it goes until all the Gensets are active. Generators are set to use only up to 90% of the total effect because the last 10% of the effect is intended redundant power. For load-interval describing the number of activated Gensets Table 5.3 is made. These load intervals are further used when the vessel's fuel consumption is calculated. In addition, the table shows the percentage of time used during the representative week operating the different amounts of Gensets.

Table 5.3: Scenario 1 - Number of operating generators

Number of operating Gensets	Load interval	Time [%]
1 × 1455kW Genset	0 - 1,309.5 [kW]	4.1 %
2 × 1455kW Gensets	1,309.5 - 2,619 [kW]	77.1 %
3 × 1455kW Gensets	2,619 - 3,928 [kW]	10.4 %
4 × 1455kW Gensets	3,928 - 5,820 [kW]	8.4 %

In order to further calculate the vessel's fuel consumption using an SFOC curve, the generators' load percentage was implemented in the data set. The load percentage for the Gensets is crucial for the SFOC calculations. The calculations for load percentage were performed as follows:

$$\text{Load \%} = \frac{\text{Total load}}{\text{1,455 kW} \times \text{Number of Active Gensets}} \times 100 \tag{5.1}$$

Fuel consumption curve

A generators Specific Fuel Consumption, SFOC measured in (g/kWh) is decreasing with the power produced P until it reaches a bottom point where consumption again rises before reaching the maximum power output [28]. At this bottom point, the operation will be most economical, in other words have the lowest fuel consumption.

To be able to estimate the vessel's SFOC at any given time, a fuel consumption curve was created based on a typical Wärtsilä engine. The consumption curve for the actual MTU engine was difficult to obtain, therefore values from a Wärtsilä engine in the same power range is used [45]. The engine used has a SFOC at 50% = 194 g/kWh, 75% = 189.4 g/kWh, 85% = 190 g/kWh, and 100% = 195.3 g/kWh. Figure 5.4 shows the SFOC curve used for calculation of fuel consumption. A polynomial estimate was then made to obtain a complete curve. The polynomial estimated fuel consumption curve was further implemented in the data set by the following equation:

$$SFOC = 0.0087381x^2 - 1.2869x + 235.535 \tag{5.2}$$

where x is the percentage of load for each Genset. The vessels active Gensets together with the load capacity is dependent on the vessels power demand at the given time.

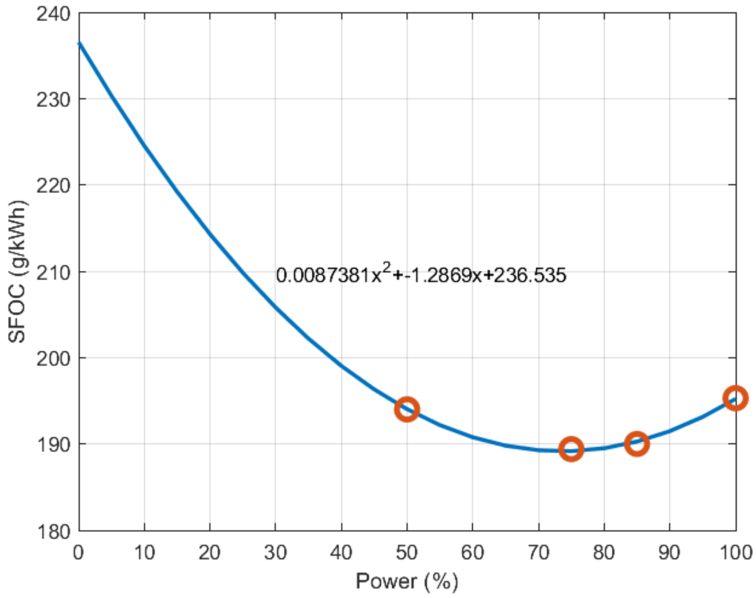


Figure 5.4: SFOC curve used for the vessel

Further, the fuel consumption for the conventional system was calculated using the following equation:

$$FOC = \sum_{t=1}^{T} P_{total}(t) \times SFOC(t) \qquad \forall t \epsilon T \tag{5.3}$$

where P_{total} is the total load in the measured point and t is the time difference between each measured point. Due to the post-process of the data, and the irregularities in the AIS signals, the difference in time between each point is not constant.

The diesel density that is used for conversation to liter is 0.835 as earlier assumed. The system's consumption is summarized in a Table 5.4. The conventional solution gives a weekly consumption of 80,916.7 liters, and the main contributors to the consumption is the transit phase and operational phase.

Table 5.4: Scenario 1 - Fuel consumption

Operational mode	**Home port**	**Distribution port**	**Transit**	**Operation**
Fuel consumption [l/week]	330.7	8799.3	31787.7	39999.0
Total Fuel consumption [l]	80916.7			

5.4.1 Fuel cost conventional system

The fuel costs are calculated with a fuel price of NOK 5.8, and the results are presented in the table 5.5. The total fuel cost for one week is calculated to be NOK 469,317.5.

Table 5.5: Scenario 1 - Fuel costs

Operational mode	**Home port**	**Distribution port**	**Transit**	**Operation**
Fuel cost [NOK/week]	NOK 1,918.3	NOK 51,035.9	NOK 184,368.9	NOK 231,994.4
Total weekly Fuel cost	NOK 469,317.5			

5.5 Case scenario 2 - Hybrid solution with peak shaving operation

Case scenario two represents a battery hybrid propulsion system. One of the Gensets has been replaced with a battery pack for peak shaving operation in this system. Therefore, there will be a combination of power output from the Gensets and the battery ESS when the load is higher than 90% of the maximum load from the three Gensets. The conceptual solution is presented in the SLD diagram shown in Figure 5.5.

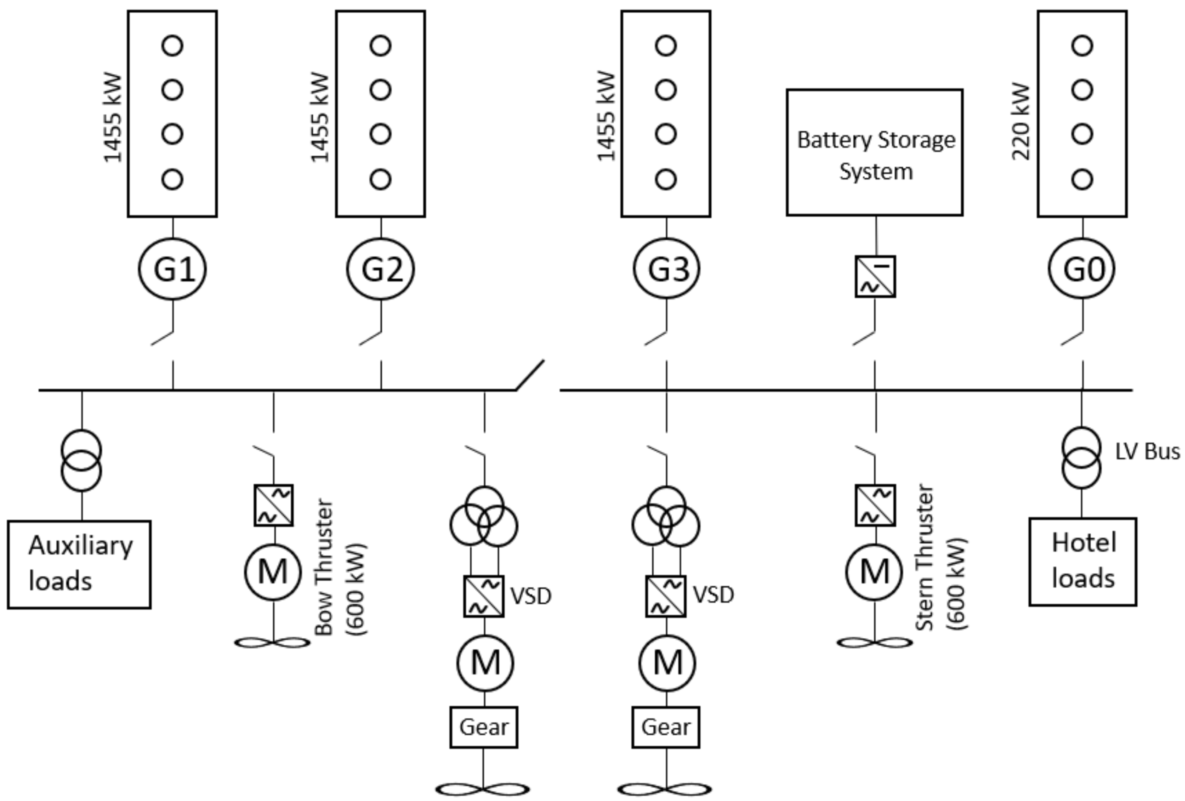


Figure 5.5: Wellboat topology for Scenario 2

Table 5.6 shows the number of activated Gensets in the given load interval. As shown in the table, the battery will only assist when the system's load demand is over 3,928 kW. In this implementation, the battery has no recharging options, which means that the battery is only discharged and has to be charged when the vessel is in port.

