A Method for Determining Feasibility of Electrification of Small Fishing Vessels

Developed Using Operational Data from Two Fishing Vessels in Kosterhavet National Park

Master's thesis in Mobility Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Mira in her home port, Fjällbacka.

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Abstract

All European industries are facing a big shift away from their dependency on fossil fuels as a result of the European Green Deal. Currently, there is no clear plan available for small fishing vessels to make that shift. The purpose of this thesis was to develop a simple and intuitive method for stakeholders to evaluate the feasibility of electrifying small fishing vessels. It was developed using mostly publicly available operational data of two fishing vessels, combined with a regulatory, environmental, and economic analysis of the two vessels. The results of the analysis where compiled into a method implemented as an excel sheet. The resulting method is applicable to most small Swedish fishing vessels. Applying the method to the two case vessels, it was found that the technical and environmental aspects of feasibility are straight forward to evaluate and the chance of electrification being feasible is good. However, the regulatory and economic aspects are less straight forward and need more thought and effort put in by the user. Furthermore, it was found that being able to use grants from *Klimatklivet* to electrify small fishing vessels is unlikely. This is because the investment tends to become profitable before the environmental performance is good enough. Finally, it was concluded that electrification will play an important role in the transition away from the use of traditional fossil fuels in the fishing fleet.

Keywords: fishing, electrification, method, operational analysis, LCA.

Preface

This report presents the outcome of our master's thesis project carried out at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology in collaboration with RISE Research Institutes of Sweden during the spring of 2024.

Acknowledgements

We would like to extend our heartfelt gratitude to our supervisors Fredrik Olsson and Luis Sanchez-Heres at RISE Research Institutes of Sweden, for their continuous support and never ending enthusiasm throughout project.

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We would also like to thank Ingemar Granqvist at Väderö Fisk, owner of Mira and Mikael Nyberg at Havstens Fiskelag, owner of Fredrika, for sharing their data in the project. They also allowed us to visit the vessels to get to know more about them and their fishing operations, which we are very grateful.

Lastly, we would like to thank Johan Borre at Transportstyrelsen for the insightful introduction and discussion regarding the regulatory premises.

Aditya Barman, Arvid Sörfeldt, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
AIS	Automatic Identification System
AP	Acidification Potential
BES	Battery Energy Storage
CO_2	Carbon Dioxide
DC	Direct Current
DER	Distributed Energy Resource
EoL	End-of-Life
GHG	Greenhouse Gas
GWP	Global Warming Potential
IC	Internal Combustion
IMO	International Maritime Oraganisation
LCA	Life-cycle Analysis
LCCA	Life-cycle Cost Analysis
MILP	Mixed-Integer Linear Programming
MG	Microgrid
NMC	Nickel Manganese Cobalt
PM	Particulate Matter
PTW	Pump-to-Wake
PV	Photovoltaic
RES	Renewable-based Energy Sources
RME	Rapseed Methyl Ester
SO_2	Sulphur Dioxide
TtW	Tank-to-Wake
VEAT	Vessel Energy Analysis Tool
WtP	Well-to-Pump
WtT	Well-to-Tank

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1

Introduction

All industries in the EU are facing a big shift away from dependence on fossil fuels during the coming years as the work to reach the sustainability goals is intensified as a part of The European Green Deal (European Commission, 2024b). It states that EU should be climate neutral by 2050 and that the net greenhouse gas emissions should have reduced by at least 55 % by 2030, compared to 1990. This also includes the European fisheries and aquaculture sector for which the European Commission presented a package of measures to improve the sustainability and resilience in the beginning of 2023 (European Commission, 2024a). It builds on four elements where one is to support the sector in improving energy efficiency and switch to renewable power sources to accelerate the energy transition of the sector. The European Commission (2023) writes in their report on the energy transition of the EU fisheries and aquaculture sector, that the sector currently mostly relies on marine diesel. Although there have been a lot of developments in alternative low carbon propulsion systems, the adoption is still low among fishing vessels.

The world's first fully electric commercial fishing vessel, Karoline, started operating in Norway in 2015 (Blich, 2016). Since then, very few other fishing vessels have been electrified. Other than Norway, only the UK and US have very recently launched their first electric commercial fishing vessels (HM Coastguard, 2023; Squires, 2023). All the three projects mentioned above were preceded by extensive research and close collaboration between different stakeholders to make electrified fishing vessels a reality. A close collaboration, especially with the country's maritime authority is highlighted as essential, but such a cooperation or an investigation of the regulations have not been made in Sweden. By conducting this thesis we aim to be the start of a process so that Sweden also gets its first electric fishing vessel soon.

Västra Götalands Län currently has the highest number of fishing vessels among Swedish counties (Havs- och vattenmyndigheten, 2022a), while also having many sensitive marine areas full of life. For example, *Kosterhavets Nationalpark* and *Väderöarnas Naturreservat* which together stretch from Fjällbacka in the south up to the Norwegian border. This is an area that would benefit from reduced local emissions due to its unique and famous biodiversity. The owners of two fishing vessels who are operating on traditional fossil fuels in this area are therefore interested in potentially electrifying, but several questions about the feasibility and course of action remains to be answered. This includes technical, environmental, economic, and regulatory feasibility.

The owners of the vessels Mira and Fredrika, *Väderö Fisk* and *Havstens Fiskelag* respectively, are a part of the PONTOS project driven by RISE Research Institutes of Sweden, which aims to advance research within the maritime sector by providing open access to operational data (RISE, 2023). This thesis is also a part of the PONTOS project and it aims to create a method for evaluating the feasibility of electrifying fishing vessels by using operational data of Mira and Fredrika from the PONTOS data-hub. It also aims to provide the owners of Mira and Fredrika with the necessary answers for them to make an informed decision if they should electrify their vessels and how that would impact their activities.

In 2015, the 2030 Agenda for sustainable development, with 17 sustainable development goals, was adopted by all member states of the United Nations (United Nations, 2024). The primary goals that motivate the execution of this thesis is goal 13 Climate Action and 14 Life Below Water. Goal 13 is pursued by identifying potential for reduced green house gases and the state of Goal 14 would be much improved by reduced local emissions and a shift towards fishing being done on smaller scales.

1.1 Purpose

The aim of the thesis is to develop a simple and intuitive method to evaluate the feasibility of electrifying small fishing vessels. The method should be general enough to fit most Swedish fishing vessels, so it can act as a clear indication for Swedish fisheries when electrification is most beneficial. In order to guarantee the relevance of the method, all aspects of such a conversion is considered, that is, regulatory, technical, environmental, and economic aspects. The purpose is to highlight current obstacles fishermen who are interested in electrifying their vessels face, so that regulators and decision makers can support the green transition of the Swedish fishing fleet more effectively.

1.2 Research questions

To aid the work of developing the method described in the purpose section, a set of research questions were identified.

1. What regulatory challenges exist when electrifying fishing vessels and what requirements do that place on the conversion?
2. Are the operational profiles of small coastal fishing vessels compatible with electrification from a technical perspective or does the operation need to change with electrification?
3. How will environmental effects change, including potential reductions in local emissions and greenhouse gas (GHG) emissions during the life cycle?
4. How will operational and investment costs change with electrification and how will it impact daily operations?

1.3 Project scope and limitations

The method mainly considers the big picture and main parameters of the vessel and operation to give an indication to the stakeholders involved since it is simple and intuitive as was the aim. The method does not give a step by step guide from project start to finished electrification project and does not consider much detail about the conversion itself. Instead, it should be used as an indicator for when electrification should be considered, and when the technology and regulatory landscape are mature enough.

Many of the details of the electric driveline are not considered, instead the focus lies with the overall system parameters and we strongly believe that the specifics should be studied further or handled by an experienced system integrator.

The thesis only considers the Swedish fleet, and is mainly influenced by the two vessels available for the case studies. Which means that the method without modification only works for small fishing vessels using passive equipment operating in Sweden. However, this is further discussed in section 5.4.

1.4 Thesis outline

The thesis starts with a presentation of the relevant background, which includes the project background, a review of relevant literature, a review of the legal landscape concerning electrification, and a review of current electric driveline technologies. Secondly, the methodology of the thesis is presented, which contains the general methodology to develop the method for determining feasibility as well as the specific methodologies for operational analysis, regulatory investigation, driveline design, and evaluation. These specific methodologies do not, on their own, form the method developed in this thesis. Then, the results from the analysis of the two case vessels are presented before the method formulation for determining feasibility of electrifying small fishing vessels, whose executive summary can be found in Appendix A. Finally, the main conclusions drawn from the thesis are presented.

2

Background

In this chapter, we present the necessary background information, which is structured in four parts. First, we present background on the project, such as the composition of the Swedish fishing fleet and what they fish, as well as the vessels analysed in this thesis. Second, we present the relevant literature on electrification of fishing vessels, models used in operational analysis, and life-cycle analysis. Third, we present the legal landscape regarding the electrification of fishing vessels. Last, we present an overview of the technologies involved in electrification.

2.1 Project background

This thesis is a part of the PONTOS project, which aims to advance research within the maritime sector by providing open access to operational data (RISE, 2023). Two fisheries, *Väderö Fisk* and *Havstens Fiskelag* are providing their data to the project and want to find out if they can be electrified. Below, more information about the vessels is presented as well as what they fish for. Furthermore, an overview of the Swedish fishing fleet is presented as well as an introduction to *Klimatklivet*.

2.1.1 The vessels

Two fishing vessels are a part of the PONTOS project, called Mira and Fredrika owned by *Väderö Fisk* and *Havstens Fiskelag* respectively. The vessels are built by Stigfjord, which is common among the fishing fleet around the Swedish west and Norwegian south coasts. Stigfjord has provided different models of fishing boats for coastal fishing, and more than 600 fishing vessels have been built with length between 21 and 47 feet (Arvidsson, 2024).

Fredrika is of type Stigfjord 40 built in 2016 and Mira is a Stigfjord 37 built 1999. The main parameters of the two vessels are presented below in Table 2.1 and pictures of the two vessels can be seen in Figure 2.1. Both are primarily used for fishing, but Mira is also used as a tourist boat for which she has a passenger certificate allowing for 30 passengers.

Table 2.1: Main parameters of the vessels Fredrika and Mira studied throughout the thesis.

Parameter	Fredrika	Mira
Model	Stigfjord 40	Stigfjord 37
Year built	2016	1999
Length [m]	11.91	11.0
Beam [m]	4.0	4.1
GT [T]	11.1	12.11
Engine Power [kW]	242	167

(a) Fredrika (Stigfjordbåtar, 2019) **(b)** Mira (MS Mira, 2024)

Figure 2.1: Pictures of the two vessels Fredrika and Mira.

Mira and Fredrika fish for Norwegian lobster, also known as crayfish, most of the year, and occasionally lobster when it is allowed between the end of September and the 31st of December using pots. Using pots is considered a passive fishing method. Passive equipment is a term to describe equipment which is passively waiting for fish to be caught in them, for example pots and gill nets (TNAU, 2015b). The alternative is active equipment which is actively being towed through the water, mostly different types of trawles and seines (TNAU, 2015a).

2.1.2 Fishing for Norwegian lobster

The Norwegian lobster, see Figure 2.2, is a type of lobster that lives on clay bottoms at a depth of 20-600 metres and can get up to 240 mm long (SLU Artbanken, 2024). It is common all along the Swedish west coast in Kattegatt and Skagerrak.

Figure 2.2: Norwegian lobster captured with cage onboard Mira (Fiskekummunerna, 2021).

The fishing of Norwegian lobster is mainly done in three different ways: mixed trawling, selective trawling, and pots (Bergenius et al., 2018). Fishing with pots is the main method for small fishing vessels operating close to shore. The pots are usually stringed together with a floater in either end so several pots can be handled with one line, like in Figure 2.3. A string commonly contains 30-80 pots which lay at a depth of 25-120 metres (Bergenius et al., 2018). Mira and Fredrika reported having around 50 pots per string.

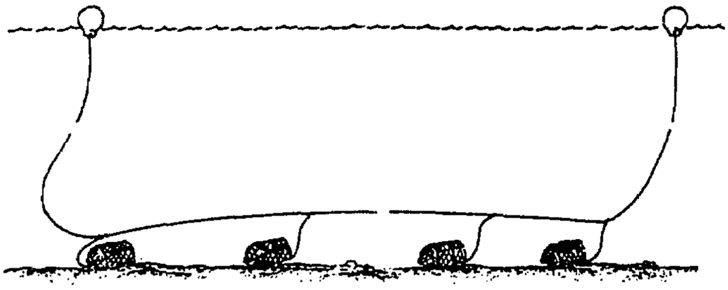


Figure 2.3: Fishing setup with pots on strings, from (Nédélec & Prado, 1990).

Fishing for Norwegian lobster is allowed all year round. With a commercial license the maximum number of cages is 800 for a single person or 1400 cages per boat if several people are involved (HVMFS, 2014:19). Fredrika caught 14.4 tons of Norwegian lobster in 2022 (Svensson, 2023), and 15.9 tons in 2021 (Svensson, 2022). During 2021 a total of 1160 tons of Norwegian lobster was caught in Sweden with a value of 143 million SEK, making it the second most valuable type of catch fished in Sweden (Havs- och vattenmyndigheten, 2022a).

2.1.3 The Swedish fishing fleet

In 2021, Sweden had 818 active registered fishing vessels with an average age of 36.1 years, which has been steadily increasing in recent years (Havs- och vattenmyndigheten, 2022b). The majority of the vessels are using passive equipment, commonly also called static gear, where most are smaller vessels below 10 metres in length; an overview of the Swedish fishing fleet by segment is shown in Table 2.2.

Table 2.2: Number of active fishing vessels and average number of days at sea by segment during 2021 (Havs- och vattenmyndigheten, 2022b).

Segment	Number of vessels	Average number of days at sea
Passive equipment $< 10\,\mathrm{m}$	508	56
Passive equipment $> 10\,\mathrm{m}$	108	58
Active equipment $< 12\,\mathrm{m}$	73	47
Active equipment 12 -$<$ 18 m	64	88
Active equipment 18 -$<$ 24 m	35	119
Active equipment $\geq 24\,\mathrm{m}$	30	128

According to the European Fleet Register (European Commission, 2024c), there are currently 32802 vessels registered with pots and traps or set gillnets as their main fishing activity with 687 of them registered in Sweden. The distribution of the length and engine power of the Swedish vessels can be seen in Figure 2.4. We see that the lengths are mainly in the range between 5 and 12 metres and most have an engine power less than 200 kW.

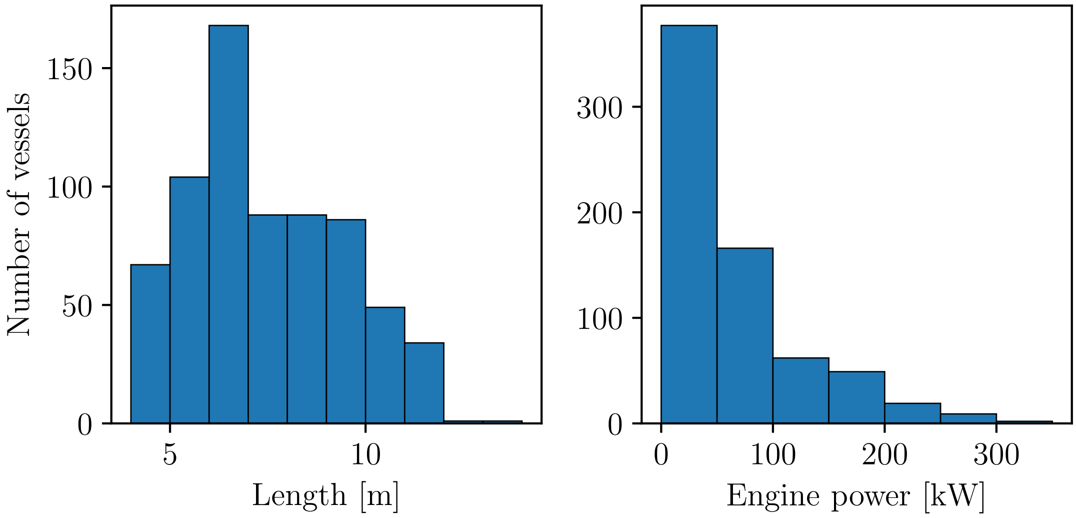


Figure 2.4: Registered length and engine power for Swedish fishing vessels with pots and traps, or set gillnets as their main fishing activity. Retreived from (European Commission, 2024c).

2.1.4 Klimatklivet

Klimatklivet is an initiative to reduce green house gas emissions by providing funding for projects contributing to accelerate the green transition. It is managed by Naturvårdsverket on the order of the Swedish government. Between 2015 and 2023, 20 212 applications had been approved, corresponding to 14.8 billion SEK in grants, which on average reduces the emissions by 2.89 kg carbon dioxide equivalents per granted SEK or 1.20 kg per invested SEK (Naturvårdsverket, 2024b).

Naturvårdsverket (2024a), recently published a statement identifying electrification of ships as a cost effective path towards reduced GHG-emissions. They identify short to medium range shipping as a sector with great potential and would like to see more applications from the sector. However, very few electrification projects have applied and received grants from *Klimatklivet*, see Table 2.3.

Table 2.3: Grants previously given by *Klimatklivet* for electrification of ships.

Title	Grant [SEK]	Share of investment cost [%]
Electrification of the ships Älvsnabben 4 and Älvsnabben 5	3 600 000	40 %
Conversion of M/S kostervåg to electric propulsion	9 000 000	43 %
Electric conversion of tugboat	2 958 000	53 %

The grant works on the principle of prioritizing measures with a long-lasting reduction in emissions of greenhouse gases. Therefore, an accurate estimate of emission reduction is a critical part of the grant application. Another important principle is that it should give grants to projects with a high likelihood of reducing emissions, i.e. the applicant has to demonstrate the financial and organisational capabilities of carrying through the project. All matters regarding *Klimatklivet* is regulated in *Förordning (2015:517) om stöd till lokala klimatinvesteringar* (SFS, 2015:517). For example, main principles, the role of Länsstyrelsen and Naturvårdsverket, and the form of the application. A template for the application is also provided by Länssyrelsen Västra Götaland (2024).

In order to be eligible for *Klimatklivet*, six different criteria need to be fulfilled (Länsstyrelsen Västra Götaland, 2022). The two most important criteria to consider for fishing vessels are that the investment has to provide an adequate reduction of greenhouse gasses, where the current target minimum is 0.75 kg/SEK, and that the project should not be profitable, which is characterized by a payback time of less than 5 years without the grant. Länsstyrelsen Västra Götaland (2022) also states that the maximum level of support is 70 % of the total investment.

2.2 Literature review

In this section the literature most relevant to the thesis is reviewed. It is separated into two parts: methods for estimating energy consumption studies and literature related to electrification of fishing vessels.

2.2.1 Methods for estimating energy consumption

There are many empirical methods for estimating vessel resistance, with the most commonly used ones being, Savitsky (1964), Holtrop (1984), and Hollenbach (1998). However, these are all out of scope for small fishing vessels since they are made for larger vessels in the commercial fleet. Resistance models for fishing boats were proposed by van Oortmerssen (1971) and Diegernes (Kleppestø, 2015). However, these methods require a large number of input parameters that are usually unavailable for the common fisherman. The exception is Diegernes, but since it approximates resistance and not power it relies on other methods for propulsive power, axuillary loads, and fuel consumption.

Small fishing vessels usually only have one main engine supplying the power for propulsion, hydraulic systems, dc-systems, and ac-systems which all contributes to the fuel consumption of the vessel. Understanding how these systems impact energy consumption onboard is crucial when dimensioning a new power and energy storage system. Several efforts have been made to develop energy analysis programmes for fishing vessels (Calisal et al., 1989), (Kemp, 2018).