Table 5.6: Scenario 2 - Number of operating generators

Number of operating Gensets	Load interval
1 × 1,455kW Genset	0 - 1,309.5 [kW]
2 × 1,455kW Gensets	1,309.5 - 2,619 [kW]
3 × 1,455kW Gensets	2,619 - 3,928 [kW]
3 × 1,455kW Gensets and one Battery	3,928 - 5,820 [kW]

Figure 5.6 shows the result from the peak shaving operation together with the total load. The orange load profile represents the Gensets load, and the blue load is the load of the battery. As the battery does not charge during transit and has to take care of the vessel's peak demands, there may be long periods when the battery has a high consumption over a longer time. The result also shows that the battery is only used during transit as this where the system's highest peak demands occur.

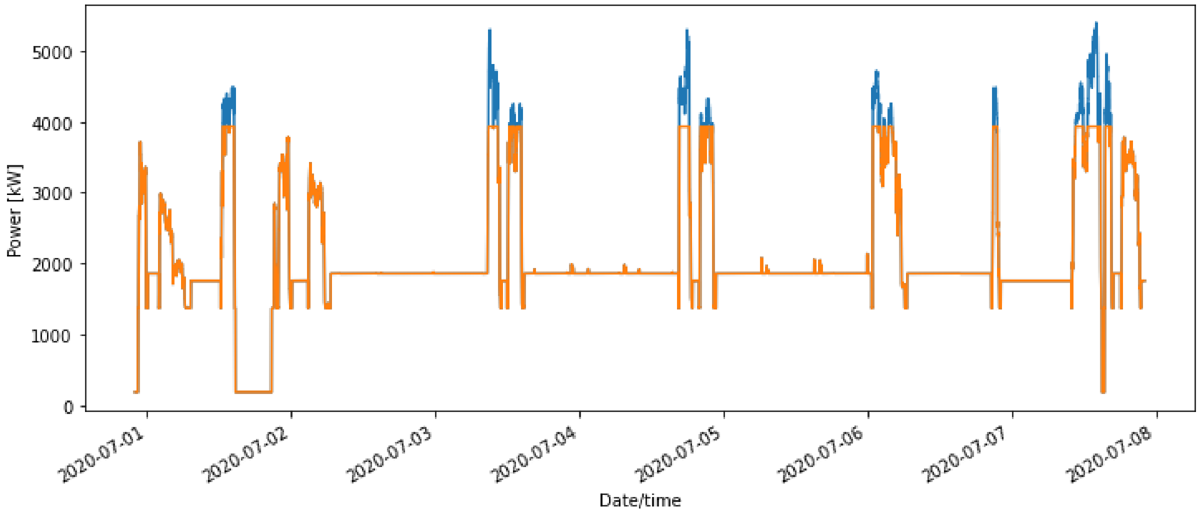


Figure 5.6: Load profile with Peak shaving operation

Figure 5.7 shows the results for the battery load for the representative week. Due to no recharging of the battery from Genset power, the battery capacity must be large enough to cover energy demand between 2 ports. Geographical data was therefore used to find out when the vessel was at a quay facility. Based on the premise that the vessel could charge the battery in port, the trip with the highest energy demand was selected for further investigation. In figure 5.7 is the selected route marked in red.

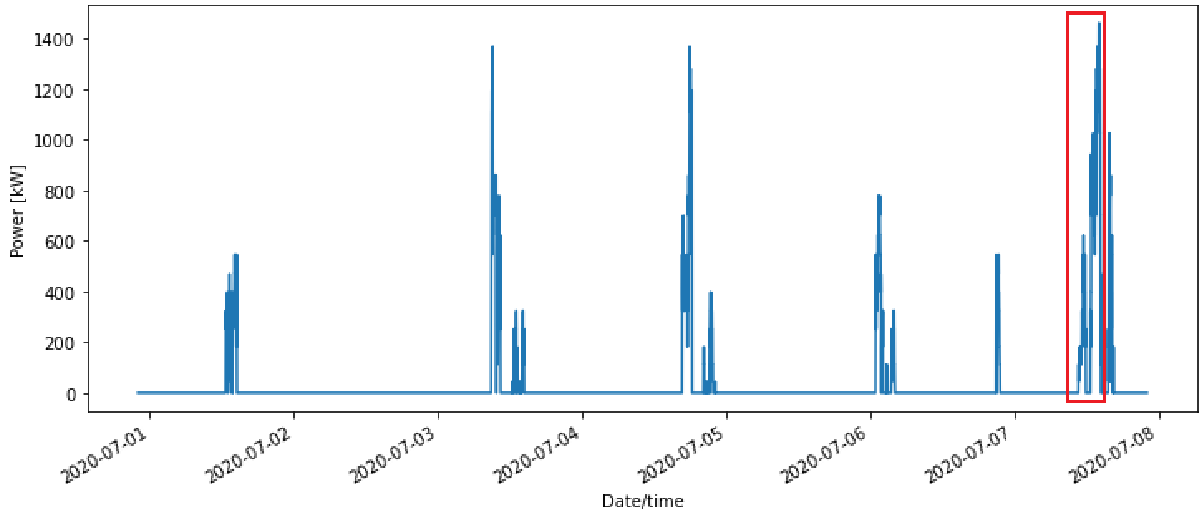


Figure 5.7: Battery load in the peak shaving operation

Figure 5.8 presents the battery load for the most energy-consuming trip. During this trip, the required consumption from the battery is 2,010 kWh, and the highest peak load is 1,457 kW. As this model only cuts the highest peaks and the battery has no regeneration of energy from Genset power, this solution will result in an excessively large battery, resulting in a high investment cost. At the same time, the battery will be too heavy for this to be a good solution.

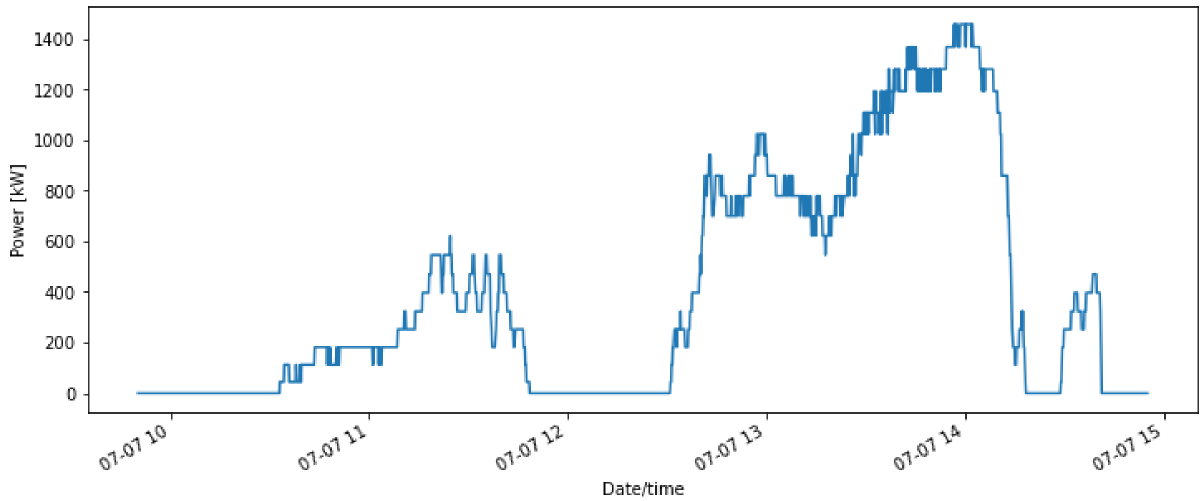


Figure 5.8: Worst case trip peak shaving operation

Table 5.7 presents the fuel consumption for scenario 2. As mentioned earlier, only during transit does the vessel achieve high enough loads that require assistance from battery. However, this solution will provide a fuel saving of 1,303 liters per week compared to the conventional solution.

Table 5.7: Scenario 2 - Fuel consumption

Operational mode	Home port	Distribution port	Transit	Operation
Fuel consumption [l/week]	330.7	8,799.3	30,484.7	39,999.0
Total Fuel consumption [l]	79,613.7			

5.5.1 Fuel cost hybrid system with peak shaving

The fuel cost for one week is presented in Table 5.8. Compared to the scenario with the conventional solution, the cost savings from the fuel savings result in a weekly savings of NOK 7,557.4. Assuming 52 weeks in one year, the fuel savings for one year is equal to NOK 392,984.8.

Table 5.8: Scenario 2 - Fuel costs

Operational mode	Home port	Distribution port	Transit	Operation
Fuel cost [NOK/week]	NOK 1,918.3	NOK 51,035.9	NOK 176,811.3	NOK 231,994.4
Total weekly Fuel cost	NOK 461,759.9			

5.6 Case scenario 3 - Load leveling

Case scenario 3 represents a battery hybrid propulsion system with battery usage for load leveling. In this system, the vessel topology has four Gensets as in the conventional system, but an extra battery is installed for load leveling. Table 5.9 shows the number of activated Gensets at the given load interval. The Genset load will in this case be smoother, and the battery will take care of the largest load variations.

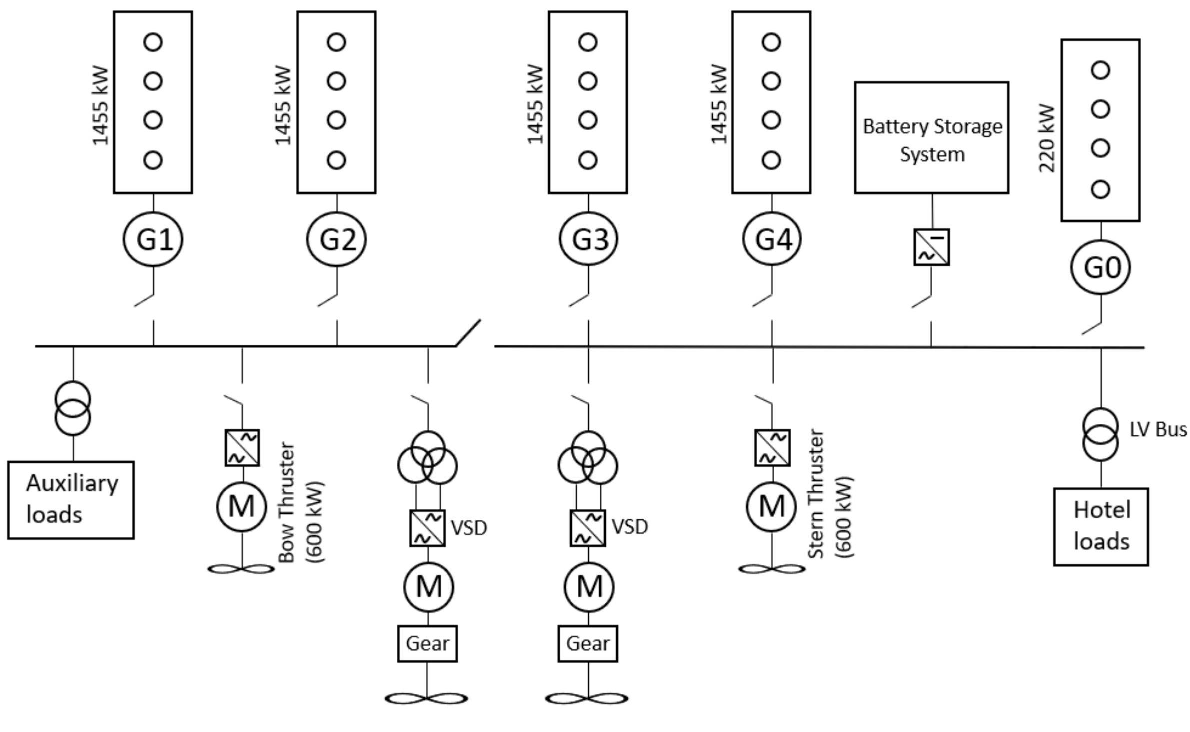


Figure 5.9: Wellboat topology for Scenario 3

For load leveling, a first-order filter or low pass filter is used. This filter only allows low-frequency dynamics in the load. Therefore, the battery will be active when there is a mismatch between the actual load and the filtered load. In cases where the filtered load is higher than the actual load, the battery will be charged by the excess load from the Gensets.

Table 5.9: Scenario 3 - Number of operating generators and battery support

Number of operating Gensets	Load interval
Battery for load levelling	0 - 5,820 [kW]
1 × 1,455kW Genset	0 - 1,309.5 [kW]
2 × 1,455kW Gensets	1,309.5 - 2,619 [kW]
3 × 1,455kW Gensets	2,619 - 3,928 [kW]
3 × 1,455kW Gensets	3,928 - 5,820 [kW]

Figure 5.10 presents the results for scenario 3. The actual load is plotted in blue together with the filtered load in orange. It is clear that the filtered load filters out the highest frequency changes. The battery will, therefore, help the Gensets operate with a smoother load.

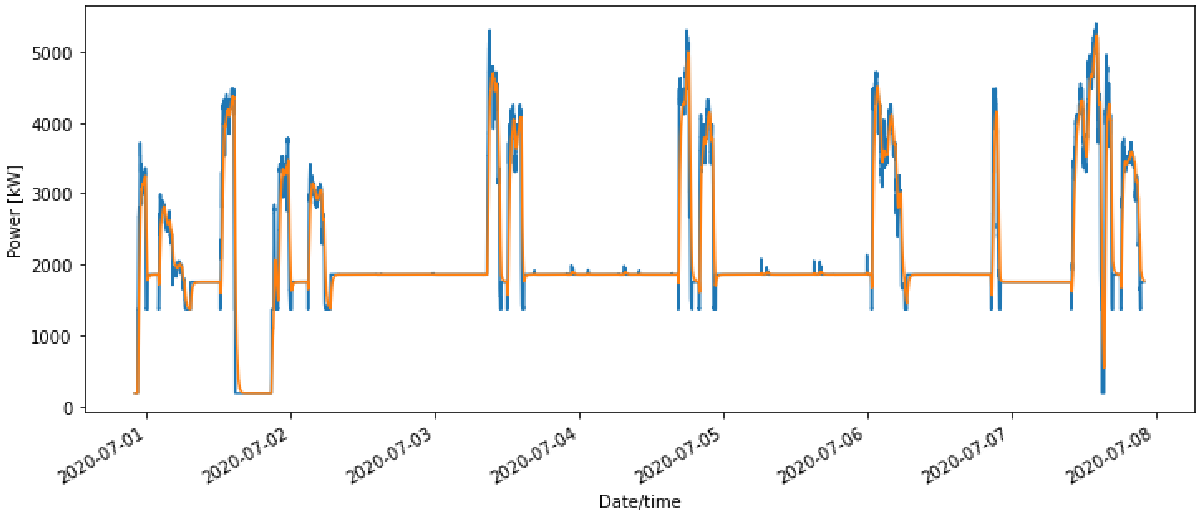


Figure 5.10: Load leveling - Scenario 3

Figure 5.11 shows the result for the battery load for the representative week. The battery appears to take the fluctuating loads as intended. Furthermore, it is clear that the battery charges in situations where the filtered load is greater than the actual load. With the same premises as scenario 2, the battery's energy consumption must be reasonable if the battery installation should be feasible and cost-effective. Furthermore, it was, therefore, looked more closely at the trip that was most energy demanding for the battery.

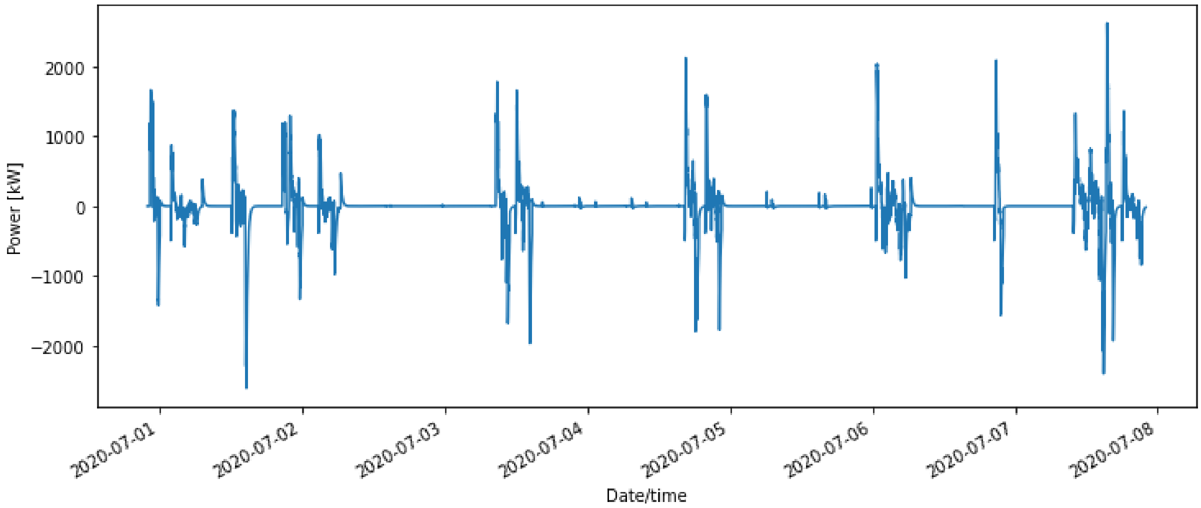


Figure 5.11: Battery load for scenario 3

Assuming as mentioned in scenario 2, the battery can be charged in each port. The battery, therefore, has to handle the trip with the highest battery consumption. Figure 5.12 presents the trip with the highest battery consumption. The blue line shows the actual load, the orange line illustrates the filtered load that will be the Genset load, and the green line presents the battery load. Thus, the battery clearly takes the fluctuations in the load. During this trip, the required consumption from the battery was 352 kWh, and the highest peak load is 1,294 kW. The results for the other trips are attached in the Appendix C.