Kemp (2018) developed The Vessel Energy Analysis Tool (VEAT) as a part of the Fishing Vessel Energy Efficiency Project (FVEEP) using data from 30 Alaskan fishing vessels. The model is applicable to non-plaining fishing vessels between 9 and 30 m in length. The VEAT model is structured as a set of different modules (Kemp, 2018). There are 5 modules for the different loads from propulsion, refrigeration, hydraulics, AC electric, and DC electric, which output the shaft power for each load, which is then input to the engine module to calculate fuel consumption. The VEAT model is presented in more detail in Appendix B. The mathematical and physical models making up the different modules are generally simpler than those in published articles aimed at the international merchant fleet. According to Kemp (2018) this is by design, as there is typically very little information about the hull and structure for fishing boats and Kemp found that the model captures the dominant trends and variability present in the Alaskan fishing fleet.

2.2.2 Electrification of fishing vessels

Lately, the interest in energy efficiency measures and electrification of fishing vessels has increased. Several studies have tried to determine the technical, environmental, and economical feasibility.

Johnson et al. (2022) conducted interviews with fishermen carrying out small-scale fishing in the United Kingdom to understand the potential and challenges with electrifying the fishing fleet with pure electric or hybrid solutions. They identify the main limiting factor for pure electric solutions to be the weight and cost of batteries, which makes pure electric only suitable for vessels doing short trips. They also identified some regulatory issues regarding battery safety since the electric fleet is still very small. This makes the validation of compliance more difficult and a risk-based approach is recommended by the Maritime and Coastguard Agency (MCA).

Kemp and Atshan (2021) investigated the equipment costs for pure electric and hybrid systems and associated fuel savings for fishing vessels with a focus on the fleet in southeast Alaska. They estimated the fuel savings to be 0.26-0.64 litres per kWh of energy storage per trip. However, just like Johnson et al. (2022), Kemp and Atshan also identify the need for short transit distances in order for a pure electric system to be feasible mainly due to weight and volume requirements for the battery system.

To assess the potential environmental benefit of a hybrid propulsion system, Kim et al. (2022) created a battery hybrid system model which was applied to three case study vessels in the Korean fishing fleet in order to determine potential emission reductions from a life cycle perspective. The analysis was done using operational data from sensors onboard the ships which allows for a more accurate life cycle assessment (LCA) compared to the conventional strategy of using the maximum output of the ship according to Kim et al. (2022). They found an average reduction of GHG emissions of 7.6 % but that it is tightly coupled with the electricity mix of the region in question.

Several studies have been carried out to analyze the impacts on the environment by using different propulsion systems for passenger ferries as well as to assess the investment costs pertaining to use of such propulsion systems (Goel & Wadelius, 2021; Perčić, Frković, et al., 2022; Perčić, Vladimir, et al., 2022; Wang et al., 2021).

Perčić, Vladimir, et al. (2022) investigated the economic and environmental impacts of swtiching to electric propulsion onbaord all ROPAX (roll on/roll off passenger) vessels operating in the Adriatic Sea in Croatia by analysing their operational data. The study concluded that the NO_X emissions is reduced by 98 % for the an electric ship compared to a diesel-powered ship. Further, he cost analysis pointed out that electric propulsion is the most cost-effective propulsion system making it a stronger case for considering electrification of ships.

Further studies by Perčić, Frković, et al. (2022) investigates different battery technologies that can be used on an all-electric ferry and concluded that lithium ion batteries are not only the most environmentally friendly option, but a cost-effective option as well.

Wang et al. (2021) evaluated the environmental and economic impacts of converting a high-speed inland catamaran passenger ferry operating on the Thames River in London, UK from a fuel-based power system to battery power system throughout the entire life cycle. They found that the battery-driven propulsion system resulted in a 30 % reduction in greenhouse gas emissions and a 15 % reduction in the life cycle costs.

Goel and Wadelius (2021) conducted a comparative LCA and LCCA study on commuter ferries in Stockholm, Sweden. The study considered eight different scenarios divided into two categories: four scenarios under the fuel-based propulsion system and four scenarios under the battery-based propulsion systems. Their finding revealed a 98 % reduction of greenhouse gas emissions when transitioning to battery-driven electric propulsion system. Additionally, they highlighted the significant impact of a country's electricity mix on greenhouse gas emissions. The study also provided valuable values for estimating costs for the installation of charging stations and costs for retrofitting ferries.

Studies have been carried out to examine the environmental impacts as well as cost investment studies of electrification of the fishing vessels Koričan et al. (2022), Perčić et al. (2023), and Siemens et al. (2017).

Siemens et al. (2017) focused on Norwegian fishing vessels between 9 and 15 metres in length, which is approximately 3000 vessels out of the 5000 in the total Norwegian fishing fleet, and how they can be electrified. They approximate that by electrifying, GHG emissions can be reduced by 50 % for the entire fleet, which would reduce emissions by 420 000 ton CO_2 per year. Their study also identified that the current government subsidies for fuel-based propulsion systems hinder electrification and proposed that these subsidies should be removed and replaced with grants for new technology.

Koričan et al. (2022) carried out a study on the various propulsion systems that could be used in a fishing trawler operating in the Adriatic sea in Croatia. The study suggests that although electrification is environmentally feasible than alternative fuel options, it requires nearly 20 times higher investment costs, making it an economically unviable option for trawler fishing vessels.

Perčić et al. (2023) investigated the economic and environmental benefits of the converting a trawler and purse seiner fishing vessel to battery electric propulsion over a 20-year lifetime. They found that the use of lithium iron phosphate (LFP) results in 40 % reduction in total greenhouse gas emissions compared to fishing vessel using an internal combustion (IC) engine.

2.3 Legal review

Shipping is an industry that is highly dependent on the regulations provided by different national and international instances to ensure safe and reliable operations. When designing new ships or making changes to existing ones, it is therefore crucial to have a good understanding of the applicable regulations to ensure a smooth path towards compliance. This section serves as a brief introduction to the applicable regulations from the perspective of Swedish fishing vessels.

The main regulatory body of the shipping sector is the International Maritime Organization (IMO), which is a specialized agency within the United Nations initially responsible for maritime safety, but later also pollution at sea (Colin de la et al., 2022). However, since small fishing vessels typically do not make international voyages and all relevant regulations are implemented in Swedish law, the IMO rules are not considered further.

Sjölagen (SFS, 1994:1009) and *Fartygssäkerhetslagen* (SFS, 2003:364) constitute the backbone of Swedish maritime law. *Sjölagen* sets the main definitions and regulates liability at sea, while *Fartygssäkerhetslagen* regulates different ship types, certification, and work environment. *Fartygssäkerhetslagen* also gives Transportstyrelsen (The Swedish Transport Agency) the mandate to manage certificates and perform inspections of vessels.

For ships operating within Swedish waters only, Transportstyrelsen have issued a set of rules that all vessels above 5 metres must comply with *Transportstyrelsens föreskrifter och allmänna råd om fartyg i nationell sjöfart* (TSFS, 2017:26). These regulations represent a shift away from prescriptive rules towards functional, technology independent rules. It is structured in 14 chapters where the first two set the framework, and the rest regulate different areas like construction and stability, fire safety, work environment, navigation, etc.

There has been recent developments in the regulations regarding battery energy storage systems (BESS) onboard ships. Most notably, the European Maritime Safety Agency recently released a set of guidelines for safety of BESS on board ships (EMSA, 2023). They were developed as a collective effort by stakeholders and experts in the marine and battery sectors, notably Transportstyrelsen and several classification societies. However, since they were published recently they have not been fully incorporated by Transportstyrelsen. They are intended to replace Transportstyrelsens guidelines for electrification of ships (Transportstyrelsen, 2023), which are currently in use and further explored in subsection 4.1.1.

2.4 Technology review

In this section, we provide a brief overview of the various components that need to be considered for an electric propulsion system including batteries and motors. Additionally, we briefly discuss the different charging technologies available.

2.4.1 Batteries

For a battery-driven electric propulsion system, the battery plays a fundamental role of an energy storage system (ESS) where chemical energy is stored that is later converted to electrical energy to drive the motor for propulsion. Battery technology has been employed on board vessels for various applications on a smaller scale such as emergency energy storage systems, powering small electronics (Andersson et al., 2017). However, in recent times, they have gained significant attention for electric propulsion applications.

Some important terminology used related to batteries in a battery-driven propulsion systems are (ReCell Center, 2024):

1. **Cell** is the fundamental unit that stores and releases electrical energy through electrochemical reactions.
2. **Battery** is a collection of cells that are connected in a specific configuration to provide the required voltage and capacity.

3. **Battery pack** is a collection of batteries arranged in a specific configuration along with a supporting electronic systems, including the battery management system (BMS), electric buses, cooling fans, and other safety systems.
4. **Battery Management System (BMS)** is an electronic system that helps monitor the various parameters of the individual cells such as temperature, voltage, state of charge, duty cycles and keeps them within the operating conditions in a battery pack.
5. **Battery capacity** is the amount of energy a battery can deliver in a single discharge and is quantified in ampere-hours (Ah).
6. **Gravimetric or specific energy density** is the amount of energy the battery can contain per unit weight. It is expressed in watt-hour per kilogram (Wh/kg).
7. **State of Charge (SOC)** is the amount of capacity available in the battery. The SOC of a battery is said to be 100 % when the battery is fully charged and 0 % when it is completely empty.
8. **Depth of Discharge (DOD)** is the opposite of SOC. It is the total battery energy capacity that has been removed. It is also measured as a percentage.
9. **Cycle life** is the number of charging and discharging cycles a battery can undergo before its capacity deteriorates.

While there are several kinds of batteries available based on the chemistry they operate on, we limit our discussion to only lithium-ion batteries (LIBs).

An LIB fundamentally consists of four parts: cathode, anode, separator, and the electrolyte. During discharging, the lithium ions (Li^+) travel from the anode towards the cathode through the electrolyte. In most LIBs, the electrolyte is made of lithium salt solutions. During charging, a potential difference is applied across the cathode and anode and the movement of lithium ions reverses. Thus, moving from cathode to anode. The separator in a LIB, as the name suggests, prevents the anode to get in direct contact with the cathode to avoid short circuiting. In majority of the cases, the anode is made of graphite coated on a copper foil. The cathode can be made of a combination of different elements and is coated on an aluminium backing. Therefore, LIB can be categorised based on the material used for the cathode. The most commonly used LIB for propulsion are as shown in Table 2.4:

Table 2.4: Different lithium ion battery chemistry used for electric propulsion (Perčić et al., 2023).

Chemistry	Cycle life [cycles]	Energy density [Wh/kg]
Lithium Titanate Oxide (LTO)	20 000	80
Lithium Cobalt Oxide (LCO)	500	180
Lithium Nickel Mangenese Cobalt (NMC) oxide	1 000	280
Lithium Iron Phosphate (LFP)	3 500	185
Lithium Nickel Cobalt Aluminum (NCA) oxide	1 000	280

2.4.2 Electric motors

An electric motor in the battery-driven propulsion system converts the electrical energy supplied by the battery to mechanical energy for propulsion. Motors are gaining popularity for marine propulsion mainly due to their high efficiency and low maintenance (Wärtsilä, 2024). There are different kinds of motors available in the market and are distinguished based on their working mechanism. Figure 2.5 shows the broad classification of electric motors that are used for electric propulsion.

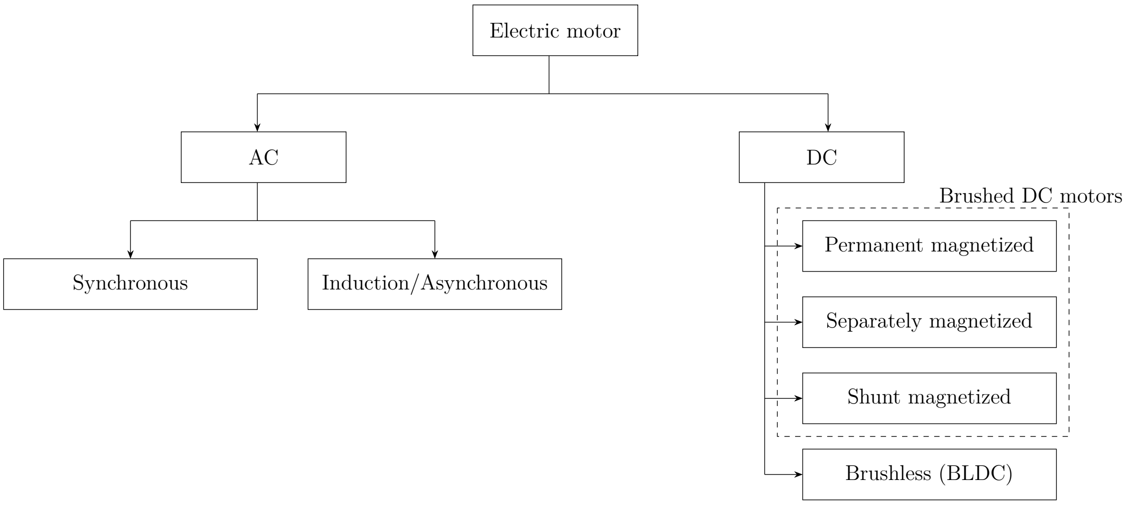


Figure 2.5: Classification of electric motors

2.4.3 Charging

In order to replenish the energy stored in the batteries, the process of charging is carried out where electrical energy, from a power source, is converted to chemical energy and is stored for later use. Charging can be done mainly in two ways:

1. **AC charging:** This works by stepping down the voltage of the local grid using a step down transformer. This stepped down voltage is fed to the onboard charger which is essentially a AC-DC converter converting the AC voltage to DC voltage. Due to the limited space on board vessels, on-board chargers are limited by their capacity. Therefore, the voltage is converted at a slower rate. Hence, AC charging is used mainly overnight when the vessel is at port for long hours. Table 2.5 shows the different AC charging sockets available in the market and the rate they can charge a battery over 14 hours. AC charging is also cost effective as the infrastructure costs are not very high.

Table 2.5: Electrical properties and maximum 14 hour charge for different common electrical connections.

Socket	Current [A]	Voltage [V]	Power [kW]	14 h charge [kWh]
1-ph household	10	230	2.3	32.2
3-ph household	16	400	11.09	155.2
3-ph industrial	32	400	22.17	310.4

2. **DC charging:** The main difference between AC charging and DC charging is that the conversion of the AC voltage to DC voltage takes place onshore rather than onboard. Thus, the charger has no size restrictions making the conversion of AC voltage to DC voltage faster. Therefore, DC charging is interchangeably called fast charging. DC charging is used when the turn around time for a vessel is very short such as inland passenger ferries. For our case vessels, DC charging is not required as they spend over 12 hours at the port. DC chargers are more expensive than AC chargers due to the infrastructure cost to set them up.

3

Methodology

In this chapter, we present the general methodology of the thesis as well as an overview of the different methods used during operational, regulatory, environmental, and economic analysis. We would like to stress that what is presented in this chapter is not the resulting method proposed for evaluating electrification of small fishing vessels. Instead, it is the tools and methodologies used throughout the thesis work to develop the method.

The methodologies used throughout the thesis can be separated into 4 main stages and a final summation stage, which is illustrated in Figure 3.1. First, the review stage where the relevant literature, regulations, and technologies were investigated. The second stage, the case studies, where the current operation as well as potential future operational scenarios were analysed. The third and fourth stage consisted of the system design and evaluation of key environmental and economic indicators. Lastly, the summation stage in which the work was summarized was the final method to determine the feasibility of electrifying small fishing vessels. The four main stages are explained in more detail in the sections below.

3.1 Review stage

The review stage was split into three main areas: literature, regulations, and technologies. The purpose of the literature review was to compile the learning outcomes and the efforts already put into electrification of fishing vessels to build the method. Therefore, the literature review also looked into methods for estimating energy consumption and Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) methodologies. It was conducted by studying published articles and reports. Both general and more technical articles were reviewed to build a broad understanding of the field. The regulatory review consisted of going through the relevant Swedish law documents, as well as the regulations and guidelines issued by Transportstyrelsen. The purpose of the technical review was to research what performance could be expected from a commercially available electric driveline. However, the purpose was also to see what the expected performance looks like in a few years.

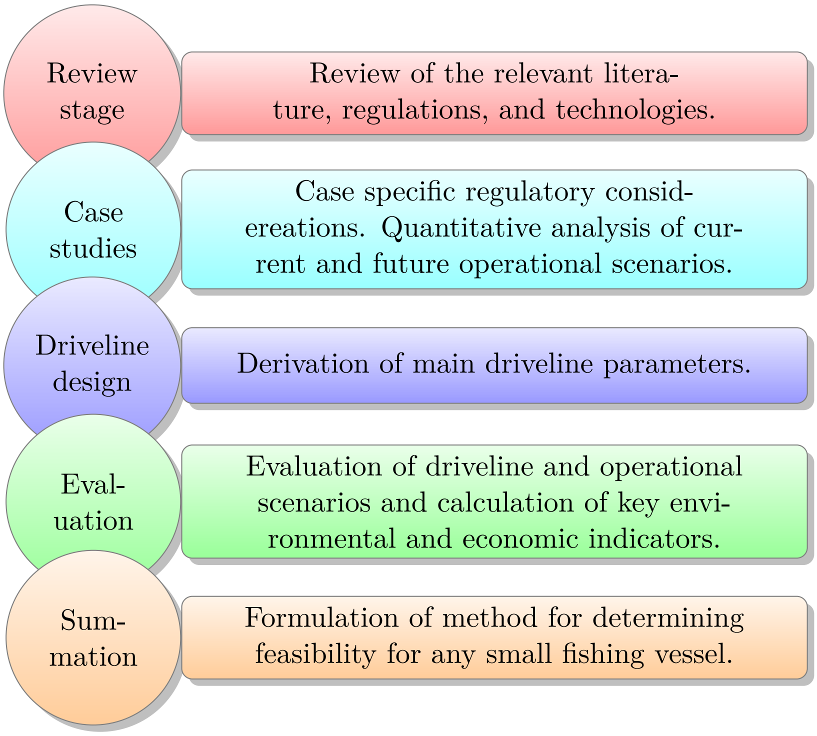


Figure 3.1: Schematic overview of the methodology used in the thesis.

3.2 Case studies

After the review stage, work began with an analysis of the two vessels. The objective of the case studies were to identify and model the main characteristics of the current operation and identify challenges with electrification. This entailed finding possible regulatory challenges and calculating the main performance parameters required from an electric driveline by a quantitative analysis of position, speed, and fuel consumption data. Furthermore, different operational patterns were investigated to illustrate the opportunities and limitations with electrification.

The first part of the case studies was to determine the regulatory challenges involved with electrification. The knowledge obtained from the review stage was used and all possible challenges were compiled.

The second part of the case studies was the operational analysis, which was split into three stages. First, an analysis of current operation, looking at main parameters such as time, distance, and fuel consumption on a daily basis. The purpose was to identify key trends in the operation and build an intuition in order to later be able to propose measures to increase efficiency. The second stage was to model the energy consumption onboard the vessels, which was used in the last stage where possible operational scenarios using electric propulsion were investigated.

3.3 Driveline design

In the third stage of the methodology, the driveline design was developed for the vessels. The current driveline was first analysed by conducting weight analysis based on technical data sheets of for the different components and information gathered from our visit to the vessels. A conceptual sketch was created to approximate the positions of the different components of the driveline, allowing an understanding of the available volume to design the electric driveline.

The information such as total consumption and peak power from the operational analysis was used to size the batteries and motor for the electric driveline. A rough weight estimation was carried out based on information gathered from different technology suppliers and system integrators.

3.4 Evaluation

The fourth stage of the methodology involved conducting an environmental and economic evaluation of both drivelines. To assess and compare which driveline has a lower impact on the environment, a life cycle analysis study was performed. Further, an economic evaluation was also done, as a propulsion system should not only be technically feasible, but also be economically viable. The economic analysis was performed in line with what is used by *Klimatklivet*.

3.5 Summation

Lastly, the analysis was summarized into the method for determining feasibility of electrifying small fishing vessels. The focus was put on capturing the main parameters so that the general feasibility could be evaluated by any owner of a fishing vessel. The method was implemented as an excel document which help the user perform the calculations according to the method. Examples were also created for the two vessels of the case study to showcase the use and interpretation of the excel implementation.

4

Analysis

In this chapter, we present the steps taken and the findings during analysis of the case studies, driveline design, and evaluation stages.

4.1 Case studies

This section presents steps taken and findings of the case studies of Mira and Fredrika, which includes the regulatory aspects specific to each vessel and the operational analysis of current and possible future operational patterns.