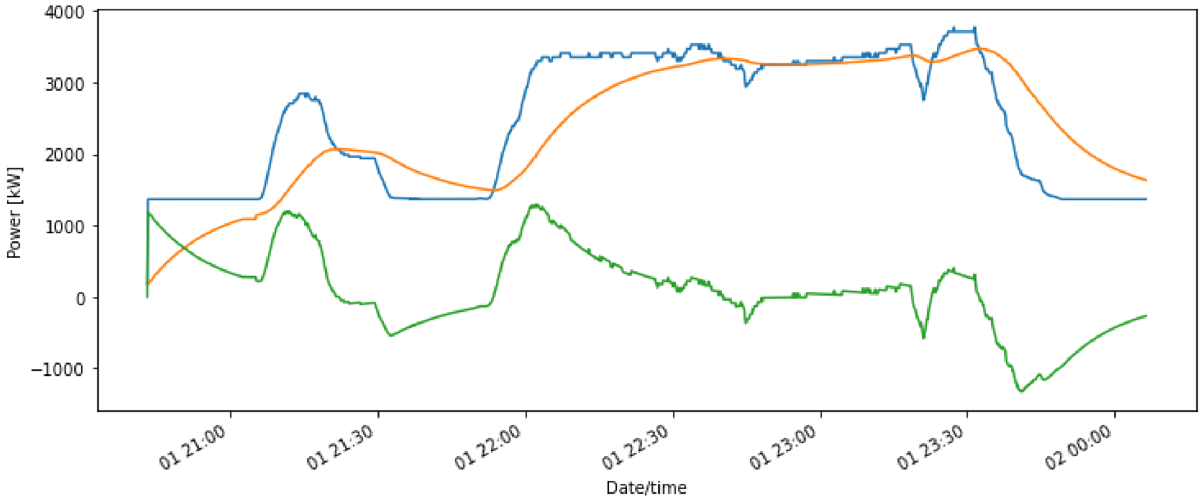


Figure 5.12: Load leveling worst case

In Table 5.10 the fuel-consumption for scenario 3 i presented. Comparing the results with the results from the conventional solution the the fuel savings is 118.9 liter. In annual fuel saving this is 6,182.8 liter.

Table 5.10: Scenario 3 - Fuel consumption

Operational mode	**Home port**	**Distribution port**	**Transit**	**Operation**
Fuel consumption [l/week]	562.1	8,800.0	31,492.9	39,942.8
Total Fuel consumption [l]	80,797.8			

5.6.1 Fuel cost for scenario 3

For case scenario 3 the fuel savings results in a fuel cost saving of NOK 689.6 per week. In annual fuel cost this is NOK 35,860.2, a cost that is insignificantly small.

Table 5.11: Scenario 3 - Fuel costs

Operational mode	Home port	Distribution port	Transit	Operation
Fuel cost [NOK/week]	NOK 3,260.2	NOK 51,040.0	NOK 182,658.8	NOK 231,668.2
Total weekly Fuel cost	NOK 468,627.2			

Chapter 6

Discussion

The findings and results in the thesis have already been discussed in the different chapters and subjects. In this discussion, however, it will be summarized and further discussed. Weaknesses in the method selected based on the limited availability of actual vessel data, together with the results, will be addressed in this chapter.

The results from the load profile characterization showed a big difference in the power consumption of the different vessels based on size and the work tasks of the vessels. In addition, the load profile characterization created an understanding and an expectation of what the later estimated load profile of the selected wellboat should look like. In the load profile estimation method, assumptions and simplifications have been made, and a conversion from the vessel's speed from AIS data to power has been carried out. However, due to the competition between the companies in the market, it was hard to obtain actual load data for wellboats. Therefore, the load profile estimation had to be carried out using AIS data as background data to generate and estimate power load data for sailing and operations. Constant values for the auxiliary and hotel loads were estimated based on input from equipment suppliers. This method does not consider waves, wind, or other external influences, since the AIS data is not providing this information. It is also assumed that this will partly be equalized over time between headwinds and against winds. In addition, the vessel draft is neither taken into consideration in this estimation. The draft of a wellboat can, in many ways, provide valuable information regarding the vessel's mode of operation. For example, the draft says something about whether the vessel is fully loaded or empty during transit or whether the vessel is loading or offloading in port or at the fish farms. The vessel's load condition will also have a significant effect on the vessel's consumption during transportation. AIS data may contain this type of information but was not included in the given data file.

A vessel's operation profile is created based on position data and vessel speed from the AIS file. Based on the position data and by studying maps, it became possible to assume the vessel's type of operation mode. Even if the position is given, it is unknown what kind of operation the vessel carried out. Nevertheless, this position data is the base for the assumptions for the auxiliary load's operation mode. Assuming a loading or offloading operation is taking place when the vessel is at the quay, but in reality, no work is carried out can mislead the vessel's consumption and thereby introduce an increased failure rate.

6.1 Case study

The case study looked at the value of implementing a battery pack and compared the different systems with ESS to the conventional solution. Fuel consumption and fuel costs were calculated for each solution. First, the calculations for the conventional solution were calculated. This solution gave fuel consumption for the representative week of 80,917 liters resulting in NOK 469,318 in weekly fuel cost. As the vessel's fuel tank is 264 cubic meters, the weekly fuel consumption corresponds to approximately 31 percent of the tank volume consumed in one week. The vessel must then bunkering fuel roughly every two to three weeks, which occurs quite realistically. It would be helpful to confirm if this was a reasonable estimate, but this was not possible without access to realistic data.

For case scenario 2, with battery use for peak shaving, the point was to replace one of the generator sets with a battery pack to take the highest energy peaks. This solution gave fuel savings of 1,303 liters resulting in NOK 392,985 in annual OPEX savings. As the battery is not charged but only consumes power when the vessel has the greatest energy demand, this scenario will require an excessively large battery pack. Since the vessel's operation pattern is unpredictable and the battery may have to supply power for longer transit periods which is not suitable for batteries.

Case scenario 3 presents the method using a battery for load leveling. This solution should simulate a scenario where the system topology is kept as it is but an extra battery is implemented for load leveling and taking care of the most considerable load variations. The simulation results look good, and the battery seems to take care of the fluctuations. On the other hand, the fuel savings is not that satisfying, as the load-leveling action gave minimal fuel savings. The reason for this can have been influenced by possible conservative estimations of the constant loads assumed for the auxiliary systems. With actual data from a vessel for the operational work, the result might come out more profitable or potentially opposite. As the vessel's operation profile shows that the vessel spends 54% of the time operating, this parameter might have a more extensive impact on the result than what was first evaluated.

Chapter 7

Conclusion and future work

This thesis is motivated by the desire to reduce the environmental footprint of the aquaculture industry by electrification of aquaculture vessels through the implementation of batteries as an energy storage system. This research has provided a good overview of existing hybrid propulsion systems and ESS systems for ship usage, in particular batteries. In addition, an overview of equipment and propulsion systems used onboard wellboats is carried out to understand the requirements the potential ESS and battery systems needs to fulfill.

A representative and credible load profile for the wellboat emerged through the load profile estimation using AIS data, even tho simplifications and assumptions were made. In addition, AIS data and geographical data proved to be essential for making the correct assumptions for the auxiliary loads to achieve the most realistic load profile and operation profile possible. Without actual data from a wellboat, it is difficult to know how far from reality the load profile is for sure.

Different configurations of electrical propulsion systems have been discussed. Both systems with AC and DC grids have been compared. The different propulsion systems have their advantages and disadvantages and should be considered when designing a new vessel. As high auxiliary loads characterize a wellboat's load profile, the AC grid system stands out as a fuel-efficient solution for vessels where the hotel load and loads from auxiliary systems are a significant part of the required propulsion power. However, the DC grid system proves to be more stable, and the ability to operate the Gensets at variable speed makes the system more capable of saving fuel. In addition, integration of ESS can easily be done as batteries operate on DC. However, retrofitting an existing vessel topology, conversion from AC to DC grid will be very extensive and expensive, so the best solution is to keep the system grid.

The role of the storage systems that will give the best effect on fuel consumption, resulting in reduced emissions, turned out to be using a battery for non-spinning reserve, peak shaving, or load leveling. Due to high consumption in port and at the fish farms, a plug-in hybrid solution with the possibility of charging the battery and carrying out operational work with a shore power connection will be the best solution. Today's technology is evolving, but this solution requires that the players and suppliers in the industry work together to develop the infrastructure needed.

Honestly, the case study did not give the result that was first expected. The implemented peak shaving operation provides an oversized battery, and the load-leveling scenario provides minimal fuel saving. Moreover, a constant load is assumed for the auxiliary load, resulting in no fluctuations disregard when there are changes in the ship's speed. Therefore, the battery is only used during transit or maneuvering, making it less profitable than it probably would be.

7.1 Future work

This section provides a short description of suggested further work related to the research in this thesis.

Suggestions for further work include the following points:

- Establish availability to a real dataset from a wellboat.
- Validate realism and accuracy in methods and calculations based on received data
- Establish a non-disclosure agreement and a good relation with wellboat operator and other relevant aquaculture vessels to be able to configure dataset with additional relevant data for future development and verification of ESS calculation models.
- Establish simulation models to compare different ESS solutions
- Get data from a vessel with already rebuilt/converted to a hybrid power system
- Ultimate to have online availability and full availability of high-resolution logging date from operation including:
  - Mode of operation
  - Power load monitoring
  - Fuel consumption
  - Transport tonnage
  - Sailing speed
  - Weather and environment conditions