4.1.1 Regulatory challenges

In this section, the regulatory landscape is analyzed with a focus on electrifying Mira and Fredrika in order to identify regulatory hurdles that would have to be overcome. As mentioned in the legal review, all commercial vessels must comply with *Transportstyrelsens föreskrifter och allmänna råd om fartyg i natonell sjöfart* (TSFS, 2017:26). The functional rules were designed to be technology independent, allowing for more innovative solutions while not compromising on safety. However, that increases the workload on the entity trying to prove compliance, especially when there is a lack of documentation and new unproven technologies are involved, as is the case when electrifying fishing vessels.

Today, both vessels are compliant, but how they are controlled differ. The reason why can be found in *Fartygssäkerhetslagen* (SFS, 2003:364) 3 c. 1 §, which says that a Swedish vessel that is at least 15 metres long or is a passenger vessel needs to be certified. So, Mira is certified as a passenger vessel since she takes 30 passengers while Fredrika has no certificate as she is less than 15 metres long. In order to get the certificate the vessel has to have been surveyed, which is the case for Mira. Furthermore, both vessels are checked by the owner themselves and then reported to Transportstyrelsen every year, known as *egenkontroll*.

The process towards electrification would also differ between the two vessels. Since Mira has a certificate, any major changes intended to be made to the vessel has to be reported to Transportstyrelsen before the change is made. Then, Transportstyrelsen decides if they deem it necessary for them to be more involved in the conversion project, which includes deciding what documentation is necessary, assessing the risk analysis, and scheduling inspections and surveys (Transportstyrelsen, 2022). The involvement of Transportstyrelsen would also come with additional costs, see Table 4.1. For Fredrika, no report has to be made before the conversion. Instead, the change will be reflected in the next *egenkontroll* sent in to Transportstyrelsen. However, Transportstyrelsen performs risk based inspections of any vessel, that is they do inspections of vessels where they identify an increased risk. The electrification of a fishing vessel would almost certainly peak the interest of the public and Transportstyrelsen, and be likely to result in an inspection of the vessel.

Table 4.1: Costs associated with electrifying fishing vessels who needs to be inspected by Transportstyrelsen. Retrieved from (TSFS, 2016:105).

Description	Cost [SEK]
Base fee for changing details of certificate	20 000
Hourly rate	1 700

Regarding the specifics of electrifying a vessel, there are a few different paths available. TSFS (2017:26) allow for three different methods to prove compliance, which are design and verification using an established set of rules or standard, comparative and risk analyses, or empirical data. It also states that parts of the regulations that have already been approved by Transportstyrelsen or another authority, does not need to be verified again using one of the methods above. A review of TSFS (2017:26) and what should be considered when verifying compliance for an electrification project for a fishing vessel can be found in Appendix C, and a summary of the chapters which need verification can be seen in Table 4.2.

Table 4.2: The chapters of (TSFS, 2017:26) that change with an electrification of the vessel and how the verification can be done. A more complete description can be found in Appendix C.

Chapter	Verification method
3 Construction and stability	Using regulatory framwork, for example *Nordisk Båtstandard* (Nordisk teknisk arbeidsgruppe, 1990) or Eurofins - Work Boat Guidelines (Eurofins, 2021).
4 Machinery, propulsion, and manoeuvring	Risk analysis.
5 Electrical equipment and installations	*Transportstyrelsens riktlinjer för elektrifiering av fartyg* (Transportstyrelsen, 2023) combined with simple risk analysis.
6 Fire safety	*Transportstyrelsens riktlinjer för elektrifiering av fartyg* (Transportstyrelsen, 2023) combined with simple risk analysis.

From Table 4.2 we see that chapters 3-6 need extra care where the main effort would be on compliance of chapter 5 and 6. Our understanding is that the most likely way to go about it would be to follow Transportstyrelsens guidelines for electrification of ships (Transportstyrelsen, 2023) and use a simplified risk analysis. However, it is strongly advised to contact Transportstyrelsen regarding a specific project to get their point of view before initiating the project plan.

4.1.2 Current operation

This section presents how the vessels are currently operated, the time spent, distance travelled, and fuel consumed in different operational modes are investigated. Throughout the analysis the terminology representative day will be used. It means a day chosen that best matches the operation for the specific vessel.

The data availability differs for the two vessels. For Fredrika, AIS data, i.e. position and speed, was collected together with real-time fuel consumption data. The data is publicly available from the PONTOS datahub. For Mira, only AIS data is publicly available from the datahub and fuel consumption data was instead gathered from the logbook onboard afterwards.

Before the analysis can start, the data must be structured. The data gathered from the datahub is not grouped together with a common timestamp. Instead, all the data points have their individual timestamp, so the first step in structuring the data is to synchronize the different variables with a common time vector. All the sensors report at 1-2 hz; therefore, a time vector of 1 hz is chosen, and the variables are synchronized by taking the most recent point of measurement by each sensor.

The main parameters obtained for the current operation are time, distance, and fuel consumption by different operational modes. The operation is split into three modes: transit to the fishing grounds, fishing, and transit back to port. The change from transit to fishing is identified by checking when the speed or fuel consumption reduces significantly after having been above a set threshold, indicating that the vessel has slowed down for the first string of pots. The change from fishing to transit pack to port is handled the same way but with the time series in reverse. The distance and total fuel consumption are then calculated by numerically integrating the speed and fuel consumption respectively.

Fredrika

The data collected from Fredrika span from the 9th of October to the 6th of December 2023. She was out fishing on 23 days of which the first four fishing days only have the consumption data available, but for the remaining 19 all data is available, that is position, speed, and fuel consumption. Any figure in this section showing data from a single day shows the same representative day which is chosen to be the 11th of November 2023.

The speed profile for the representative day is shown in Figure 4.1, with the different operational modes highlighted. Furthermore, the 12 strings of pots handled during the day are marked with numbers. We see that the operational speed in transit and when relocating between the different strings of pots is 9 knots, and that the speed while handling pots is around 0.7 knots. The same operational speeds are observed throughout the entire data set. The positional data corresponding to the speed profile above is shown in Figure 4.2, where we also see that the fishing is quite concentrated around 7 nm out.

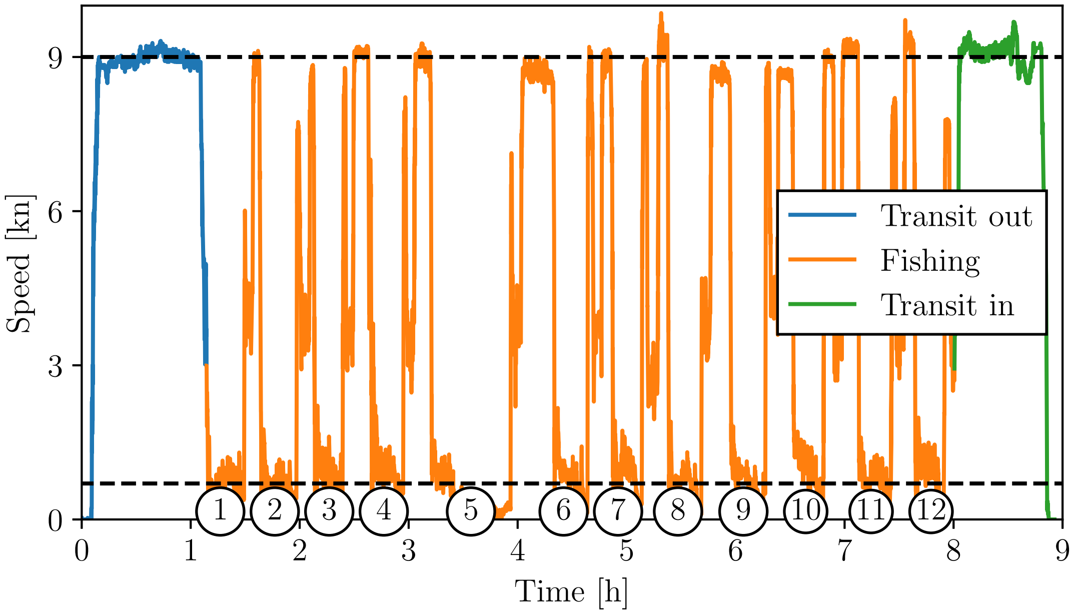


Figure 4.1: Speed profile of Fredrika on the representative day fishing. The different operational modes are highlighted in different colors and the 12 strings of pots handled are shown with numbers. The dashed lines show the transit speed and speed when picking up pots at 9 and 0.7 knots respectively.

Figure 4.2: Positional data of Fredrika on the same representative day as the speed profile above in Figure 4.1. The operational modes are highlighted in color and the strings of pots are shown with black circles.

In Table 4.3 the average time, distance, and fuel consumption by operational mode is presented. We note that a clear majority of the time, around 72 %, is spent fishing but the fuel consumption is closer to 48 %. We also note that on an average day of fishing, Fredrika is out for just below 8 hours and consumes 90 litres of fuel while handling 10.3 strings of pots.

Table 4.3: Average time, distance, and fuel consumption by operational mode of Fredrika for the 19 days out fishing with all data available.

Variable	Steaming out	Fishing	Steaming in	Total
Time [h]	1.0 (13.1 %)	5.7 (72.1 %)	1.2 (14.8 %)	7.9 (100 %)
Distance [nm]	8.0 (23.5 %)	18.6 (54.8 %)	7.4 (21.7 %)	34.0 (100 %)
Consumption [l]	23.6 (26.1 %)	43.2 (47.9 %)	23.4 (25.9 %)	90.2 (100 %)

The most common number of strings handled in a day was 12, and the most recorded was 13 which happened twice. In order to find the design point, we chose to look more closely at the days with a higher number of pots handled. In Table 4.4, the average time, distance, and fuel consumption by operational mode is shown for the days with 12 or 13 strings handled.

Table 4.4: Average time and fuel consumption by operational mode of Fredrika for the 10 days with 12 or more strings of pots.

Variable	Steaming out	Fishing	Steaming in	Total
Time [h]	1.0 (11.5 %)	6.8 (77.6 %)	1.0 (10.9 %)	8.8 (100 %)
Distance [nm]	7.7 (20.6 %)	22.6 (60.1 %)	7.2 (19.3 %)	37.5 (100 %)
Consumption [l]	22.7 (23.1 %)	53.1 (53.9 %)	22.7 (23.0 %)	98.5 (100 %)

Compared to the average of all days we note that the time and fuel consumption in transit remains roughly the same but it increases for the fishing mode. This is expected as the distance to the fishing grounds remain the same. We note that these longer fishing days typically last 8 hours and 45 minutes, and use 98.5 litres of fuel.

Mira

The data collected from Mira span from the 5th of March to the 11th of May 2024. She was out sailing 34 days of which 19 were for fishing. The data includes speed and positional data for all the days. As mentioned previously there is no real-time fuel consumption data available, but refueling amounts were collected from the logbook. The representative day chosen for Mira is the 22nd of April 2024.

Figure 4.3 shows the speed profile of the representative day for Mira where we see that, just like Fredrika, Mira picks up pots at around 0.7 kn, but a lower speed of 7 kn is used in transit and between pots. We also see that Mira stops at different points on the way back to port. The map corresponding to the speed profile is shown in Figure 4.4. There we see that the transit out is quite short and most strings are grouped together quite close to each other allowing for distance traveled in fishing mode to be short while the transit back is long and includes some stops close to port increasing the time spent in that mode.

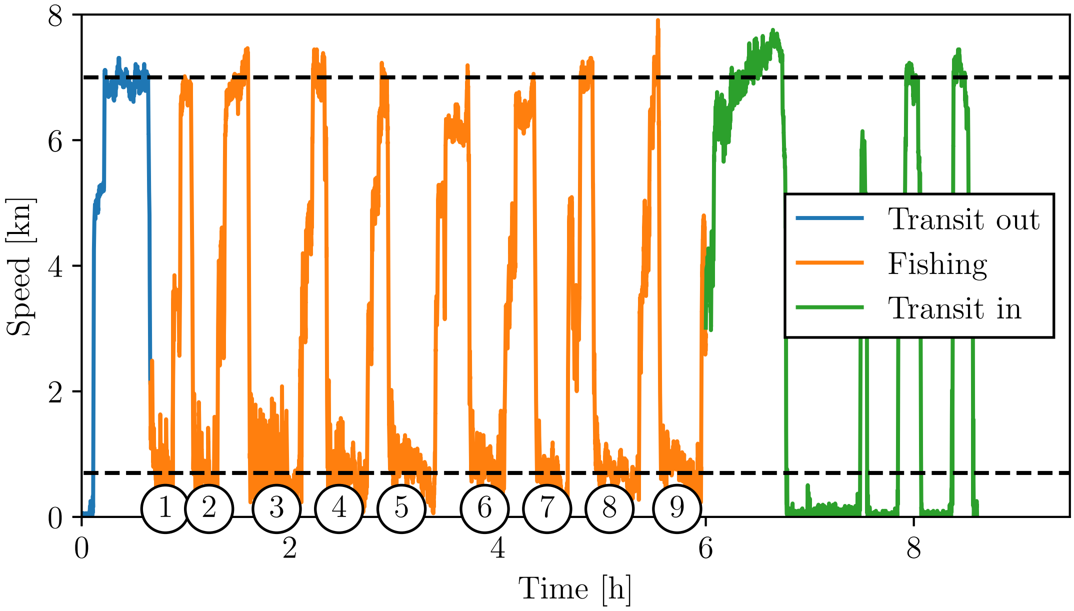


Figure 4.3: Speed profile of Mira on the representative day fishing. The different operational modes are highlighted in different colors and the 9 strings of pots handled are shown with numbers. The dashed lines show the transit speed and speed when picking up pots at 7 and 0.7 knots respectively.

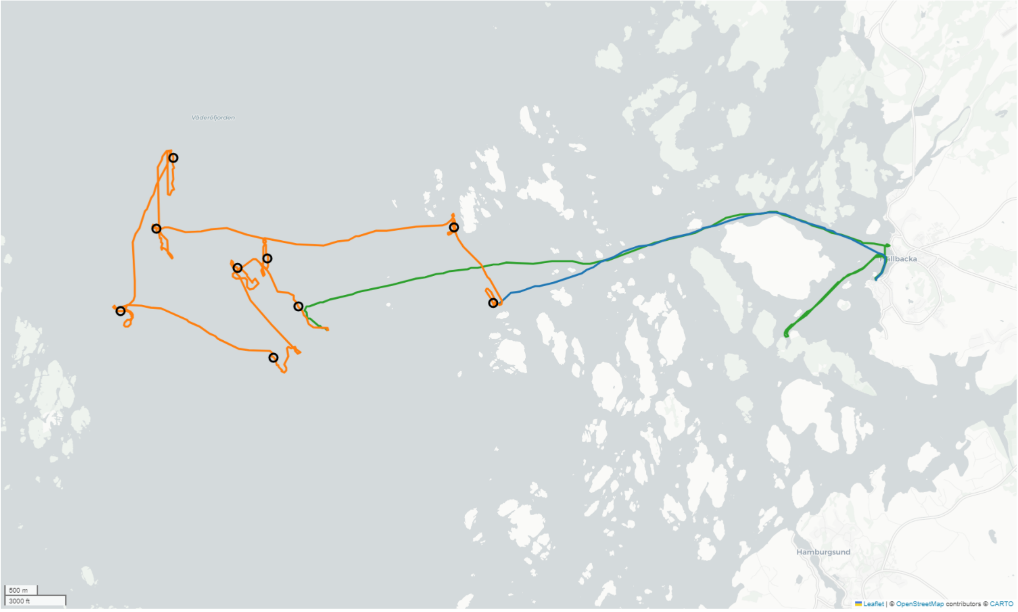


Figure 4.4: Positional data of Mira on the same day as the speed profile above in Figure 4.3. The operational modes are highlighted in color and the strings of pots are shown with black circles.

Mira averages 7 strings of pots per day which takes 7.1 hours and covers 21.3 nm. How that is split over the different operational modes is shown in Table 4.5.

Table 4.5: Average time and distance by operational mode of Mira for the 19 days out fishing.

Variable	Steaming out	Fishing	Steaming in	Total
Time [h]	0.9 (13.3 %)	4.2 (59.2 %)	1.9 (27.5 %)	7.1 (100 %)
Distance [nm]	5.4 (25.4 %)	9.6 (45.1 %)	6.3 (29.6 %)	21.3 (100 %)

From the logbook it was recorded that Mira refueled 449 litres of fuel on May 11th and was out sailing on 23 days since the last refill, which gives an average fuel consumption of 19.5 litres per day.

4.1.3 Modeling energy consumption

An implementation of the Vessel Energy Analysis Tool (VEAT) developed by Kemp (2018) is used to model the energy consumption onboard the vessels, the details of which can be found in Appendix B. Modeling energy consumption is necessary in order to predict how altering the operation and propulsion system impacts the energy consumption. Three out of the five different load types modeled by the VEAT are used: propulsion, hydraulics, and DC-electric, as well as the engine model, see section B.1, B.3, B.5, and B.6. The other two, refrigeration and AC-electric are not in use for Fredrika and Mira. Throughout the analysis the default values presented by Kemp (2018) are used. First we look at the data collected from Fredrika and then Mira.

Fredrika

Before looking at the speed and consumption data for Fredrika, we have to acknowledge that the data is inherently skewed, which is shown in Figure 4.5. We see that a clear majority of the data points are collected between 0-2 and 8-10 knots which is expected as these regions represent the fishing and transit operational speeds respectively. The speeds in between only occur when changing between the two modes, which is coherent with what we saw in Figure 4.1. Note that the first bar starts at 0.1 knots to remove all the points laying still in port, which would otherwise make up a majority of the dataset.

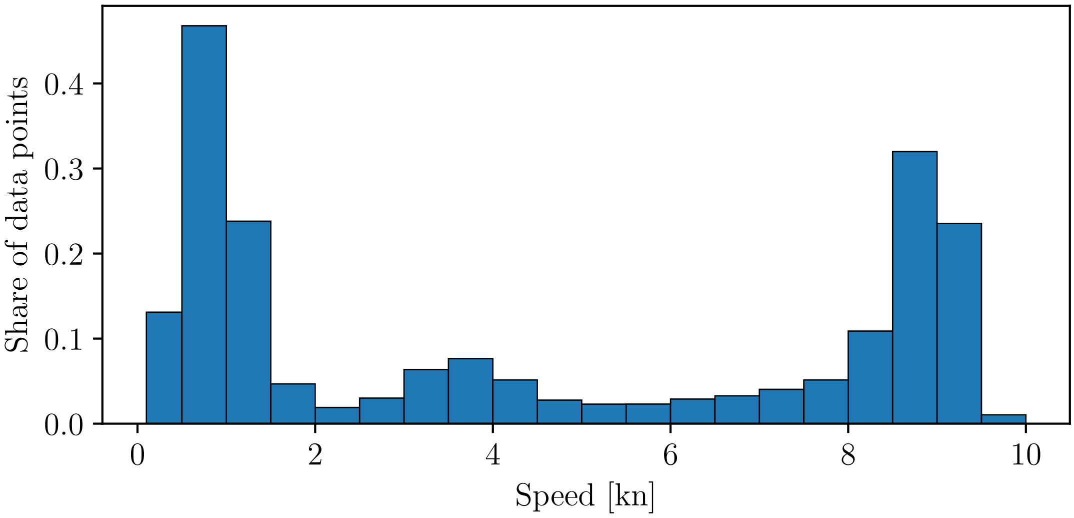


Figure 4.5: Share of data points collected in each speed range for Fredrika.

In order to evaluate the model it is compared with the data collected from Fredrika. First, the real-time fuel consumption is plotted against the speed and compared with the propulsion model combined with the engine model. The models do not consider acceleration so the the data points with high acceleration are filtered out. The points are filtered out by removing points where the difference to the next point is greater than 0.001 kn/s after taking a 60 second moving average. Then, the model is compared to the data and fitted by a constant using least squares.

In Figure 4.6, the Kemp (2018) propulsion and engine model combined is shown together with all the collected data as well as the data points with low acceleration. We see that the model fits the low acceleration data quite well, especially at the main operating points at 1-3 and 8-9 knots.