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Appendix

A Overview of time use for the typical wellboat

Week of operation				
Position	**t1**	**t2**	**Total time**	**beskrivelse**
Siholmen kai	1593554400	1593556059	1659	Liggekai/hjemmehavn, manskapsbytte
Transit	1593556059	1593562226	6167	Transit
Langskjæra Lokasjon	1593562226	1593568637	6411	Opprasjon
Transit	1593568637	1593587748	19111	Transit
Lerøy midt Hitra Vest	1593587748	1593605577	17829	Slakte og fordelingsanlegg
Transit	1593605577	1593614468	8891	Transit
Siholmen kai	1593614468	1593636187	21719	Liggekai/hjemmehavn, manskapsbytte
transit	1593636187	1593648379	12192	Transit
Lerøy midt Hitra Øst	1593648379	1593658080	9701	Akva group - Service eller distribusjon
Transit	1593658080	1593671600	13520	Transit
Edøya Lokasjon	1593671600	1593765720	94120	Opprasjon
Transit	1593765720	1593774000	8280	Transit
Lerøy midt Hitra Øst	1593774000	1593777367	3367	Akva group - Service eller distribusjon
Transit	1593777367	1593787549	10182	Transit
Edøya Lokasjon	1593787549	1593880008	92459	Opprasjon
Transit	1593880008	1593888448	8440	Transit
Lerøy midt Hitra Øst	1593888448	1593892359	3911	Akva group - Service eller distribusjon
Transit	1593892359	1593902396	10037	Transit
Edøya Lokasjon	1593902396	1593995747	93351	Opprasjon
Transit	1593995747	1594016987	21240	Transit
Halsbukta Lokasjon	1594016987	1594067308	50321	Opprasjon
Transit	1594067308	1594073136	5828	Transit
Kristiansund	1594073136	1594115418	42282	Lerøy Kristiansund
Transit	1594115418	1594133686	18268	Transit
Siholmen kai	1594133686	1594135189	1503	Liggekai/hjemmehavn, manskapsbytte
Transit	1594135189	1594140389	5200	Transit
Langskjæra	1594140389	1594144948	4559	Lokasjon
Transit	1594144948	1594157086	12138	Transit
Lerøy midt Hitra Vest	1594157086	1594159200	2114	Slakte og fordelingsanlegg
SUM			168	
SUM PORT TIME [t]			29	
SUM OPERATION [t]			95	
SUM PORT %			23,37381486	
SUM OPERATION %			76,62618514	

Figure 1: Time table for the wellboat - One week of operation

B Consumption values from Cflow

WELLBOAT 3000-3500m3 440V				CARGO						TREATMENT						WASHING		EMERGENCY	
				Loading		Transit Fully Loaded-11 Knots		Offloading		Loading		Treatment		Offloading		Washing - 10 Knots		Emergency	
440V MSB Consumers	Nos	kW	T Kw	DF	kW	DF	kW	DF	kW	DF	kW	DF	kW	DF	kW	DF	kW	DF	kW
Fish Handling System Circulation Pump 1-8	8	165	1320	0,7	924	0,7	924	0,7	924	0,7	924	0,7	924	0,7	924	0,2	264	0	0
Fish Handling System Compressor 1-2 For Vacuum	2	63	126	1	126	0	0	0	0	1	126	0	0	0	0	0	0	0	0
Bilge Pump PS-SB	2	22	44	0	0	0	0	0,9	39,6	0	0	0	0	0,9	39,6	0,6	26,4	0	0
Air Compressor 1-2	2	75	150	1	150	1	150	1	150	1	150	1	150	1	150	1	150	0	0
CO2 Removing System Air Blower PS-SB	2	86	172	0	0	0,8	137,6	0,8	137,6	0	0	0,8	137,6	0,8	137,6	0	0	0	0
Ozone Generator 1-2	2	26	52	0	0	0	0	0	0	0	0	1	52	0	0	1	52	0	0
Back Flushing and Waste Recovery System Control Box 1-2	2	3	6	0	0	1	6	1	6	0	0	1	6	1	6	1	6	0	0
Fish Handling System Water Pump Starter	1	4,4	4,4	1	4,4	0	0	0	0	1	4,4	0	0	0	0	0	0	0	0
Fish Handling System Fish Pump Starter 1-2	2	64	128	1	128	1	128	1	128	1	128	1	128	1	128	1	128	0	0
Fish Handling System Mix Pump PS-SB Starter	2	5,5	11	0	0	0	0	0	0	1	11	1	11	0	0	0	0	0	0
Fish Handling System Drumfilter (+HFC1)	1	3,55	3,55	0	0	1	3,55	1	3,55	0	0	1	3,55	1	3,55	1	3,55	0	0
Fish Handling System Drumfilter (+HFC2)	1	3,55	3,55	0	0	1	3,55	1	3,55	0	0	1	3,55	1	3,55	1	3,55	0	0
Fish Handling System Beltfilter (+BF1)	1	6,3	6,3	0	0	1	6,3	1	6,3	0	0	1	6,3	1	6,3	1	6,3	0	0
Fish Handling System Beltfilter (+BF2)	1	6,3	6,3	0	0	1	6,3	1	6,3	0	0	1	6,3	1	6,3	1	6,3	0	0
Fish Handling System Hyd. Aggr fwd	1	22	22	1	22	0	0	1	22	1	22	0	0	1	22	1	22	0	0
Fish Handling System Injector Pump 1-6	6	18,5	111	1	111	1	111	1	111	1	111	1	111	1	111	0,5	55,5	0	0
Fish Handling System UV Reactor 1-2	2	64	128	0	0	1	128	1	128	0	0	1	128	1	128	0	0	0	0
Fish Handling System Backwash Pump 1-2	2	3	6	0	0	1	6	1	6	0	0	1	6	1	6	1	6	0	0
Fish Handling System Washing Pump 1-2	2	3	6	0	0	0	0	0	0	0	0	0	0	0	0	1	6	0	0
Fish Handling System Washing Booster Station	1	22	22	0	0	0	0	0	0	0	0	0	0	0	0	1	22	0	0
					1465,4		1610,3		1671,9		1476,4		1673,3		1671,9		757,6		0