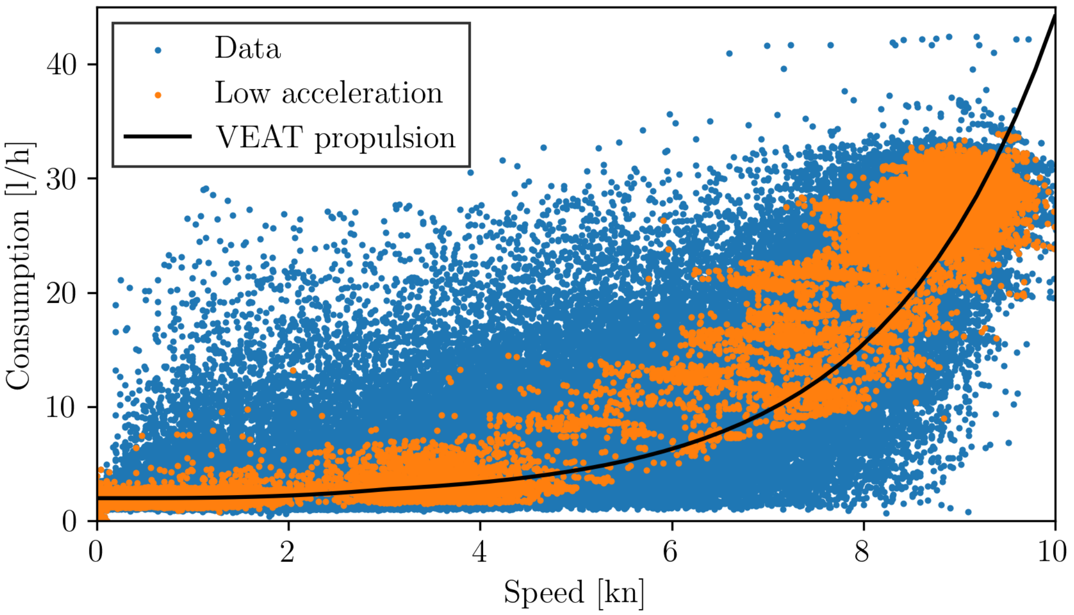


Figure 4.6: Fuel consumption as a function of speed for Fredrika together with the Kemp propulsion and engine model. All data available is shown in blue while the points with low acceleration are shown in orange.

Figure 4.7 shows the fuel consumption data transformed to delivered power using the Kemp (2018) engine model. It also shows the standard and fitted propulsion models. The fitted model predicts 11.1 % higher power compared to the standard model. The root mean squared error (RMSE) also reduces from 15.0 % to 12.7 % at transit speed, i.e. above 8.5 knots. Considering the 28 % RMSE reported by Kemp (2018) for vessels without stabilizers and tanked holds, we are in the expected range.

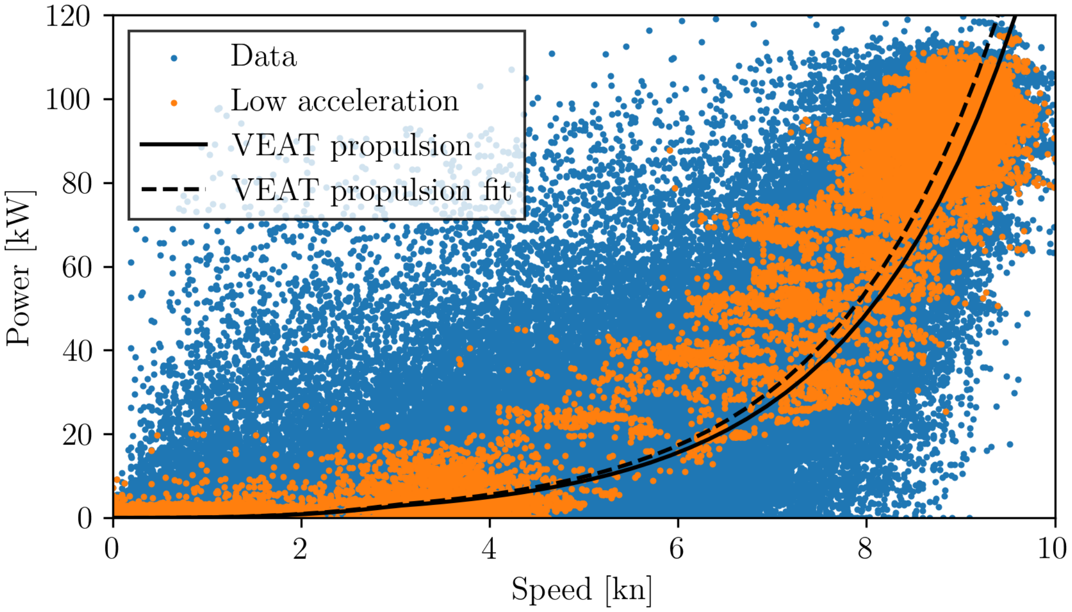


Figure 4.7: Power as a function of speed for Fredrika together with the Kemp propulsion model, both standard and fitted by a constant. All data available is shown in blue while the points with low acceleration are shown in orange.

The spread of the data with low acceleration is shown in Figure 4.8. We see that the spread increases with speed as expected until 8 knots but then reduces again. We believe this to be the caused by how the vessel is operated; the power is usually controlled rather than speed. The throttle is set to a predetermined rpm where the engine operates well and the speed varies depending on the sea state and wind resulting in less spread in the upper speed range.

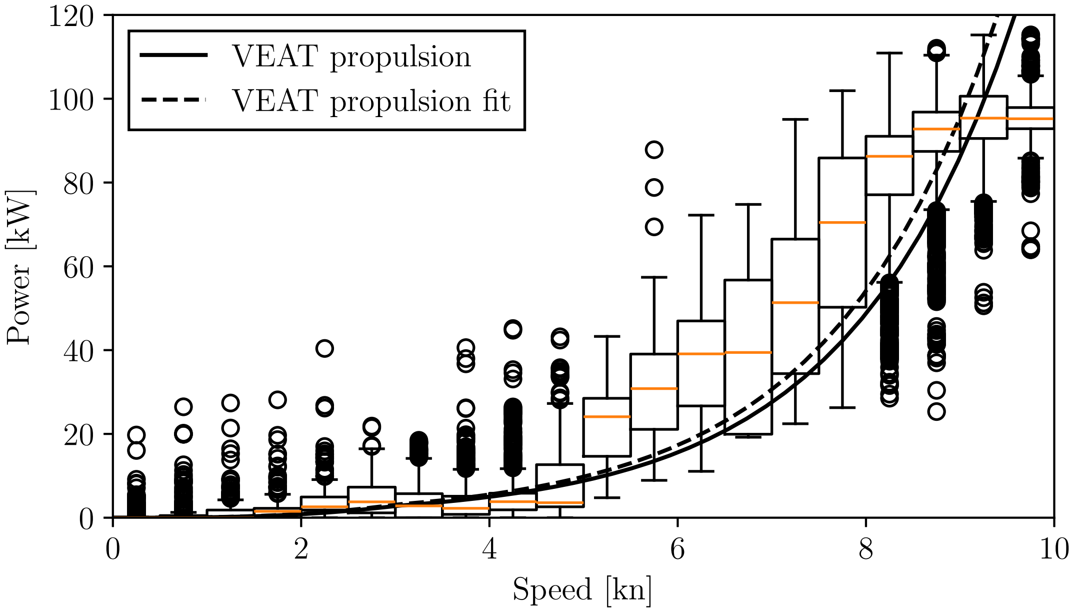


Figure 4.8: Box plot showing the low acceleration power data for Fredrika as a function of speed together with the standard and fitted propulsion model. The boxes show the first and third quartile. The whiskers go to the last point within 1.5 times the inter-quartile range. The circles are points outside of the whiskers.

Applying the Kemp model to a measured speed profile we can estimate the fuel consumption as shown in Figure 4.9. We see that the profile generated by the models follow the measurements well. It also accurately predicts the consumption while fishing when the engine is almost idling. It generally lags behind during acceleration and deceleration as its coupled with the speed which is delayed compared to the measured fuel consumption.

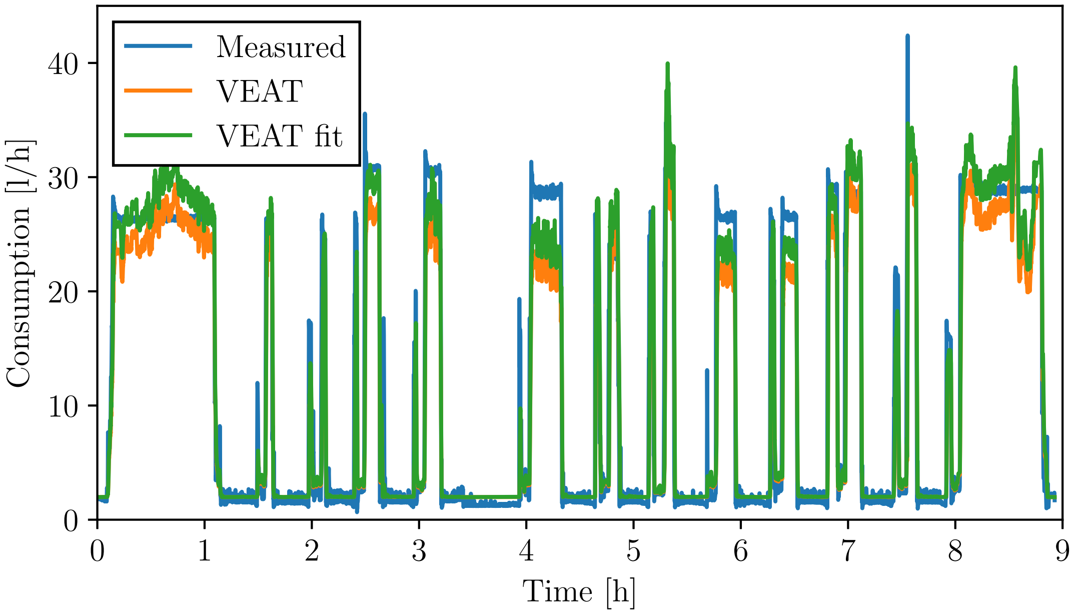


Figure 4.9: Measured and modeled consumption profiles for Fredrika. The modeled profiles are calculated from the measured speed profile.

So far, we have only looked at the propulsion model by Kemp (2018). However, the total measured consumption also includes the hydraulic and DC-electric system. Table 4.6 shows the average fuel consumption for the different load types as well as the average measured consumption. It should be noted that the idle consumption from running the engine is included in the propulsion load type.

Table 4.6: Average fuel consumption by load type as well as the totals for standard model, fitted model, and measured.

	Hydraulics [l]	DC-electric [l]	Propulsion [l]	Total [l]
Kemp model	3.1	1.4	78.7	83.2
Kemp fit constant	3.1	1.4	85.7	90.1
Measured	-	-	-	90.2

In Figure 4.10, the total consumption, both measured and predicted by the model, for each day is shown. The predicted fuel consumption by the standard model underestimates the fuel consumption for all days while the fitted model both over- and under-estimates the consumption but generally predicts the fuel consumption well. This can also be seen when looking at the mean absolute error which is 6.951 for the standard model and 2.841 for the fitted model.

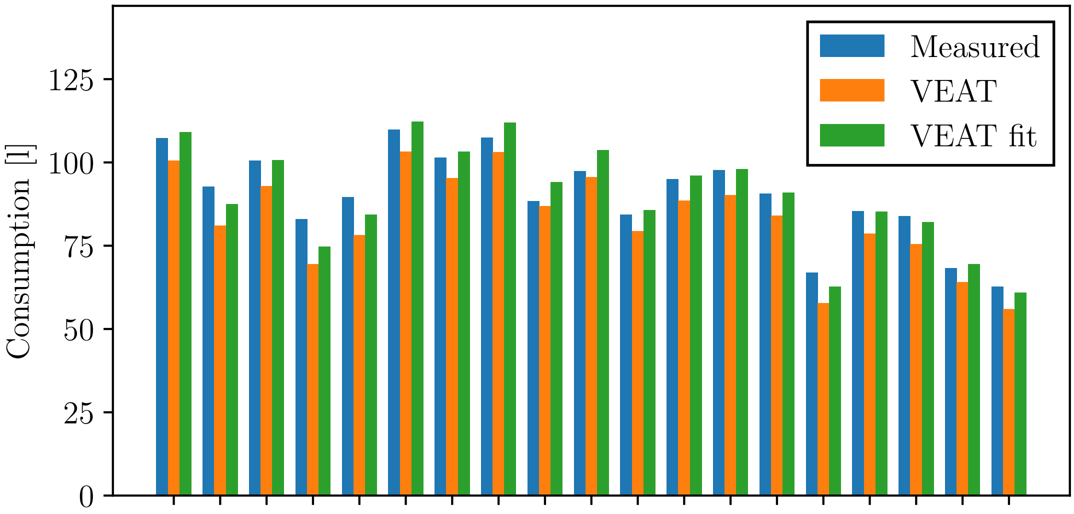


Figure 4.10: Measured total and predicted fuel consumption for each day using both the standard and fitted model for Fredrika. The values include propulsion, hydraulics, and DC-electric consumption.

Mira

The analysis for Mira is not as thorough as for Fredrika because of the lack of real time consumption data. For Mira, the fuel consumption between April 5th and May 11th is found to be 449 litres by reading the values from refueling in the logbook. Calculating the fuel consumption using the VEAT model for all days in between, we get a consumption 482 litres using the VEAT, which is and error of 7.4 %.

Summary

To summarize the modeling of energy consumption we recall how much the standard model differed from the measured value which can be seen in Table 4.7. Note that these are average values and during any particular day the consumption might vary depending on weather or any other circumstance not captured by the model. We see that the standard form of the VEAT predicts fuel consumption reasonably well and with data it can be made to fit the specific vessel well, like is the case with Fredrika.

Table 4.7: Measured fuel consumption compared to the prediction from the VEAT for Fredrika and Mira.

Vessel	Measured Consumption [l]	Predicted Consumption [l]	Error
Fredrika	90.2 per day	83.2 per day	−7.8 %
Mira	449 between refuel	482 between refuel	7.4 %

4.1.4 Operation with electric propulsion

This section presents what the operation and energy consumption could look like for Fredrika and Mira if electrified. That includes different daily operational profiles and their impact long term, but also the effects of current variations observed in the operations of Fredrika and Mira.

When modeling energy consumption for vessels using the traditional diesel fuels, the accuracy of the modeling has not been as crucial as for electric propulsion. Since, carrying extra fuel, even for several days, has come with very little cost, and in most cases even been beneficial as the refueling station was not necessarily in the home port. However, for an electric vessel the situation is quite different since it is very expensive and heavy to carry around extra unused battery capacity.

First, the delivered energy required is calculated for all days based on the Kemp models developed previously. The energy represents what would have been measured at the shaft after any engine and gearbox and is the method used in the VEAT. It would have been desirable to have measured the shaft power to be able to assess the VEAT engine model; however, that was not available.

To be able to compare how different operational patterns would impact consumption more simply, a representative date is chosen for both vessels. In order to allow for a breakdown of the operational profile, so that a simplified speed profile can be made. However, it is not realistic for most fishing vessels to be able to operate under optimal proposed operational profiles every day. Therefore, current variations in the operation are considered. The results from this section were input to the driveline design.

Fredrika

In Table 4.8 the energy consumption is shown for the different load types for Fredrika during the representative day. That is the same day whose speed profile and positional data is shown in subsection 4.1.2. Recall that during that day 12 strings of pots are handled during just below 9 hours. The row labeled measured represents the consumption if the fuel consumption data is converted to delivered power using the VEAT engine model and then integrated to get the total. We note that the measured value is between what is predicted by the VEAT and the fitted VEAT.

Table 4.8: Energy consumption by load type as well as the totals for measured, VEAT, and fitted VEAT for the representative day of Fredrika.

	Hydraulics [kWh]	DC [kWh]	Propulsion [kWh]	Total [kWh]
Measured	-	-	-	329.9
VEAT	13.7	5.6	288.8	308.1
VEAT fit	13.7	5.6	320.8	340.1

A simplified speed profile is created which can be seen in Figure 4.11. The simplified speed profile assumes that one string of pots takes 24 minutes and that the transit speed is 8.8 knots.

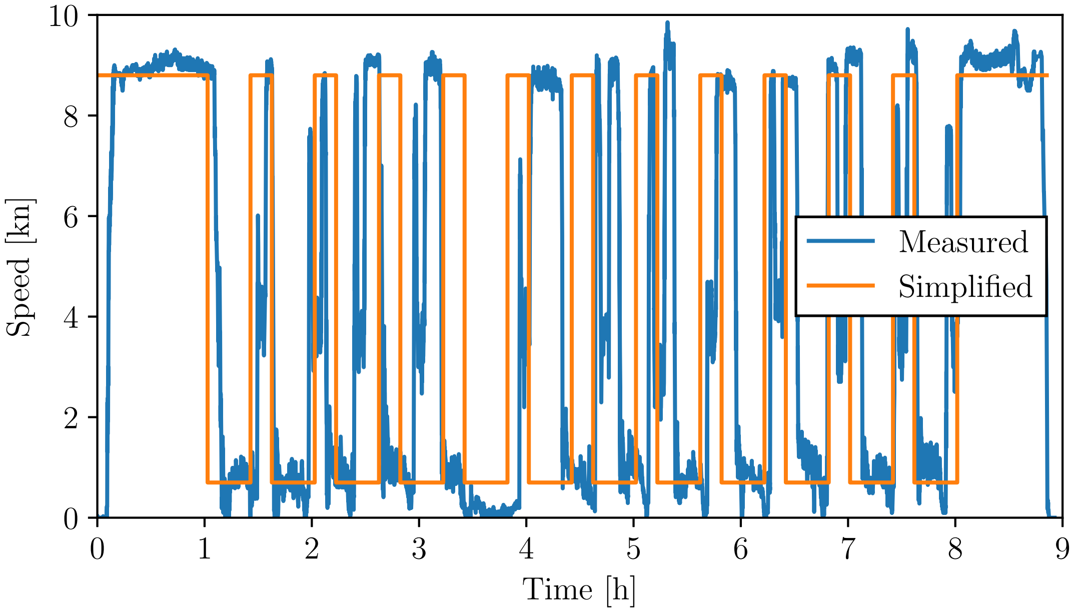


Figure 4.11: Measured speed profile of the representative day compared to the a simplified square speed profile for Fredrika. The simplified profile uses a transit speed of 8.8 knots and a fishing speed of 0.7 knots.

The total consumption for the two speed profiles shown in Figure 4.11 can be seen in Table 4.9. The measured consumption is calculated by transforming the fuel consumption data to delivered power with the Kemp engine model. We see that the measured consumption slots in between the standard and fitted Kemp models, while using both the measured and simplified speed profile.

Table 4.9: Time and consumption calculated for different combinations of speed profiles and two variations of the Kemp model for the representative day of Fredrika.

	Time [h]	Energy consumption [kWh]
Measured consumption	8.93	329.9
Measured speed with VEAT	8.93	308.1
Measured speed with VEAT fit	8.93	340.1
Simplified speed with VEAT	8.85	311.7
Simplified speed with VEAT fit	8.85	346.2

Knowing the accuracy of the simplified speed profile we can vary the operational speed in transit and between strings of pots, but also the number of pots handled in a day. In order to vary the number of pots in a day, a linear relationship is assumed between the distance in fishing mode and number of pots but the distance in transit is assumed constant, and is fitted to the collected data. In Figure 4.12, the energy consumption per day is shown as a function of the operational speed for different number of strings. We note that the operational speed has a larger impact on energy consumption compared to the number of strings.

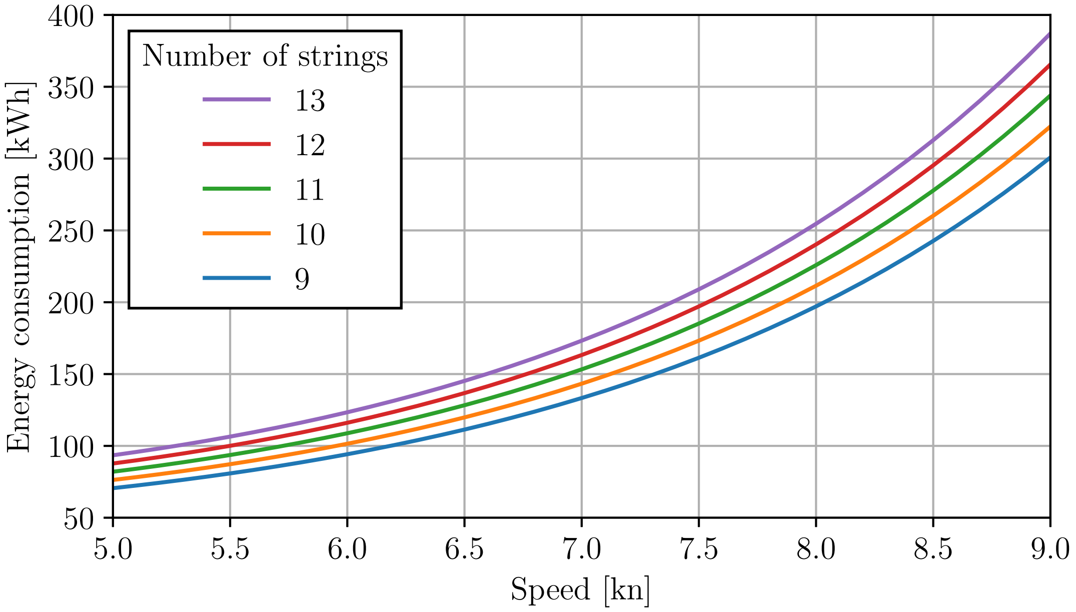


Figure 4.12: Energy consumption per day for Fredrika as a function of operational speed for varying number of strings of pots handled calculated using the simplified speed profile.

The story changes a bit when you also consider the time spent at sea. Figure 4.13 shows the energy consumption per day as a function of time spent at sea for different number of strings. If the maximum acceptable time at sea for Fredrika would be 9 hours, there is a significant difference in energy consumption between the different number of strings handled.

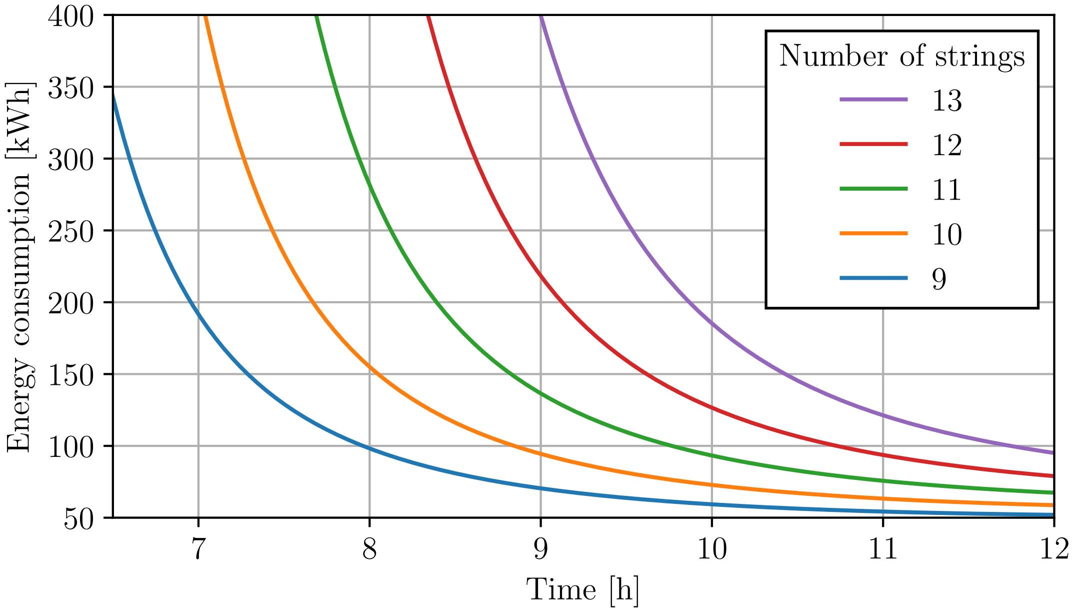


Figure 4.13: Energy consumption per day for Fredrika as a function of time spent at sea for varying number of strings of pots handled calculated using the simplified speed profile.

The consequences the information in Figure 4.12 and Figure 4.13 will be further investigated in the following chapters. But note that Fredrika on average handles 10 pots per day which could be done in under 8 hours with a consumption less than 200 kWh. But currently there is a great variation in the daily consumption and consumptions towards 350 kWh are common.

Mira

In Table 4.10 the predicted energy consumption is shown for each load type for the standard VEAT model during the representative day of fishing for Mira. Recall that during this day 9 strings of pots are handled during 8.6 hours and the speed profile was shown in Figure 4.3.

Table 4.10: Energy consumption by load type as well as the totals for VEAT and fitted VEAT for a representative day for Mira.

	Hydraulics [kWh]	DC [kWh]	Propulsion [kWh]	Total [kWh]
VEAT	10.7	5.4	68.1	84.1

Fitting a simple profile to the measured one results in the profile shown in Figure 4.14. Here, the time to handle one string of pots is assumed to be 27 minutes and the last stops are disregarded, but the distance accounted for in the last stretch back to port.

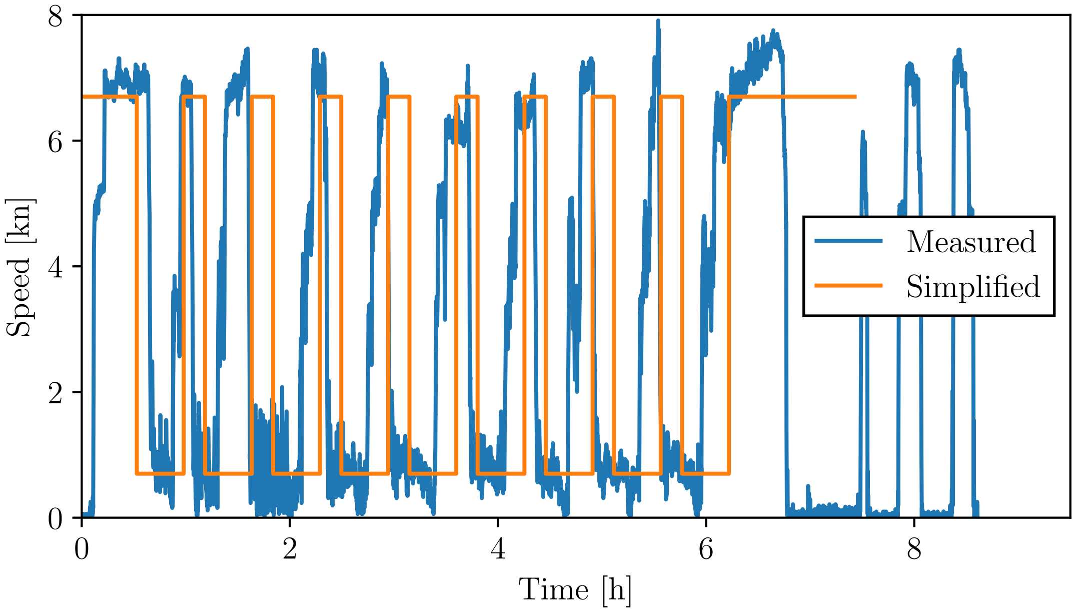


Figure 4.14: Measured speed profile compared to the a simplified square speed profile for Mira. The simplified profile uses a transit speed of 6.7 knots and a fishing speed of 0.7 knots.

Applying the VEAT model, the energy consumption is calculated and shown in Table 4.11. The energy consumption is very similar for the two speed profiles. However, the time differs which we already noted in Figure 4.14 since we are disregarding the time for the last stops with the simple profile.

Table 4.11: Time and energy consumption calculated for different combinations of speed profiles and two variations of the VEAT model for Mira during a representative day of fishing.

	Time [h]	Energy consumption [kWh]
Measured speed with VEAT	8.6	84.1
Simplified speed with VEAT	7.4	89.3

Just like for Fredrika, we can now vary the number of pots and the operational speed handled in a day while assuming the distance fishing vary linearly with the number of pots and the distance in transit remain the same. How the daily consumption varies depending on the number of strings handled and the transit speed for Mira can be seen in Figure 4.15. We see that compared to Fredrika, Mira can pick up the same amount of pots at a higher speed but with less energy consumed. That is mainly because of the shorter distances travelled by Mira as we discovered in subsection 4.1.2.

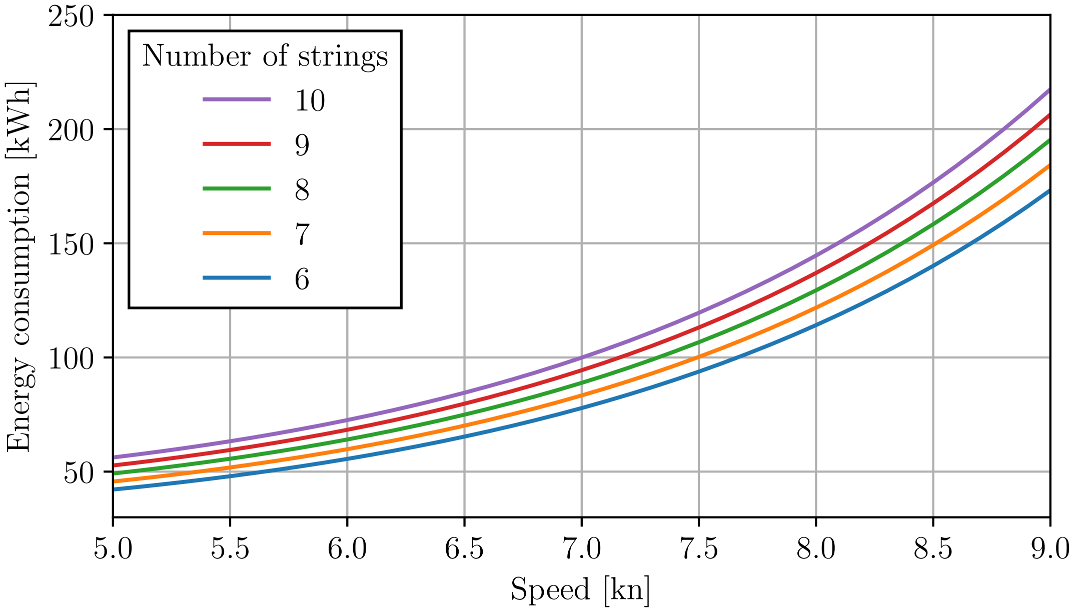


Figure 4.15: Energy consumption per day fishing for Mira as a function of operational speed for varying number of strings of pots handled calculated using the simplified speed profile.

Looking at the dependence between the daily energy consumption and time spent at see, which is shown in Figure 4.16, we see that the time varies significantly between different number of pots when considering a fixed consumption. That is the same as we saw for Fredrika.

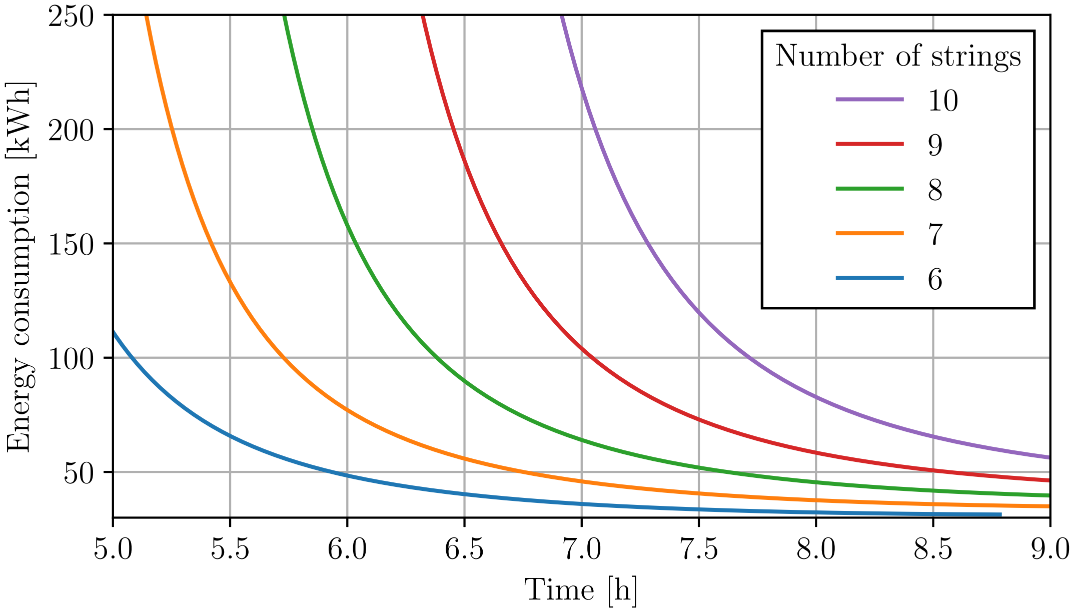


Figure 4.16: Energy consumption per day fishing for Mira as a function of time spent at sea for varying number of strings of pots handled calculated using the simplified speed profile.

4.2 Driveline design

In this section the current drivelines used in small fishing vessels are analysed as well as how it could look after going electric. Furthermore, the status of currently available commercial driveline parts are investigated as well as a future outlook.

4.2.1 Current driveline

The current drivelines of Mira and Fredrika use a straight shaft coupled to a gearbox mounted to the engine shaft, which is a traditional setup common in most small fishing vessels. A conceptual sketch of the driveline is shown in Figure 4.17 and the parts and their weights are shown in Table 4.12.

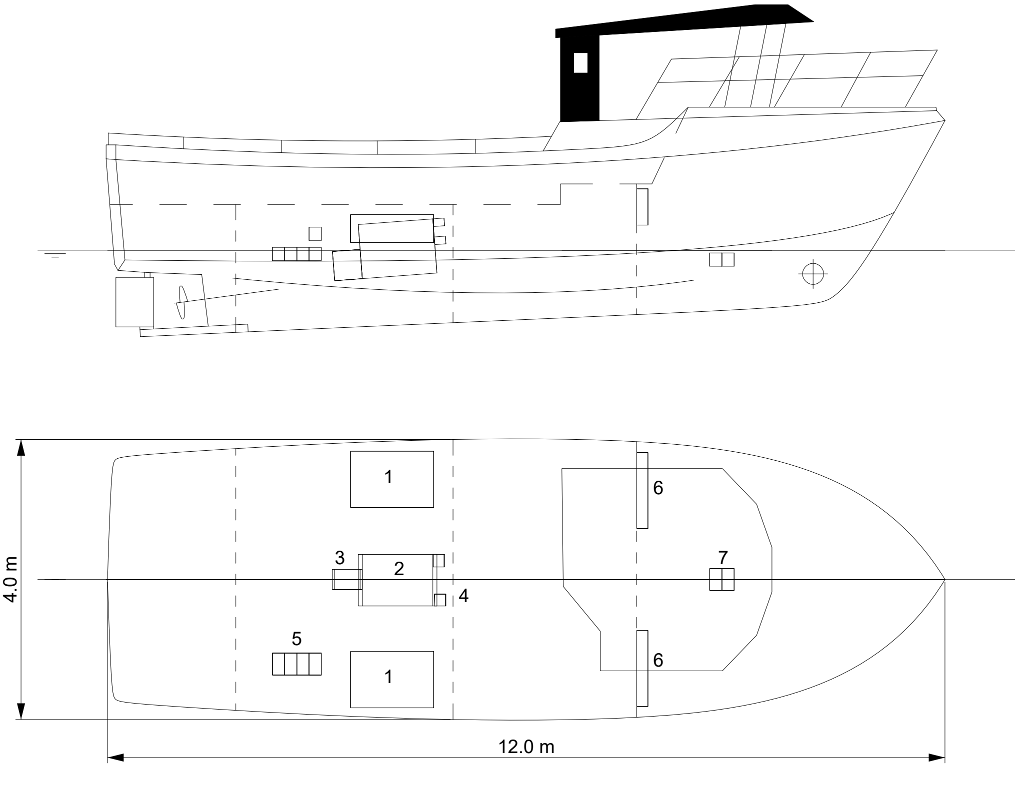


Figure 4.17: Conceptual sketch of the conventional driveline found in both Mira and Fredrika. The exact measurements differ slightly. A description of each part corresponding to a number can be seen in Table 4.12.

Table 4.12: Conventional driveline parts and their weights. The weights are an example based on Fredrikas parts.

Number	Part	Weight [kg]
1	Diesel tanks	480 (filled)
2	Engine	595
3	Gearbox with hydraulic pump	40
4	Alternator and start motor	- (included in engine)
5	House batteries and starter battery	100
6	Power electronics, inverters and charger	40
7	Bow thruster batteries	40
		Total 1295 kg

4.2.2 Electric driveline

For the electric driveline, we considered the same traditional straight shaft but directly coupled to an electric inboard motor. A conceptual sketch can be seen in Figure 4.18 and a description of the parts as well as their weights can be found in Table 4.13.

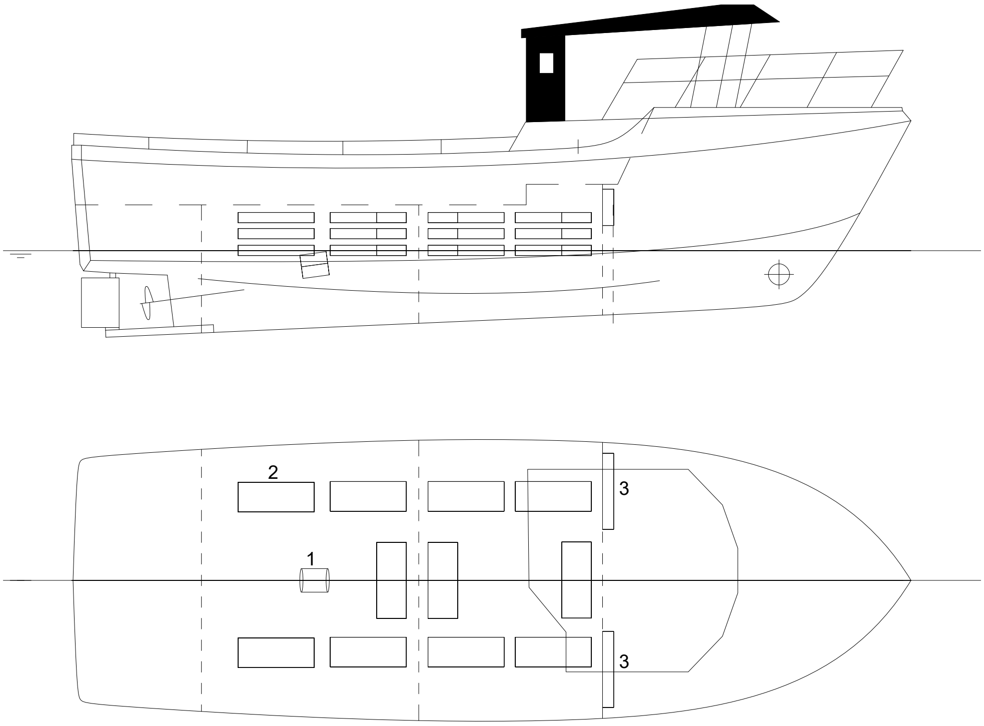


Figure 4.18: Conceptual sketch of an electric driveline. A description of each part corresponding to a number can be seen in Table 4.13.

Table 4.13: Electric driveline parts and example weights using ePropulsion H-series motor and EPTechnologies High voltage batteries.

Number	Part	Weight [kg]
1	Electric motor ePropulsion H60 or H85	110-150
2	Batteries EPTechnologies HV 200 - 400 kWh	1000-2000
3	Power electronics, inverters and charger	100
		Total 1210-2250 kg

The main parameters of the electric driveline is the battery capacity and rated power of the motor. However, if the battery capacity is simply determined by the daily energy consumption and a motor is selected based on maximum peak power one is bound to encounter some problems. The first one being the size of the batteries, characterized by the batteries volumetric energy density. The batteries shown in Figure 4.18 have a volumetric energy density of 0.231 kWh/l which place them in the top of the marine batteries currently available, see subsection 4.2.3. The batteries shown also have a competitive gravimetric energy density of 0.19 kWh/kg.