Figure 2: Consumption values for auxiliary equipment for well-boat

C Load leveling - case study

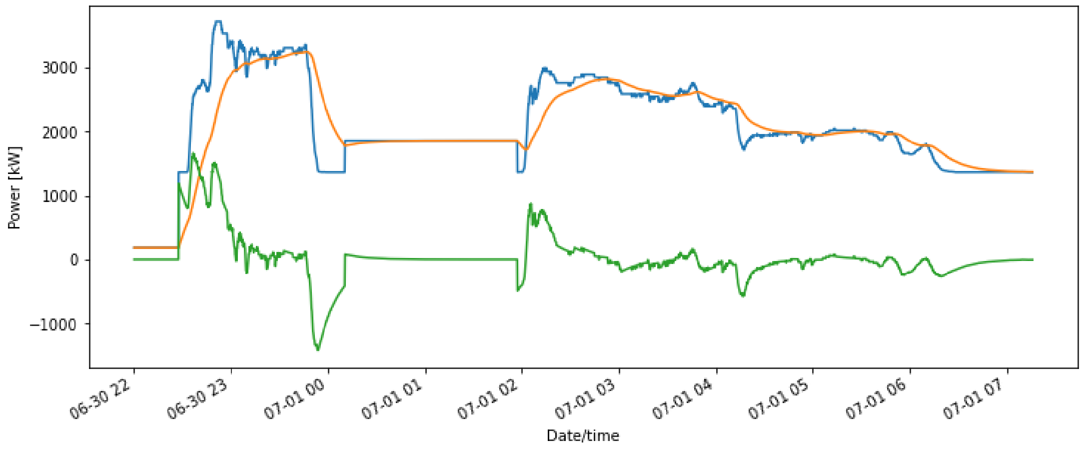

Figure 3: Load leveling - Trip 1

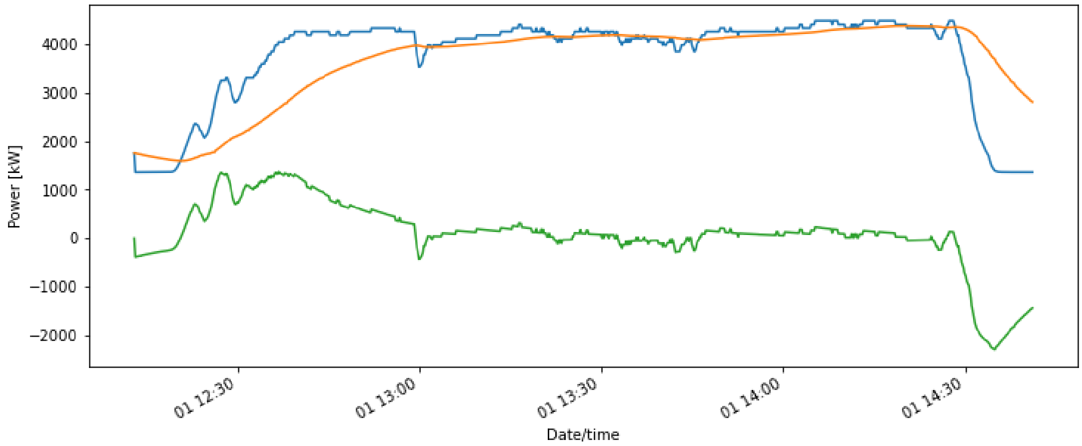

Figure 4: Load leveling - Trip 2

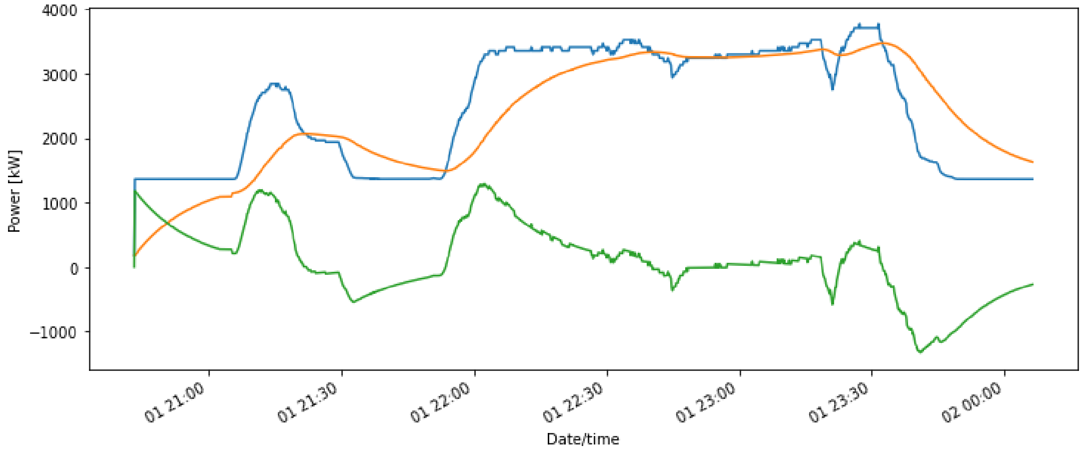

Figure 5: Load leveling - Trip 3

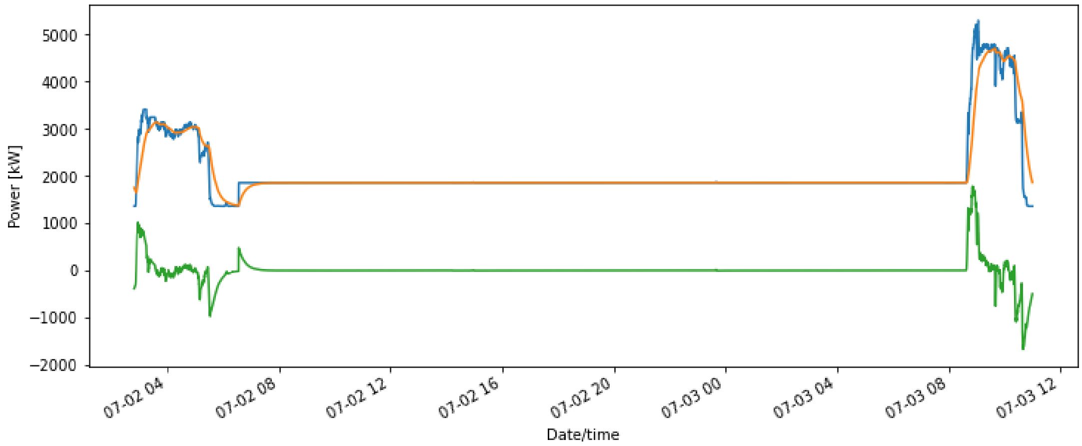

Figure 6: Load leveling - Trip 4

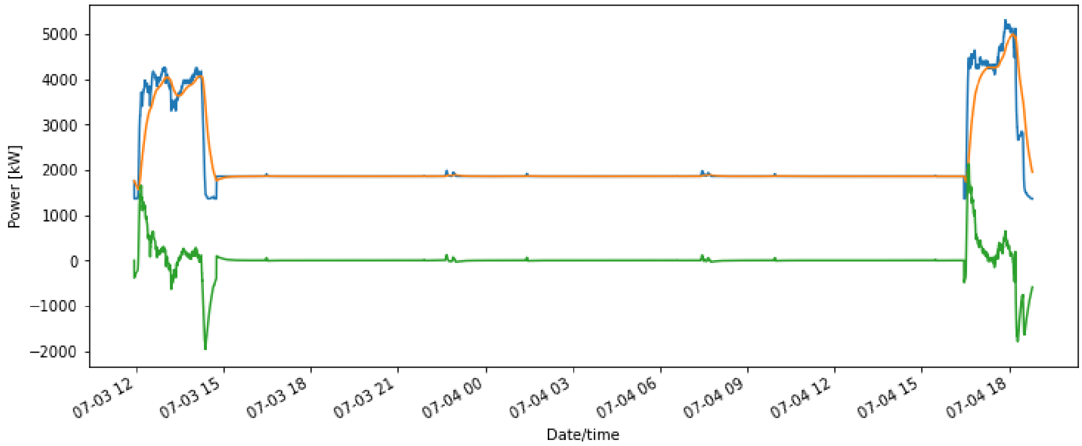

Figure 7: Load leveling - Trip 5

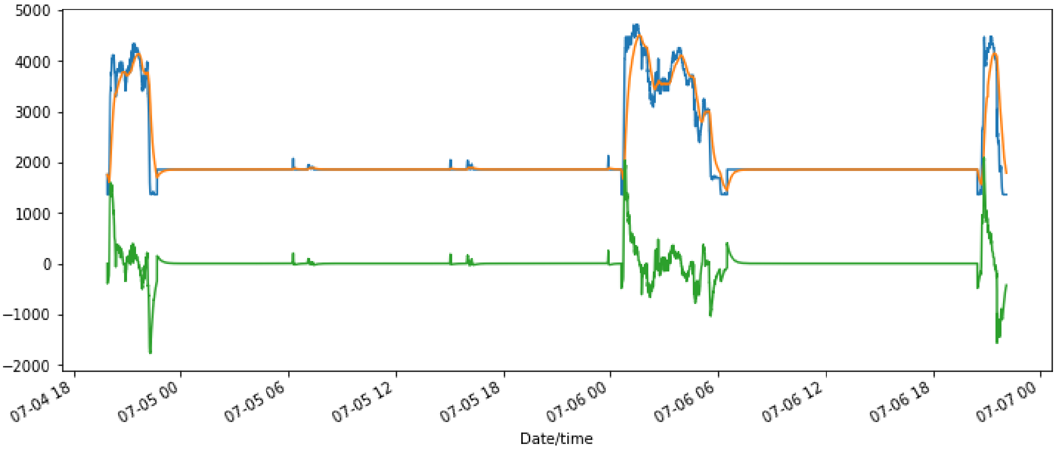

Figure 8: Load leveling - Trip 6

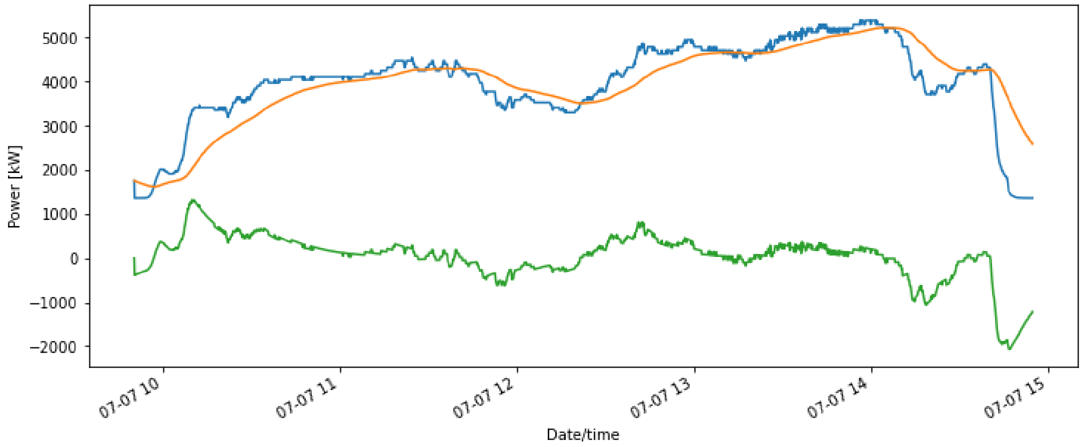

Figure 9: Load leveling - Trip 7

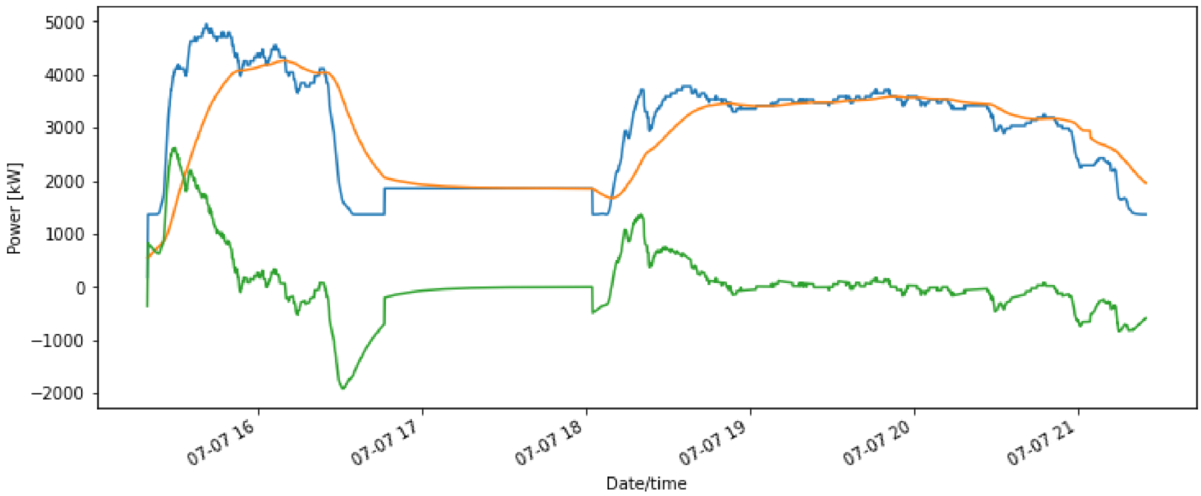

Figure 10: Load leveling - Trip 8

D Code

```
#!/usr/bin/env python
# coding: utf-8

# In[1]:


import sqlite3 as lite
import numpy as np
import pandas as pd
from mpl_toolkits.basemap import Basemap
import matplotlib.pyplot as plt
import datetime as datetime


# In[2]:


import os
os.environ['PROJ_LIB'] =
↪  'C:/......./....../Anaconda3/Lib/site-packages/mpl_toolkits/basemap'


# In[3]:


databasepath =('../../../SAISGlobalTotal.db')


# In[4]:


inputquery =("SELECT * FROM sqlite_master")


# In[5]:


# WELLBOAT VESSELS
vesseldata = pd.read_csv("Wellboat.csv")


# In[6]:


# LOCATIONS FOR THE WELLBOAT
loc = pd.read_csv("Loc_GV.csv", delimiter=',')


# In[7]:


# LOCATIONS FOR THE WELLBOAT
loc_l = pd.read_csv("Loc_L.csv", delimiter=',')


# In[8]:
```

```
# READS, SORT BY MMSI AND UNIXTIME BEFORE PRINT
pd_vessel1 = vesseldata[vesseldata.mmsi == MMSI]

pd_vessel1 = pd_vessel1.sort_values(by = ['unixtime'])

pd_vessel1 = pd_vessel1[pd_vessel1['sog'].between(0, 15)]

pd_vessel1 = pd_vessel1.drop_duplicates(subset=['unixtime'], keep='first')

#---------------Adding time/date column-----------------------
pd_vessel1['Date/time'] = pd_vessel1['unixtime']

pd_vessel1['Date/time'] = pd.to_datetime(pd_vessel1['unixtime'], unit='s')


# In[9]:


#---------------Adding power column-----------------------
c = 1.671          #constant
pd_vessel1['Hl'] = 180      #Hotel load

pd_vessel1['Prop'] = (c*(pd_vessel1['sog'])**3)

pd_vessel1['Power'] = pd_vessel1['Prop']+pd_vessel1['Hl']


# In[10]:


pd_vessel1['delta_t'] = pd_vessel1['unixtime'].diff()
print(pd_vessel1)


# In[11]:


# DEFINES THE DIFFERENT STATES USING SPEED
pd_vessel1.loc[(pd_vessel1.sog <= 0.2),'Operationmode'] = 'Port/time at
↪ loacation'
pd_vessel1.loc[(pd_vessel1.sog > 0.2)&(pd_vessel1.sog <= 3.5),
↪ 'Operationmode'] = 'Manuvering'
pd_vessel1.loc[(pd_vessel1.sog > 3.5)&(pd_vessel1.sog < 10), 'Operationmode']
↪ = 'Slow speed'
pd_vessel1.loc[(pd_vessel1.sog >= 10)&(pd_vessel1.sog <= 14), 'Operationmode']
↪ = 'Transit'
pd_vessel1.loc[(pd_vessel1.sog >= 14)&(pd_vessel1.sog <= 15), 'Operationmode']
↪ = 'Full Speed'


# In[12]:


#DEFINES ONE WEEK OF OPERATION
pd_week = pd_vessel1[(pd_vessel1['unixtime']>=1593554400)&
                     (pd_vessel1['unixtime']<=1593554400+86400*7)]


# In[13]:
```

```
# OPERATION STAT
pd_week.loc[(pd_week.unixtime >= 1593554400)&(pd_week.unixtime <=
↪  1593556059),'Operationstat'] = 'Siholmen'
pd_week.loc[(pd_week.unixtime > 1593556059)&(pd_week.unixtime <= 1593562226),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593562226)&(pd_week.unixtime <= 1593568637),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1593568637)&(pd_week.unixtime <= 1593587748),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593587748)&(pd_week.unixtime <= 1593605577),
↪  'Operationstat'] = 'Lerøy' #vest
pd_week.loc[(pd_week.unixtime > 1593605577)&(pd_week.unixtime <= 1593614468),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593614468)&(pd_week.unixtime <= 1593636187),
↪  'Operationstat'] = 'Siholmen'
pd_week.loc[(pd_week.unixtime > 1593636187)&(pd_week.unixtime <= 1593648379),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593648379)&(pd_week.unixtime <= 1593658080),
↪  'Operationstat'] = 'Lerøy' #øst
pd_week.loc[(pd_week.unixtime > 1593658080)&(pd_week.unixtime <= 1593671600),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593671600)&(pd_week.unixtime <= 1593765720),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1593765720)&(pd_week.unixtime <= 1593774000),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593774000)&(pd_week.unixtime <= 1593777367),
↪  'Operationstat'] = 'Lerøy' #øst
pd_week.loc[(pd_week.unixtime > 1593777367)&(pd_week.unixtime <= 1593787549),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593787549)&(pd_week.unixtime <= 1593880008),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1593880008)&(pd_week.unixtime <= 1593888448),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593888448)&(pd_week.unixtime <= 1593892359),
↪  'Operationstat'] = 'Lerøy' #øst