How the main parts of the electric driveline are connected and work together is illustrated in Figure 4.19. It also contains the assumed efficiencies of each part, which results in a total efficiency from the battery to the shaft of $\eta_t = \eta_b \eta_p \eta_m = 0.82$.

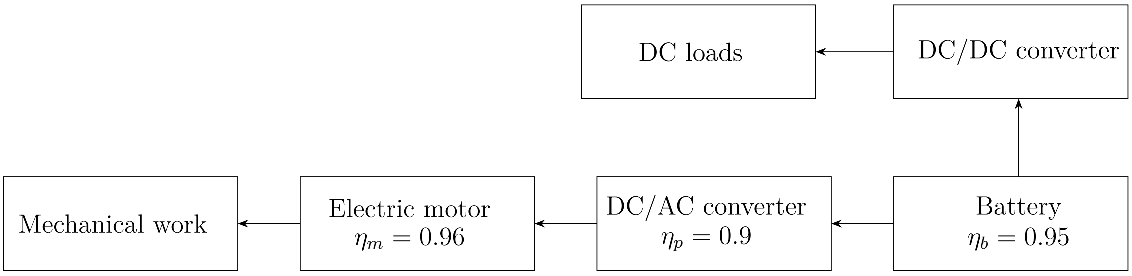


Figure 4.19: Driveline schematic showing how the different components of the electric driveline are connected and their efficiencies.

To get to the battery size estimation from the useful shaft energy consumption the total efficiency must be considered, but also a safety factor variations in the operation or bad weather, and the depth of discharge of the batteries. The safety factor is chosen as 20 % and the depth of discharge is assumed to be 80 %. The relationship between the calculated daily energy consumption and battery size becomes,

$$\text{Battery capacity} = 1.83 \cdot \text{Calculated consumption.} \tag{4.1}$$

If we apply Equation 4.1 to the energy consumptions predicted by VEAT for both vessels during their representative days, we get the battery sizes as in Table 4.14. One quickly realizes that a battery pack of 604 kWh can not be accommodated in a fishing vessel like Fredrika, as it would require 38 packs like those shown in Figure 4.18 where 33 are accommodated. That means that in order to be electrified, Fredrika would have to change her operation.

Table 4.14: Battery properties for the different vessels to accommodate for the current representative daily operation. A gravimetric density of 0.19 kWh/kg and volumetric density of 0.231 kWh/l is assumed.

Vessel	Battery size [kWh]	Battery weight [kg]	Battery volume [l]
Mira	164	863	710
Fredrika	604	3179	2615

4.2.3 The status of commercially available electric drivelines and future outlook

In order to get an idea of the status of marine electric drivelines and parts, the current commercially available options were investigated and compiled. The result of which is shown in Table 4.15 and Table 4.16.

Table 4.15: Main parameters of some currently available battery systems for marine use.

Name	Manufacturer	Gravimetric energy density [kWh/kg]	Volumetric energy density [kWh/l]	Cost [€/kWh]
High voltage high energy battery cells	EPTechnologies	0.191	0.231	500
Solid state technology battery cells	EPTechnologies	0.141	0.167	-
MLI Ultra 24/6000	Mastervolt	0.128	0.138	-
KBP63	Kreisel	0.160	0.203	-
RS 230	MG	0.124	-	-
LFP 304	MG	0.144	0.211	-
Nomada	SUPER B	0.133	0.193	-
DeepBlue 40	Torqeedo	0.146	0.137	950
DeepBlue 80	Torqeedo	0.141	0.154	600
Orca Energy	Corvus Energy	0.077	0.088	600
Dolphin Energy	Corvus Energy	0.168	0.2125	550
Blue Whale	Corvus Energy	0.104	0.0058	500
Average		0.135	0.153	617

Table 4.16: Main parameters of some currently available electric inboard motors.

Name	Manufacturer	Power [kW]	Gravimetric power density [kW/kg]	Cost [€/kW]
Deep Blue 50i 2000	Torqeedo	50	0.625	260
Deep Blue 100i 2500	Torqeedo	100	0.500	-
Breeze	Evoy	90	0.500	421
H-60	Epropulsion	60	0.545	-
H-85	Epropulsion	85	0.567	-
I-40	Epropulsion	40	0.471	-
EP-100	Elco	42.5	0.127	494
Average			0.476	392

The average gravimetric density and cost of batteries were found to be 0.135 kWh/kg and 617 €/kWh respectively. That is in line with what was found by DNV-GL (2019), who reported the gravimetric energy density to be 0.9-0.12 kWh/kg and the cost to be 500-1000 $/kWh, equivalent to approximately 460-920 €/kWh.

The electrification efforts of the marine sector are still in its early stages and the developments are expected to continue and adoption increase (EMSA, 2020). Looking forward, the gravimetric energy density of battery packs are predicted to rise to 0.391 kWh/kg to 2030 and 510 kWh/kg to 2040 (Tiede et al., 2022).

4.3 Environmental analysis

This section outlines the steps employed to evaluate the environmental aspects of the two propulsion systems. In addition, the results derived from the assessment are presented.

4.3.1 Background

To assess the environmental impact of the different propulsion systems that could be used for fishing vessels, a life cycle assessment (LCA) study is carried out. According to (Farjana et al., 2021), there are three levels of an LCA study based on the quality of data available: conceptual, simplified, and detailed LCA. For our thesis, the conceptual level of LCA chosen to keep the study simple whilst giving an overview rather than a detailed insight on the environmental impacts of different propulsion systems.

The LCA study is carried out according to ISO14040:2006 standards where the LCA study for a particular product is divided into four phases: definition of the goal and scope, inventory analysis, impact assessment, and interpretation of the results. Figure 4.20 shows how the four phases of LCA are corelated.

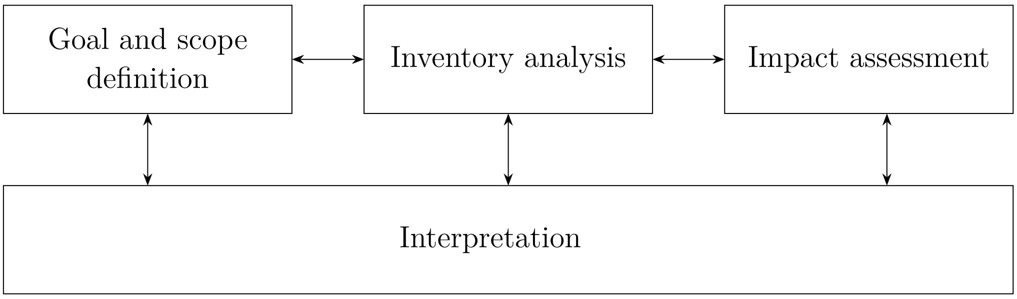


Figure 4.20: The four phases of a life cycle assessment study (International Organization for Standardization, 2006).

Goal and scope definition

The primary goal of the LCA study for the thesis is to evaluate and compare the environmental impacts of two propulsion systems for both Fredrika and Mira. The two propulsion systems are considered as two scenarios:

Scenario 1: A fuel-based propulsion system using an IC engine with a low sulfur content diesel as the fuel.

Scenario 2: A battery-driven electric propulsion system driven by electric motor using electric energy stored from batteries.

A cradle-to-grave approach was adopted, where "cradle" refers to the extraction of raw materials and "grave" refers to the point where all parts of the propulsion system are either recycled or discarded into the environment.

While a complete cradle-to-grave assessment is carried out for both propulsion systems, only the use phase and end-of-life phase are considered in the case of the conventional propulsion system. In contrast, the complete life-cycle analysis is performed for the battery-driven propulsion system. This is because the environmental feasibility is concerned only in the potential environmental impacts for retrofitting the current propulsion system with the electric propulsion system.

To keep the LCA study simple and clear, the following assumptions were made to define the scope of the study.

- The system boundary was limited to the fishing vessels themselves. It is assumed that no changes will be made to the hull (the main dimensions remain unchanged) when replacing the current fuel-based propulsion system with the battery-driven propulsion system.
- The functional unit used to compare the two propulsion systems was set to 1 kWh of energy consumed.
- The environmental impacts were measured for a 15-year lifespan of each propulsion system. 15 years was chosen as the lifetime to estimate the total incentive ship owners could receive from *Klimatklivet* for switching to cleaner propulsion systems. (Naturvårdsverket, 2024a).

Inventory analysis

The second stage of the LCA study is the life cycle inventory analysis. Here, data is collected using the several available databases. For our LCA study, the Ecoinvent 3.8 cut-off database was used primarily. To estimate the environmental impacts of the end-of-life phase, approximate values from various sources were used.

Impact analysis

The third stage of an LCA study is to evaluate the environmental impacts (impact indicators) related to the phases considered for the LCA. The following impact indicators were evaluated:

- **Global Warming Potential (GWP100a):** The GWP100a is a widely used impact indicator that quantifies the greenhouse gas potential over a period of 100 years and is measured in kgCO2eq (CLEAR Center at UC Davis, 2022). Throughout the text, GWP100a is used interchangeably with GWP.
- **Acidification Potential (AP):** This is the metric used to compare which propulsion system would contribute more towards depositing acidifying components in the soil, groundwater, and surface waters. It is measured in kgSO2eq (STiCH (Sustainable Tools for Integrated Cultural Heritage), 2024).
- **Fine particulate matter formation:** Particulate matter (PM) are the tiny particles suspended in the air that have a diameter less than 2.5 μm. This is a metric used to track the air quality.

While several indicators are being measured in this LCA study, GWP100a stands out as the main focus due to its critical role in assessing the potential CO2 emissions to the environment.

Interpretation of results

This is the final stage of the LCA study. Here, the data from the impact assessment are analysed, sensitivity analysis is performed, and then presented using graphs and tables.

4.3.2 LCA for fuel-based propulsion system

A fuel-based propulsion system consists of an IC engine and fuel that is combusted in the engine to produce the required mechanical power. The LCA study is divided into four phases: manufacturing phase, Well-to-Tank phase (WtT), the Tank-to Wake (TtW) or use phase, and the end-of-life (EOL) phase. Figure 4.23 shows the life cycle of the fuel-based propulsion system.

Manufacturing phase

The manufacturing phase consists of manufacturing of the engine. While exact values were unavailable, approximate values for manufacturing of the engine were

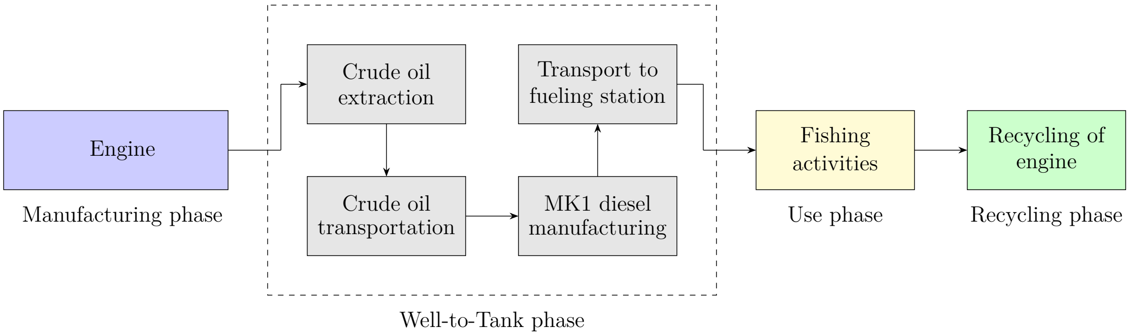


Figure 4.21: Life cycle phases of the fuel-based propulsion system.

taken from the Ecoinvent 3.8 cutoff database. Table 4.17 indicates the approximate weight ratios of major materials used in the engine manufacturing process.

Table 4.17: Weight ratio of materials used in manufacturing of the engine.

Material	Weight ratio (%)
Iron	57 %
Aluminium	19 %
Copper	1 %
Zinc	3 %

The engine is assumed to be manufactured in Germany and transported directly by road to the vessel covering a total distance of 2000 km. Table 4.18 shows the different impact indicators for the manufacturing phase for both Fredrika and Mira.

Table 4.18: Emissions from the manufacturing phase of the fuel-based propulsion system for both Fredrika and Mira.

Emissions	Unit	Fredrika	Mira
GWP100a	kgCO$_2$eq	4994.39	3745.79
Acidification potential	kgSO$_2$	40.41	30.31
PM	kg PM2.5eq	13.70	10.28

Well-to-Tank phase

The well-to-tank phase consists of the extraction of the crude oil, its transportation for refining, and finally, the distribution of the fuel to the fueling station. Norway is the largest exporter of crude oil to Sweden (Figure 4.22). Therefore, it is assumed that crude oil was extracted off the coast of Norway and then is transported by sea, covering a distance of 700 km to the port of Gothenburg. The crude oil is then refined in the refinery near the port of Gothenburg where diesel is obtained. Finally, diesel is transported to the fuel station by fuel trucks. The impact indicators for the WtT phase for both vessels is presented in Table 4.19.

Table 4.19: Emissions from the well-to-tank phase of the fuel-based propulsion system for both Fredrika and Mira.

Emissions	Unit	Fredrika	Mira
GWP100a	$kgCO_2eq$	4334.28	3657.90
Acidification potential	$kgSO_2eq$	25.16	14.58
PM	kg PM2.5eq	7.74	6.29

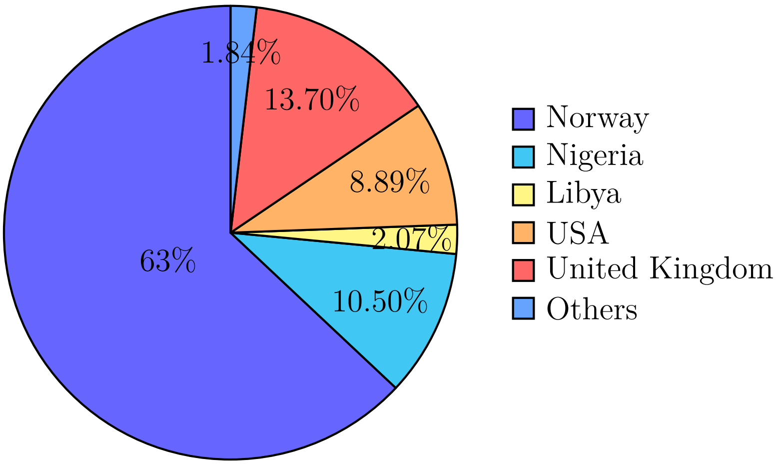


Figure 4.22: Importers of crude oil to Sweden in 2022 (Observatory of Economic Complexity, 2024).

Tank-to-Wake phase

For the fuel-based propulsion system, the Tank-to-Wake or use phase involves the combustion of the fuel in the engine during fishing activities, resulting in tailpipe emissions. From personal interviews with vessel owners, it was found that the fuel used is labeled fuel, also known as low-taxed diesel. Thus, for the LCA study, MK1 diesel was used. The MK1 diesel, also known as Environmental Class 1 diesel was introduced in Sweden in the early 1990s which has a maximum of 10 ppm sulphur content. The fuel properties are as shown in Table 4.20

Table 4.20: Chemical properties of MK1 diesel without rapeseed methyl ester (RME) (Preem AB, 2012).

Property	Unit	Value
Density @ 15 °C	kg/m^3	814.0
Lower heating value	MJ/kg	43.1
Sulphur content	ppm	<10

To estimate the impacts indicators for the use phase, the following formulas were used that were obtained from (Perčić et al., 2023) and the characterisation factors under the ReCiPe 2016 midpoint (H) life cycle impact assessment (LCIA) method

(Huijbregts, 2016).

$$\mathrm{GWP100a} = \mathrm{C_f} \cdot (\mathrm{EF_{CO_2}} + 36 \cdot \mathrm{EF_{CH4}} + 298 \cdot \mathrm{EF_{N_2O}})$$

$$\mathrm{AP} = \mathrm{C_f} \cdot (\mathrm{EF_{NO_X}} + 36 \cdot \mathrm{EF_{CH4}} + 298 \cdot \mathrm{EF_{N_2O}})$$

$$\mathrm{PM} = \mathrm{C_f} \cdot (\mathrm{EF_{PM}} + 0.29 \cdot \mathrm{EF_{SO_2}} + 0.11 \cdot \mathrm{EF_{NO_x}})$$

Where $\mathrm{C_f}$ is the total fuel consumption (in kilograms) over the 15-year period for each vessel and $\mathrm{EF_i}$ is the emission factors for different gases from the use phase obtained from the CPM LCA database and are as shown in.

Table 4.21: Emission Factors of Various Gases for MK1 Diesel measured in kg gas/kg fuel (Tivander, 2020).

Emission factor	Value
CO_2	3.1203
CH4	0.0029
NO_x	0.0107
SO_2	0.000006
PM	0.00016

The emissions from fishing activities for both vessels are therefore calculated and presented in Table 4.22.

Table 4.22: Emissions from the use phase for the fuel-based propulsion system for both Fredrika and Mira.

Emissions	Unit	Fredrika	Mira
GWP100a	$kgCO_2eq$	550495.34	125469.02
Acidification potential	$kgSO_2eq$	1839.57	419.28
PM	kg PM2.5eq	230.13	53.69

End-of-life phase

The EOL phase for the conventional driveline consists of dismantling and recycling the engine materials. It is assumed that 90 % of the metals used in the manufacturing of the engine are recyclable. It was estimated that 2200 kgCO2 can be saved if the engine is recycled in the case of Fredrika and 2600 kgCO2 for the case of Mira. These values are calculated based on percentages presented by Stena Recycling (2024).

4.3.3 LCA for battery-based propulsion system

For the battery-driven propulsion system, the cycle life is also subdivided into four phases: manufacturing phase, WtT phase, and TtW or use phase, recycling phase.

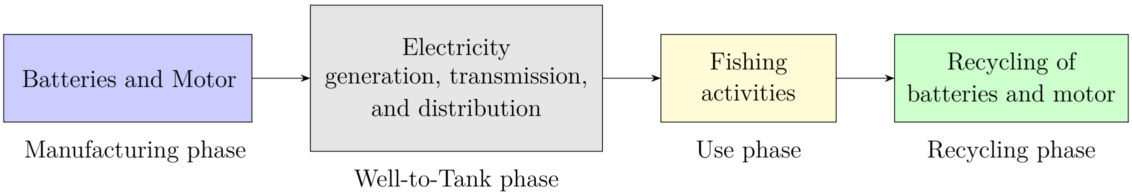


Figure 4.23: Life cycle phases of a battery-driven propulsion system.

Manufacturing phase

The manufacturing phase of the battery-driven propulsion system includes the production of both the motor and batteries. The assumptions made to estimate the environmental impact from the manufacturing phase are:

- NMC811 cells energy density of 0.209 kWh/kg are used in the battery pack.
- The individual cells are manufactured in China and transported by sea to the vessels.
- The energy required for the assembly of the cells to battery pack is not included in the LCA study.
- For the motor, an electric passenger car motor is considered. It is assumed to be manufactured in Germany and transported to the vessels by road.

Table 4.23: Emissions from the manufacturing stage for the battery-driven propulsion system for both Fredrika and Mira.

Emissions	Unit	Fredrika	Mira
GWP100a	kgCO_2eq	31926.59	15124.16
Acidification potential	kgSO_2eq	419.04	198.05
PM	kg PM2.5eq	121.90	57.86

Well-to-tank phase

For the battery-driven propulsion system, the WtT phase consists of the generation and supply of electricity. The electricity mix of a country plays a vital role in estimating the environmental impact. For our LCA study, the Swedish electricity mix available from the Ecoinvent 3.8 cutoff database was used. The data was collected between 2017 and 2021. Figure 4.24 illustrates that most of the electricity generated in Sweden comes from nuclear and hydro power. The impact indicators for WtT phase for the battery-driven propulsion system is as shown in Table 4.24

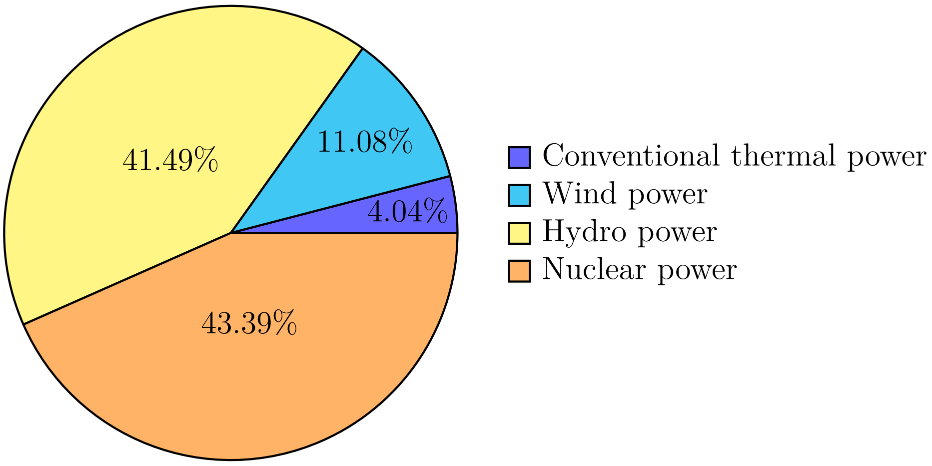


Figure 4.24: Swedish electricity mix

Table 4.24: Emissions from the well-to-tank stage for the battery-driven propulsion system for both Fredrika and Mira.

Emissions	Unit	Fredrika	Mira
GWP100a	$kgCO_2eq$	17 935.60	7 686.68
Acidification potential	$kgSO_2eq$	63.68	27.29
PM	kg PM2.5eq	24.14	10.35

Tank-to-Wake phase

In the TtW phase for the battery-driven propulsion system, the vessels are driven by the energy stored in the battery packs. As chemical energy is directly converted to electrical energy, there are no tailpipe emissions, therefore, there are no emissions to the environment during the use phase.

End-of-life phase

The recycling phase of the battery-driven propulsion system includes several steps to recycle materials. According to Zackrisson (2019), 10-12 $kgCO_2$ can be prevented from entering the atmosphere if the materials are recycled instead. Therefore, the total estimated $kgCO_2$ savings for the EOL stage is 17 500 $kgCO_2$ for Fredrika and 6400 $kgCO_2$ for Mira.

4.3.4 Interpretation of results

The results indicate that most of the emissions are generated during the use phase in the case of the conventional or fuel-based propulsion system. The use phase contributes to more than 90 % of GWP emissions.

The results also indicate that the manufacture and transportation of batteries contribute to around 65 % total GWP emissions if recycling is not included. These values can be further reduced if battery manufacturing is carried out in Europe instead of China and if recycled materials are used for manufacturing batteries. Figure 4.25 and Figure 4.26 provides an overview of the main contributors of greenhouse gas emissions for the two propulsion systems for Fredrika and Mira respectively.

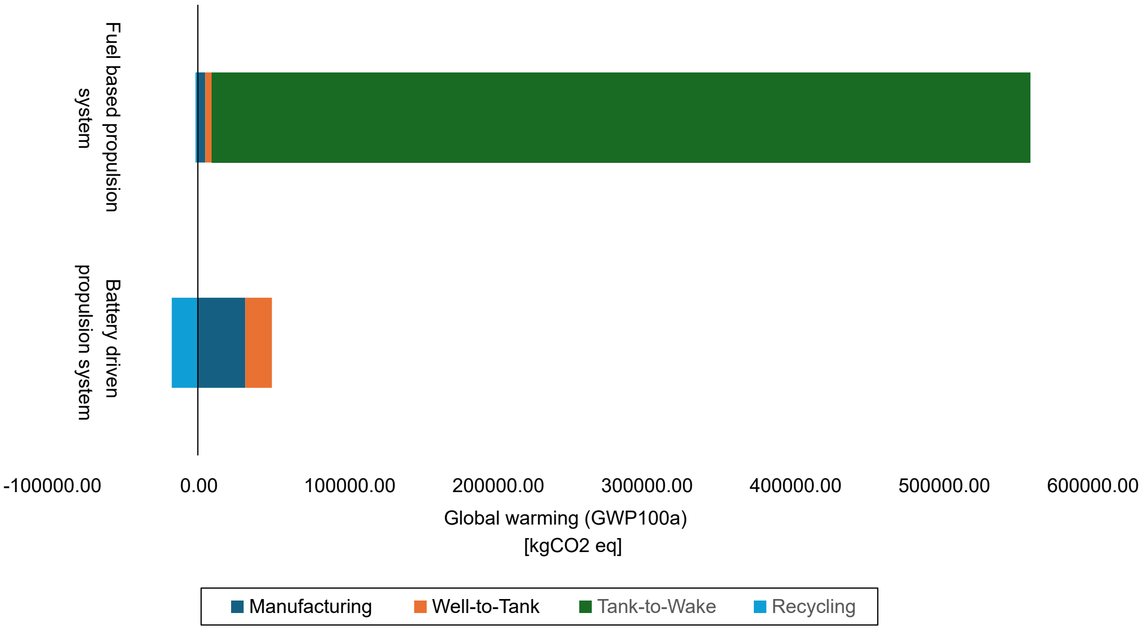


Figure 4.25: The total GWP100a emissions over the entire life cycle of the fuel-based propulsion system and battery-driven propulsion system for Fredrika.

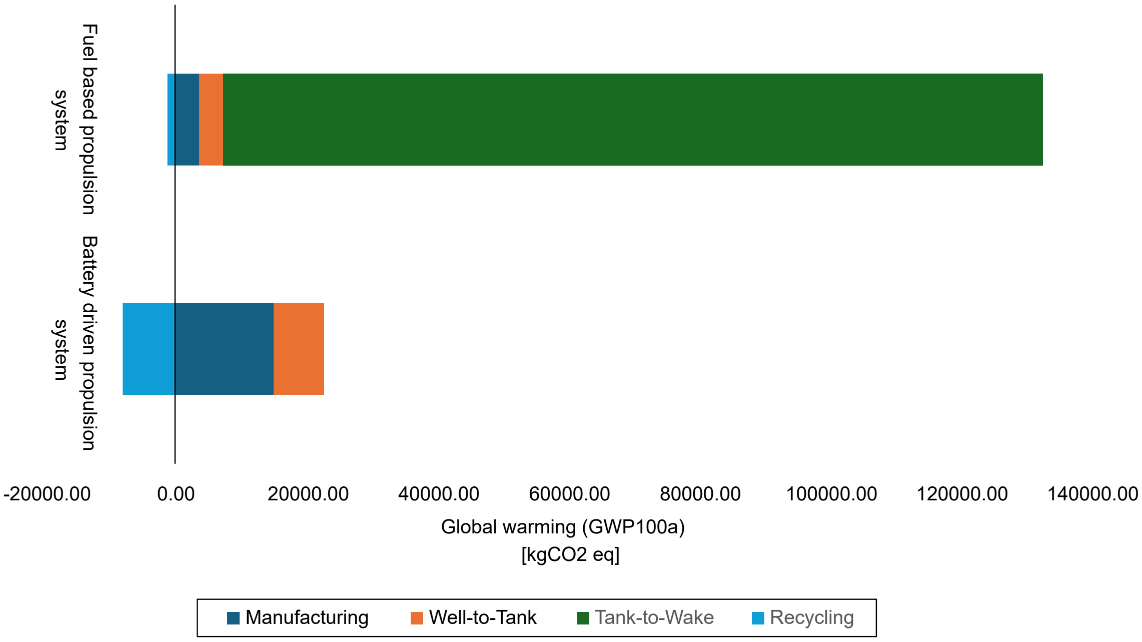


Figure 4.26: The total GWP100a emissions over the entire life cycle of the fuel-based propulsion system and battery-driven propulsion system for Mira.

4.4 Economic analysis

There are three main costs which must be considered when looking at electrifying a fishing vessel. That is, the fuel price, electricity price, and investment cost for the electric installation. What makes this tricky is that all three have varied greatly during the past years and will probably continue to do so.

Mira

Mira used 3200 litres of fuel during 2023 and we assume that it will continue like that for the foreseeable future. A breakdown of the yearly costs is presented in Table 4.25, where we see that the electric driveline is around 45 843 SEK cheaper per year to operate. However, we must also consider the investment cost associated with converting to electric.

Table 4.25: Yearly costs related to the drivetrain for Mira.

	Current	Electric
Yearly consumption	3200 l	9146 kWh
Cost for consumption	18 SEK/l	1.78 SEK/kWh
Yearly maintenance cost	5 000 SEK	500 SEK
Total yearly cost	62 600 SEK	16757 SEK

In order for an investment to be regarded as profitable we look at the discounted payback period using a discount rate of 4 % and a lifetime of the investment of 15 years. We consider the investment profitable when the payback period is less than 5 years, which would mean a maximum investment of 205 000 SEK for Mira to be electrified. We quickly realize that with the current prices of batteries, it is not financially viable to electrify Mira as the battery alone is estimated to cost around 800 000 SEK for 154 kWh assuming a price of 5000 SEK/kWh.

Klimatklivet would not provide funds to electrify Mira either, as the environmental performance of the investment is too low. The total carbon emission reduction during the lifetime is 175 000 kgCO2e which with a minimum performance of 0.75 kgCO2e/SEK would mean a maximum investment cost of 233 000 SEK in order for a grant from *Klimatklivet* to be applicable.

Fredrika

For Fredrika the situation is slightly more complicated to assess. First, we already noted that the operation would have to change in order for her to be electrified since there the amount of batteries can not be accommodated because weight and space constraints. Below we look into the financial situation of installing a 300 or 200 kWh battery system with the yearly consumption assumed to fully utilize the battery by operating at the appropriate speed. The yearly cost of operation for the current and electric drivelines are shown in Table 4.26.

Table 4.26: Yearly costs related to the drivetrain for Fredrika and maximum investment for a payback time of 5 years with a discount rate of 4 %.

	Current	Electric 200 kWh	Electric 300 kWh
Yearly consumption	14 040 l	20 792 kWh	25 574 kWh
Cost for consumption	18 SEK/l	1.78 SEK/kWh	1.78 kr/kWh
Yearly maintentece cost	5 000 SEK	500 SEK	500 SEK
Total yearly cost	257 720 SEK	37458 SEK	55 937 SEK
Yearly surplus	-	220 262 SEK	201 783 SEK
Maximum investment	-	980 000 SEK	900 000 SEK

The maximum investment of 980 000 SEK for the 200 kWh battery system is in the neighbourhood of the system costs looking forward a few years. However, that is if the operational limitations of a 200 kWh battery system are acceptable. From the analysis previously that would mean a maximum useful energy consumption of 110 kWh which is enough for 10 strings of pots in around 9 hours.

Neither here *Klimatklivet* would provide funding. Since, the total emission reduction is 657 000 kgCO2eq which corresponds to a maximum investment of 876 000 SEK. We see that for both Fredrika and Mira that the investment would become profitable around the same point when the environmental performance is just good enough for *Klimatklivet*.

4.5 Summary of the analysis

To summarize the analysis we would like to revisit the research questions in section 1.2. The research questions together with the results of our analysis are presented below.

- What regulatory challenges exist when electrifying fishing vessels and what requirements do that place on the conversion?

  We found that the regulatory landscape for electrification of these small fishing vessels has not been explored yet. The same functional rules which apply for larger vessels apply to these small fishing vessels. The functional rules do not put any specific requirements like the old descriptive rules. However, the only regulatory path decided feasible is to follow the guidelines for electrifying vessels by Transportstyrelsen (Transportstyrelsen, 2023), which require the installation to be made using marine certified equipment up to some standards described in the guidelines.

- Are the operational profiles of small coastal fishing vessels compatible with electrification from a technical perspective or does the operation need to change with electrification?

  We found that the operational profile of Mira fits well with electrification. She generally operates quite close to shore and and slower speeds allowing for low energy consumption and would therefore need a smaller more manageable battery. However, for Fredrika the operation would have to change since the energy consumption is simply too large. She typically operates further out, travels faster, and is out for longer compared to Mira. So the operational profiles of small fishing vessels are not automatically compatible with electrification, but as seen with Fredrika the operation can likely be adapted to fit with electrification.

- How will environmental effects change, including potential reductions in local emissions and GHG emissions during the life cycle?

  From the environmental analysis, we found that there is a significant reduction of local emissions (90 % for Fredrika and 82 % for Mira) when converted to electric propulsion. Additionally, it was also found that the battery-driven propulsion system can potentially reduce overall emissions over their life cycle if they are manufactured in Europe instead of China as it reduces emissions generated during their transportation.

- How will operational and investment costs change with electrification and how will it impact daily operations?

  We found that the operational costs for the battery-driven propulsion system are significantly lower compared to that of the traditional propulsion system. However, we also found it not to be enough to compensate for the high investment costs related mainly to the battery. Furthermore, it was found that the chances of utilizing the grant from *Klimatklivet* are slim as the environmental performance of the investment is too low and the investment becomes profitable around the same time as the environmental performance surpasses to lowest acceptable threshold.

5

Results and discussion

In this chapter, we present the proposed method formulation for determining feasibility of electrifying small fishing vessels. We also discuss its applicability, limitations, how it compares to the literature, and its future outlook.

5.1 Method formulation

Our method stands on four pillars, regulatory, technical, environmental, and economic feasibility. A schematic overview of the method is shown in Figure 5.1. The main principle of the method is that all four pillars must be feasible under the same operational assumptions. If any pillar fails, the method should be reiterated with a modified operational profile to combat the previous shortcoming.

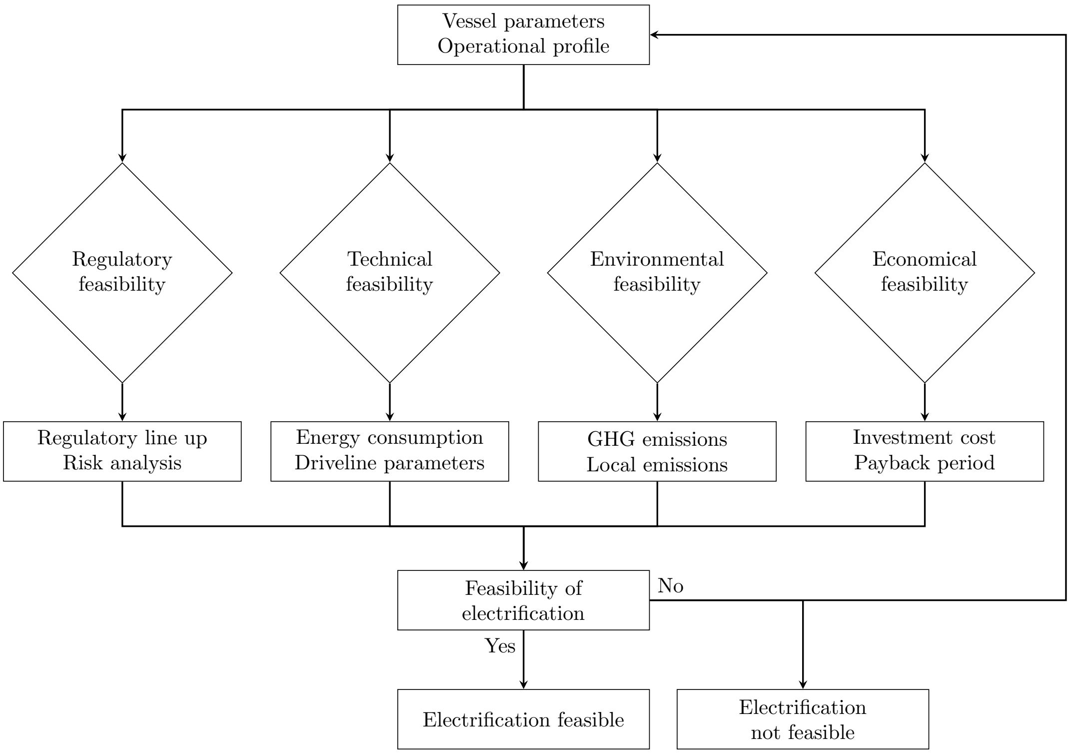


Figure 5.1: Overview of the suggested method for evaluating feasibility of electrification of small fishing vessels.

The method is implemented in an excel sheet to allow for any vessel owner to easily assess the feasibility of electrification. A easy to understand description of the method and its excel sheet can be found in Appendix A. Below, the scope and limitations stated, and examples for applying the method to Mira and Fredrika given. Lastly there is also a discussion about the method and how it fits into the current research field.

5.2 Scope and limitations of the method

The method is aimed at giving an indication for when electrification is feasible. However, there are always specific details for each vessel which needs to be accounted for separately. Furthermore, installation details are not provided through this method because of the variation in the fleet. Instead the method should be used to understand the driving parameters of the operation, emissions, and costs present in the study of feasibility of electrification.

The method mainly inherits its limitations from the VEAT. That it is intended for slower going vessels between 9 and 30 metres as it was those who provided data to the project Kemp (2018). It also disregards the propeller and only looks at delivered power and fuel propulsion therefore assuming all propellers are equally efficient.

Other limitations come from the LCA since the fuel is assumed to be diesel refueled in Sweden and the electricity mix used is also based on data from Sweden to calculate emissions.

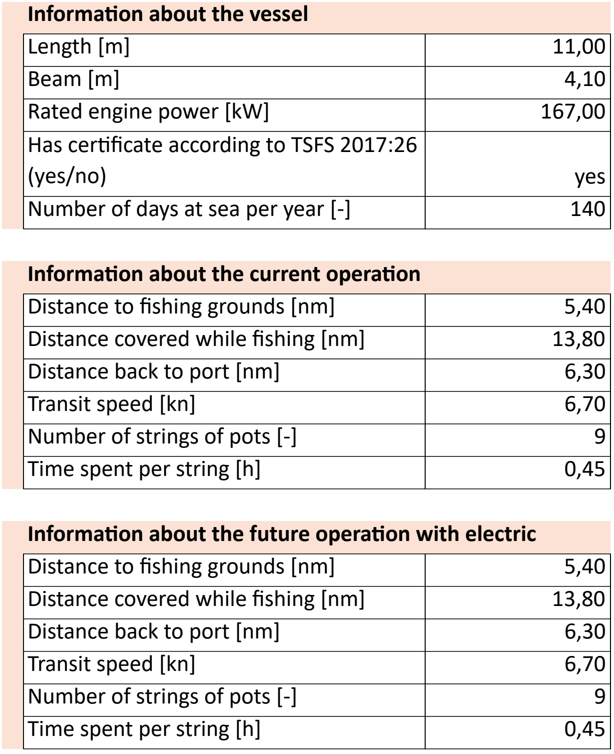
The method does not take change of draft into consideration, but can be compensated for using the power multiplier. It also does not automatically consider heating which for most fishing vessels would be required when removing the heat from a combustion engine, but that can be added as an AC load. Default values are provided for heating by Kemp (2018).

5.3 Examples

In this section the method is exemplified for the two case study vessels Mira and Fredrika using the excel implementation.

5.3.1 Mira

Mira, the Stigfjord 37 which operates as a fishing vessel fishing for Norwegian lobster. A fishing trip is on average 21 nm which takes 7 hours to pick up 7 strings of pots. She also does fishing and archipelago tours for tourists. Mira wants to know if electrification would be possible and follows the method using the excel sheet. The inputs to the method are shown in Figure 5.2, where instead of the average operation the most representative operation is input. The current operation would like to be continued so the same inputs are given for the current and future electric operation.