pd_week.loc[(pd_week.unixtime > 1593892359)&(pd_week.unixtime <= 1593902396),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1593902396)&(pd_week.unixtime <= 1593995747),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1593995747)&(pd_week.unixtime <= 1594016987),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1594016987)&(pd_week.unixtime <= 1594067308),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1594067308)&(pd_week.unixtime <= 1594073136),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1594073136)&(pd_week.unixtime <= 1594115418),
↪  'Operationstat'] = 'Lerøy' #kristiansund
pd_week.loc[(pd_week.unixtime > 1594115418)&(pd_week.unixtime <= 1594133686),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1594133686)&(pd_week.unixtime <= 1594135189),
↪  'Operationstat'] = 'Siholmen'
pd_week.loc[(pd_week.unixtime > 1594135189)&(pd_week.unixtime <= 1594140389),
↪  'Operationstat'] = 'Transit'
pd_week.loc[(pd_week.unixtime > 1594140389)&(pd_week.unixtime <= 1594144948),
↪  'Operationstat'] = 'Oprasjon'
pd_week.loc[(pd_week.unixtime > 1594144948)&(pd_week.unixtime <= 1594157086),
↪  'Operationstat'] = 'Transit'
```

```
pd_week.loc[(pd_week.unixtime > 1594157086)&(pd_week.unixtime <= 1594159200),
↪  'Operationstat'] = 'Lerøy' #vest


# In[14]:


# DEFINES AUXILIRY LOAD
pd_week.loc[(pd_week.Operationstat == 'Siholmen'),'Auxload'] = 0
pd_week.loc[(pd_week.Operationstat == 'Oprasjon'), 'Auxload'] = 1673 #RSW og
↪  sirkulasjon
pd_week.loc[(pd_week.Operationstat == 'Transit'), 'Auxload'] = 1184
pd_week.loc[(pd_week.Operationstat == 'Lerøy'), 'Auxload'] = 1571


# In[15]:


#DEFINES TOTAL LOAD - AUXILARY LOAD + PROP LOAD + HOTEL LOAD
pd_week['Tot_load'] = pd_week[0::1]['Power'] + pd_week[0::1]['Auxload']


# In[16]:


# DEFINES NUMBER OF OPERATING GENSETS BASED ON POWER
pd_week.loc[(pd_week.Tot_load <= 1309.5),'no.genset'] = 1
pd_week.loc[(pd_week.Tot_load > 1309.5)&(pd_week.Tot_load <= 2619),
↪  'no.genset'] = 2
pd_week.loc[(pd_week.Tot_load > 2619)&(pd_week.Tot_load <= 3928), 'no.genset']
↪  = 3
pd_week.loc[(pd_week.Tot_load > 3928)&(pd_week.Tot_load <= 5820), 'no.genset']
↪  = 4


# In[17]:


#LOAD PERCENT PER GENSET
pd_week['Load %'] = pd_week['Tot_load']/(1455*pd_week['no.genset'])*100


# In[18]:


pd_week['SFOC'] = ((0.0087381*pd_week['Load %']**(2)-1.2869*pd_week['Load
↪  %']+236.535)) #Wartzila


# In[19]:


#ONE BATTERY PACK
pd_week.loc[(pd_week.Tot_load <= 3928),'Battery'] = 0
pd_week.loc[(pd_week.Tot_load > 3928),'Battery'] = pd_week.Tot_load - 3928
pd_week['Battery'].value_counts(normalize=True)


# In[20]:
```

```
# DEFINES NUMBER OF OPERATING GENSETS BASED ON TOTAL LOAD
pd_week.loc[((pd_week.Tot_load - pd_week.Battery) <= 1309.5),'no.genset2'] = 1
pd_week.loc[((pd_week.Tot_load - pd_week.Battery) > 1309.5)&((pd_week.Tot_load
↪  - pd_week.Battery) <= 2619), 'no.genset2'] = 2
pd_week.loc[((pd_week.Tot_load - pd_week.Battery) > 2619)&((pd_week.Tot_load -
↪  pd_week.Battery) <= 3928), 'no.genset2'] = 3


# In[21]:


#LOAD PERCENT PER GENSET WITH BATTERY
pd_week['Load_B %'] =
↪  (pd_week['Tot_load']-pd_week['Battery'])/(1455*pd_week['no.genset2'])*100


# In[22]:


pd_week['SFOC_B'] = ((0.0087381*pd_week['Load_B
↪  %']**(2)-1.2869*pd_week['Load_B %']+236.535)) #Wartzila


# In[23]:


# FUEL CONSUMPTION
pd_week['FOC'] =
↪  (pd_week['SFOC']*pd_week['Tot_load']*(pd_week['delta_t'])/3600)/1000


# In[24]:


#########Fuel calculation for Scenario 1 ###########


# In[25]:


# FUEL CONSUMED IN [KG]
pd_week.FOC.sum()


# In[26]:


FOC_liter = pd_week.FOC.sum()/0.835
print(FOC_liter)


# In[27]:


# FUEL COST IN [NOK] ASSUMING 5.5 NOK PER LITER
fuel_cost = pd_week.FOC.sum()/0.835*5.8
print(fuel_cost)
```

```
# In[28]:


FOC_sum = 0
a = 'Transit'
for i, FOC in enumerate(pd_week['FOC']):
    if pd_week['Operationstat'].iat[i] == a:
        FOC_sum+=FOC
print(FOC_sum/0.835*5.8)


# In[29]:


FOC_sum = 0
a = 'Oprasjon'
for i, FOC in enumerate(pd_week['FOC']):
    if pd_week['Operationstat'].iat[i] == a:
        FOC_sum+=FOC
print(FOC_sum/0.835*5.8)


# In[30]:


FOC_sum = 0
a = 'Lerøy'
for i, FOC in enumerate(pd_week['FOC']):
    if pd_week['Operationstat'].iat[i] == a:
        FOC_sum+=FOC
print(FOC_sum/0.835*5.8)


# In[31]:


FOC_sum = 0
a = 'Siholmen'
for i, FOC in enumerate(pd_week['FOC']):
    if pd_week['Operationstat'].iat[i] == a:
        FOC_sum+=FOC
print(FOC_sum/0.835*5.8)


# In[44]:


#DEFINES MAP FOR THE WHOLE AIS-FILE
# Defines the area for the map
minlon = 7.635
minlat = 63
maxlon = 9.4
maxlat = 63.9
lat0 =(maxlat+minlat)/2
lon0 =(maxlon+minlon)/2
lat1 =(maxlat+minlat)/2-20


# In[45]:
```

```
# PRINTING THE WHOLE CSV FILE TO THE MAP
# Figure size and resolution
fig,ax=plt.subplots(figsize=(15,15))
m=Basemap(llcrnrlon=minlon,llcrnrlat=minlat,urcrnrlon=maxlon,
          urcrnrlat=maxlat,rsphere=(6378137.00,6356752.3142),
          resolution='f',projection='merc',lat_0=lat0,lon_0=lon0,lat_ts =lat1)

# Defining the map colour and lines.
m.drawmapboundary(fill_color='white')
m.fillcontinents(color='lightgrey',lake_color='white')

# Map (long, lat) to (x, y) for plotting the Locations.
x1,y1 = m(loc_l['lengdegrader'].values, loc_l['breddegrader'].values)
# Printes the Location points for Lerøy Vest to the map.
m.scatter(x1,y1,s=20,c='red',marker='o',alpha=0.9)

# Map (long, lat) to (x, y) for plotting.
x,y = m(pd_week['longitude'].values, pd_week['latitude'].values)


# Printes the AIS line to the map.
m.scatter(x,y,s=0.01,c='black',marker='o',alpha=0.9)


# In[46]:


pd_week['Operationmode'].value_counts(normalize=True)


# In[47]:


# Calc percetage use of gensets with out battery
pd_week['no.genset'].value_counts(normalize=True)


# In[48]:


max_value = pd_week.max()
print(max_value)


# In[49]:


avg_value = sum(pd_week.Tot_load) / len(pd_week.Tot_load)
print(avg_value)


# In[51]:


(counts, bins) = np.histogram(pd_week['Tot_load'], bins = 20, range=(0,6000))
factor = 10.2387/(3600)
plt.hist(bins[:-1], bins, weights = factor * counts)
plt.xlabel('Power [kW]')
plt.ylabel('Time [h]')
```

```
plt.show()


# In[52]:


# Power profile for GV
plt.figure(figsize=(12, 5))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Prop']))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Auxload']))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Hl']))
plt.gcf().autofmt_xdate()
plt.title('')
plt.xlabel('Date/time')
plt.ylabel('Power [kW]')
plt.show()
```

```
#!/usr/bin/env python
# coding: utf-8

# In[1]:


import math
Load = pd_week.Tot_load.to_numpy()
t_step = pd_week.delta_t.to_numpy()
N= len(t_step)
print(max(t_step))
Load_ft = np.zeros((N,1))
Load_ft[0] = Load[0]
T_low = 800
for i in range(1,N):
    Ts = t_step[i-1]
    if math.isnan(Load_ft[i-1]):
        print(Load_ft[i-1])
    Load_ft[i] = (1-Ts/T_low)*Load_ft[i-1]+(Ts/T_low)*Load[i-1]


# In[2]:


pd_week['Load_ft'] = Load_f #Filtered load
pd_week['Load_consumption'] = (pd_week['Load_ft'])
pd_week['Battery2'] = pd_week['Tot_load'] - pd_week['Load_ft']
pd_week['B_kwh'] = pd_week['Battery2']*pd_week['delta_t']/3600


# In[3]:


# DEFINES NUMBER OF OPERATING GENSETS BASED ON POWER
pd_week.loc[(pd_week.Load_consumption <= 1309.5),'no.genset'] = 1
pd_week.loc[(pd_week.Load_consumption > 1309.5)&(pd_week.Load_consumption <=
↪ 2619), 'no.genset'] = 2
pd_week.loc[(pd_week.Load_consumption > 2619)&(pd_week.Load_consumption <=
↪ 3928), 'no.genset'] = 3
pd_week.loc[(pd_week.Load_consumption > 3928)&(pd_week.Load_consumption <=
↪ 5820), 'no.genset'] = 4
```

```
# In[4]:


# Power profile for GV
plt.figure(figsize=(12, 5))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Tot_load']))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Load_ft']))
plt.gcf().autofmt_xdate()
plt.title('')
plt.xlabel('Date/time')
plt.ylabel('Power [kW]')
plt.show()


# In[5]:


#Oprasjon 1 - 8 defined
pd_bat1 = pd_week[(pd_week['unixtime']>=1593554400) &
↪  (pd_week['unixtime']<=1593587748)]
pd_bat2 = pd_week[(pd_week['unixtime']>=1593605577) &
↪  (pd_week['unixtime']<=1593614468)]
pd_bat3 = pd_week[(pd_week['unixtime']>=1593636187) &
↪  (pd_week['unixtime']<=1593648379)]
pd_bat4 = pd_week[(pd_week['unixtime']>=1593658080) &
↪  (pd_week['unixtime']<=1593774000)]
pd_bat5 = pd_week[(pd_week['unixtime']>=1593777367) &
↪  (pd_week['unixtime']<=1593888448)]
pd_bat6 = pd_week[(pd_week['unixtime']>=1593892359) &
↪  (pd_week['unixtime']<=1594073136)]
pd_bat7 = pd_week[(pd_week['unixtime']>=1594115418) &
↪  (pd_week['unixtime']<=1594133686)]
pd_bat8 = pd_week[(pd_week['unixtime']>=1594135189) &
↪  (pd_week['unixtime']<=1594157086)]


# In[6]:


# Power profile for Wellboat
plt.figure(figsize=(12, 5))
plt.plot(pd_bat8[0::1]['Date/time'] ,(pd_bat8[0::1]['Tot_load']))
plt.plot(pd_bat8[0::1]['Date/time'] ,(pd_bat8[0::1]['Load_ft']))
plt.plot(pd_bat8[0::1]['Date/time'] ,(pd_bat8[0::1]['Battery2']))
plt.gcf().autofmt_xdate()
plt.title('')
plt.xlabel('Date/time')
plt.ylabel('Power [kW]')
plt.show()


# In[7]:


pd_bat3.B_kwh.sum()


# In[8]:
```

```
pd_week.B_kwh.sum()


# In[9]:


#LOAD PERCENT PER GENSET WITH BATTERY
pd_week['Load_B %'] =
↪  (pd_week['Load_consumption'])/(1455*pd_week['no.genset'])*100


# In[10]:


#SFOC
pd_week['SFOC_B'] = ((0.0087381*pd_week['Load_B
↪  %']**(2)-1.2869*pd_week['Load_B %']+236.535)) #Wartzila


# In[11]:


#FUEL CONSUMPTION FOR LOAD LEVELING
pd_week['FOC_B'] = (pd_week['SFOC_B']*(pd_week['Load_consumption'])
                    *(pd_week['delta_t'])/3600)/1000


# In[12]:


pd_week.FOC_B.sum()/0.835


# In[13]:


FOC_B_sum = 0
a = 'Transit'
for i, FOC_B in enumerate(pd_week['FOC_B']):
    if pd_week['Operationstat'].iat[i] == a:
        FOC_B_sum+=FOC_B
print(FOC_B_sum/0.835)


# In[14]:


# BATTERY LOAD
plt.figure(figsize=(12, 5))
plt.plot(pd_week[0::1]['Date/time'] ,(pd_week[0::1]['Battery2']))
plt.gcf().autofmt_xdate()
plt.title('')
plt.xlabel('Date/time')
plt.ylabel('Power [kW]')
plt.show()


# In[ ]:
```

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Electrification and Emission Reduction for Aquaculture Vessels: Case Study of a Wellboat

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Science and Technology