Information about the vessel	
Length [m]	11,00
Beam [m]	4,10
Rated engine power [kW]	167,00
Has certificate according to TSFS 2017:26 (yes/no)	yes
Number of days at sea per year [-]	140

Information about the current operation	
Distance to fishing grounds [nm]	5,40
Distance covered while fishing [nm]	13,80
Distance back to port [nm]	6,30
Transit speed [kn]	6,70
Number of strings of pots [-]	9
Time spent per string [h]	0,45

Information about the future operation with electric	
Distance to fishing grounds [nm]	5,40
Distance covered while fishing [nm]	13,80
Distance back to port [nm]	6,30
Transit speed [kn]	6,70
Number of strings of pots [-]	9
Time spent per string [h]	0,45

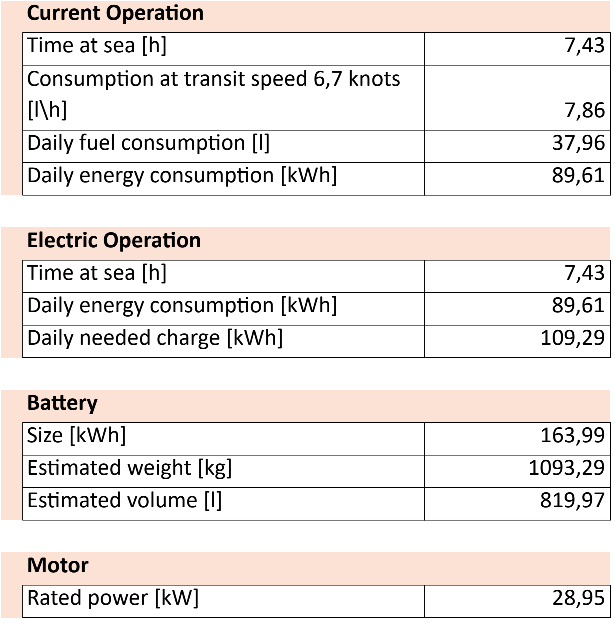
Figure 5.2: Inputs to the method for Mira.

Regulatory feasibility

Mira holds a certificate for passenger vessels. A renewal of the certificate is considered to work intense and therefore not considered feasible from a regulatory point of view according to the method. However, as the technologies spread and are implemented on more vessels the story might be different so it is recommended to contact Transportstyrelsen to check the current status.

Technical feasibility

All of the advanced settings were left as is for Mira as both the DC and hydraulic loads fit well. The technical outputs are calculated automatically according to the VEAT and they are shown in Figure 5.3. We get a total daily energy consumption using VEAT Mira gets 89.6 kWh, which corresponds to a battery size of 164 kWh. The size and weight of the batteries can be accommodated in Mira as the weight ends up very similar to the current driveline. The operational profile can also remain the same with this option. For charging, a 3-phase household socket would be enough and is available at the location. The electrification is therefore feasible from a technical perspective.



Current Operation	
Time at sea [h]	7,43
Consumption at transit speed 6,7 knots [l\h]	7,86
Daily fuel consumption [l]	37,96
Daily energy consumption [kWh]	89,61

Electric Operation	
Time at sea [h]	7,43
Daily energy consumption [kWh]	89,61
Daily needed charge [kWh]	109,29

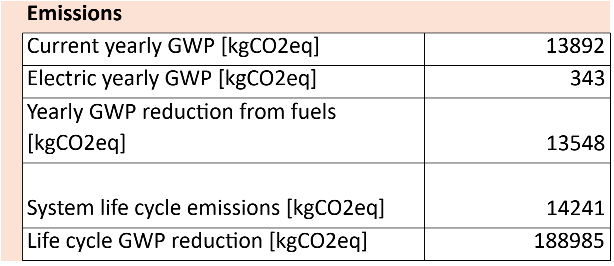
Battery	
Size [kWh]	163,99
Estimated weight [kg]	1093,29
Estimated volume [l]	819,97

Motor	
Rated power [kW]	28,95

Figure 5.3: Outputs of the technical feasibility section of the method for Mira.

Environmental feasibility

The environmental outputs from the excel sheet is shown in Figure 5.4. We see that the emissions from changing to an electric driveline would be compensated for in just over one year and that the life cycle emission reduction is around 190 tons of CO2eq. It is for the reasons above considered environmentally feasible.

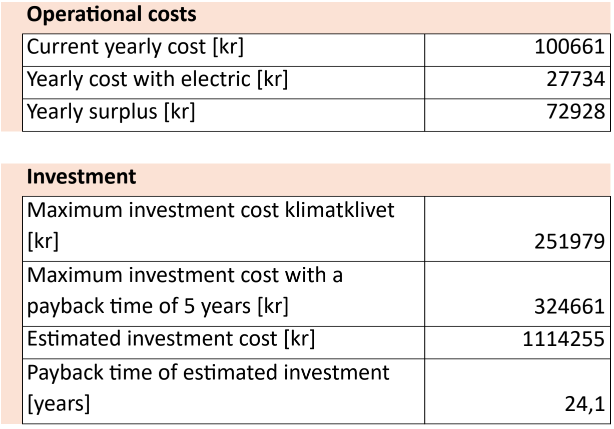


Emissions	
Current yearly GWP [kgCO2eq]	13892
Electric yearly GWP [kgCO2eq]	343
Yearly GWP reduction from fuels [kgCO2eq]	13548
System life cycle emissions [kgCO2eq]	14241
Life cycle GWP reduction [kgCO2eq]	188985

Figure 5.4: Outputs of the environmental feasibility section of the method for Mira.

Economic feasibility

The outputs from the economic analysis of the excel sheet is shown in Figure 5.5. The difference in yearly operational costs is calculated to be 73 000 SEK in favour of the electric driveline. In order for it to have a discounted payback period of less than 5 years with and discount rate of 4 % the maximum investment cost would be 325 000 SEK. At that price point there is no available electric drivelines with a capacity of 164 kWh as illustrated by the estimated investment cost of 1 115 000 SEK. We also note that the maximum investment cost to consider *Klimatklivet* is lower meaning that the investment becomes profitable before the environmental performance is good enough so *Klimatklivet* is not an option. Therefore, the conversion is not feasible from an economic perspective.



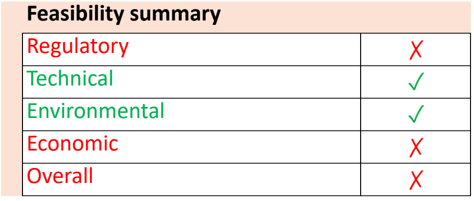
Operational costs	
Current yearly cost [kr]	100661
Yearly cost with electric [kr]	27734
Yearly surplus [kr]	72928

Investment	
Maximum investment cost klimatklivet [kr]	251979
Maximum investment cost with a payback time of 5 years [kr]	324661
Estimated investment cost [kr]	1114255
Payback time of estimated investment [years]	24,1

Figure 5.5: Outputs of the economic feasibility section of the method for Mira.

Overall feasibility

Out of the four pillars only the technical and environmental aspects were determined to be feasible. So with current prices and regulatory setting the electrification of Mira is not considered feasible. The feasibility summary from the excel sheet is shown in Figure 5.6.

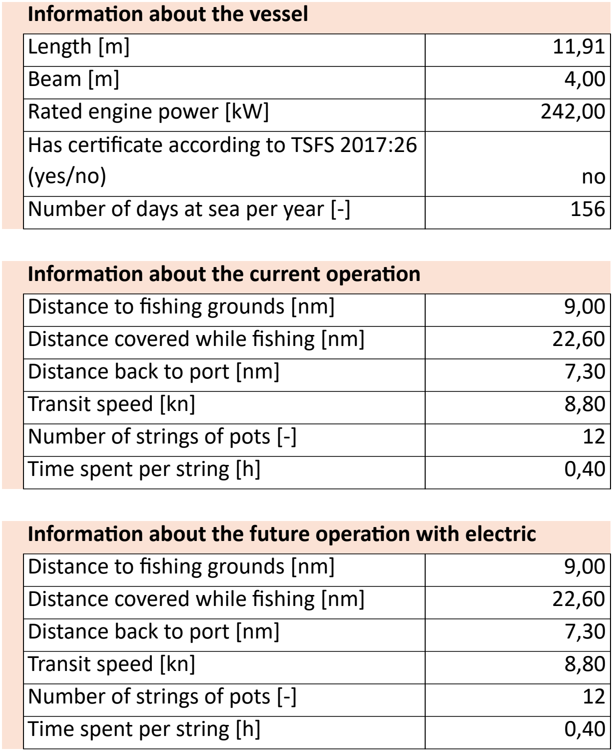


Feasibility summary	
Regulatory	✗
Technical	✓
Environmental	✓
Economic	✗
Overall	✗

Figure 5.6: Resulting overall feasibility from the method for Mira.

5.3.2 Fredrika

Fredrika, the Stigfjord 40 fishes for Norwegian lobster. A typical day is 8 hours long and she covers a distance of 34 nm and picks up 10 strings of pots. Fredrika wants to know if electrification would be possible and follows the method using the excel sheet. The initial inputs are shown in Figure 5.7 where the operation is assumed to remain the same after the conversion. We also figured through analysis that the accuracy of the consumption calculations can be improved by increasing the power by 11 %, so that is input in the advanced settings as a power multiplier of 1.11.



Information about the vessel	
Length [m]	11,91
Beam [m]	4,00
Rated engine power [kW]	242,00
Has certificate according to TSFS 2017:26 (yes/no)	no
Number of days at sea per year [-]	156

Information about the current operation	
Distance to fishing grounds [nm]	9,00
Distance covered while fishing [nm]	22,60
Distance back to port [nm]	7,30
Transit speed [kn]	8,80
Number of strings of pots [-]	12
Time spent per string [h]	0,40

Information about the future operation with electric	
Distance to fishing grounds [nm]	9,00
Distance covered while fishing [nm]	22,60
Distance back to port [nm]	7,30
Transit speed [kn]	8,80
Number of strings of pots [-]	12
Time spent per string [h]	0,40

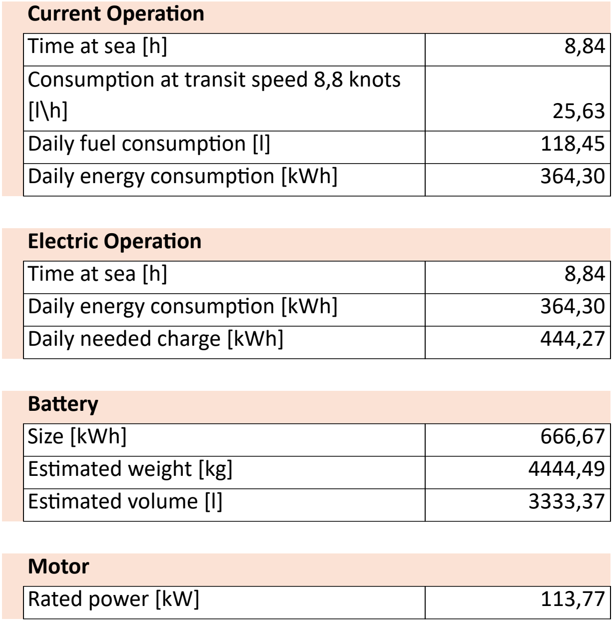
Figure 5.7: Inputs to the method for Fredrika.

Regulatory feasibility

Fredrika does not hold a certificate issued by Transportstyrelsen and is instead controlled through *egenkontroll*. With a collaboration with Transportstyrelsen, an electric conversion is considered feasible.

Technical feasibility

The outputs from the technical feasibility section is shown in Figure 5.8. Calculating the daily energy consumption using the VEAT, Fredrika gets 364 kWh, which corresponds to a battery size of 667 kWh. The size and volume of the battery both surpass the default thresholds for it to be considered feasible and the thresholds are set reasonable so we do not see a reason to modify them in the advanced settings. The daily needed charge is also larger than the maximum available using a 3-phase socket. For the reasons above it is not considered feasible from a technical perspective with the current operation.



Current Operation	
Time at sea [h]	8,84
Consumption at transit speed 8,8 knots [l\h]	25,63
Daily fuel consumption [l]	118,45
Daily energy consumption [kWh]	364,30

Electric Operation	
Time at sea [h]	8,84
Daily energy consumption [kWh]	364,30
Daily needed charge [kWh]	444,27

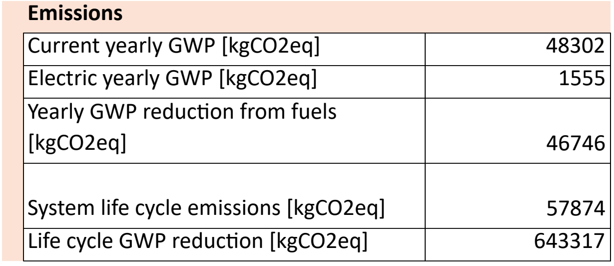
Battery	
Size [kWh]	666,67
Estimated weight [kg]	4444,49
Estimated volume [l]	3333,37

Motor	
Rated power [kW]	113,77

Figure 5.8: Inputs to the method for Fredrika.

Environmental feasibility

In Figure 5.9, the outputs from the environmental section of the excel sheet are shown. We see that just like for Mira the system life cycle emission for going electric are compensated for after a little above one year. We also see that the life time emissions reductions are 640 tons of CO2eq. The set requirement is for the emissions to be reduced by 50 % which is fulfilled as the reduction is close to 90 %.

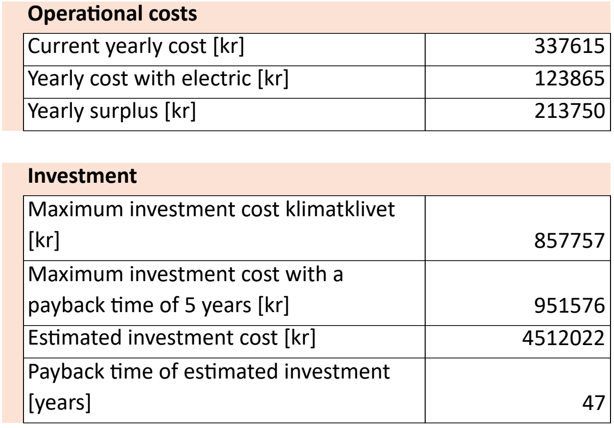


Emissions	
Current yearly GWP [kgCO2eq]	48302
Electric yearly GWP [kgCO2eq]	1555
Yearly GWP reduction from fuels [kgCO2eq]	46746
System life cycle emissions [kgCO2eq]	57874
Life cycle GWP reduction [kgCO2eq]	643317

Figure 5.9: Outputs of the environmental feasibility section of the method for Fredrika.

Economic feasibility

The outputs from the economic feasibility section of the excel sheet is shown in Figure 5.10. The difference in operational expenses is calculated to be 213 000 SEK. That gives a maximum investment cost of 950 000 SEK. With current prices of the commercially available solutions, that can not be considered enough for it to be economically feasible. It is also illustrated by the payback time of 47 years which correspond to several lifetimes of the investment. The situation with *Klimatklivet* is the same as for Mira. The investment would become profitable before the environmental performance is good enough for a grant.



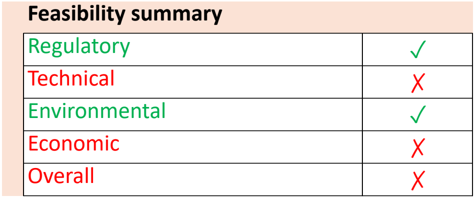
Operational costs	
Current yearly cost [kr]	337615
Yearly cost with electric [kr]	123865
Yearly surplus [kr]	213750

Investment	
Maximum investment cost klimatklivet [kr]	857757
Maximum investment cost with a payback time of 5 years [kr]	951576
Estimated investment cost [kr]	4512022
Payback time of estimated investment [years]	47

Figure 5.10: Outputs of the economic feasibility section of the method for Fredrika.

Overall feasibility

Out of the four pillars, the technical and economic feasibilities fail, which can be seen in Figure 5.11. Both do so due to the large energy consumption resulting in a very large battery. This could be combated by changing the operation which is exemplified below.

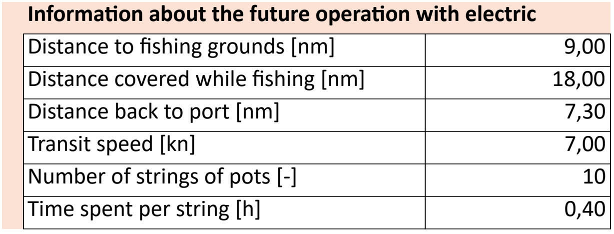


Feasibility summary	
Regulatory	✓
Technical	✗
Environmental	✓
Economic	✗
Overall	✗

Figure 5.11: Resulting overall feasibility from the method for Fredrika.

Operational changes with electric

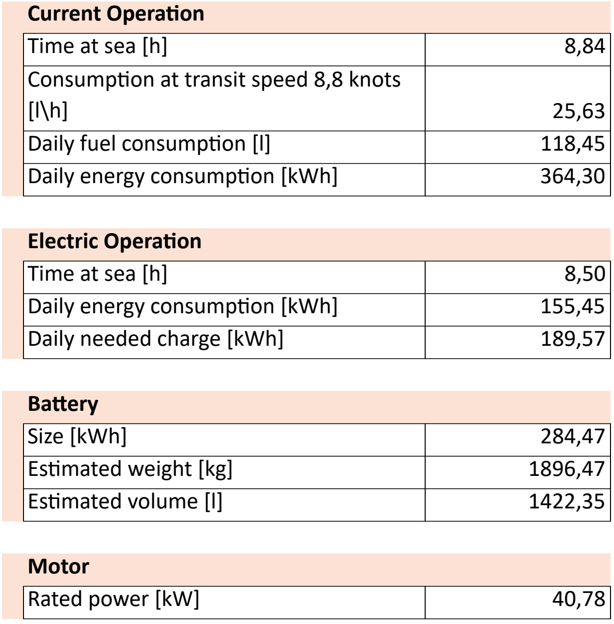
When looking at changing the operation to allow for a smaller battery size, there are a few main parameters to consider. The first one being the transit speed. As we saw in the analysis reducing transit speed is an effective way of reducing the energy consumption. However that increases the time spent at sea. Therefore, it will most likely be in a combination with our second parameter, the number of strings of pots handled. The inputs for the alternative operation can be seen in Figure 5.12. We note that the number of strings is reduced from 12 to 10, the transit speed is reduced from 8.8 to 7 knots, and the distance covered while fishing is lower to compensate for two less strings of pots.



Information about the future operation with electric	
Distance to fishing grounds [nm]	9,00
Distance covered while fishing [nm]	18,00
Distance back to port [nm]	7,30
Transit speed [kn]	7,00
Number of strings of pots [-]	10
Time spent per string [h]	0,40

Figure 5.12: Alternative operational inputs for Fredrika.

The combinations of operational changes results in a significantly reduced battery size of 284 kWh, which can be seen in Figure 5.13 where the technical outputs of the excel sheet are shown. Also note that the time at sea is less with the alternative operation. Remember, that the number of strings that can be handled are reduced which limits the operation compared to the current one. However, on average 10 strings are handled per day by Fredrika so if all days were the same the operational parameters can be optimized in such a way that the battery size is reduced significantly. This illustrates the issue of overdimensioning quite well. In traditional drivelines with diesel, carrying more fuel than necessary is not a big issue. However, not fully utilizing the battery to its full capabilities most days is very expensive.



Current Operation	
Time at sea [h]	8,84
Consumption at transit speed 8,8 knots [l\h]	25,63
Daily fuel consumption [l]	118,45
Daily energy consumption [kWh]	364,30

Electric Operation	
Time at sea [h]	8,50
Daily energy consumption [kWh]	155,45
Daily needed charge [kWh]	189,57

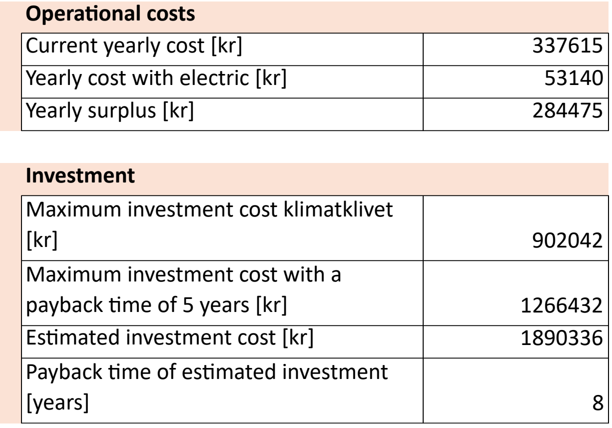
Battery	
Size [kWh]	284,47
Estimated weight [kg]	1896,47
Estimated volume [l]	1422,35

Motor	
Rated power [kW]	40,78

Figure 5.13: Outputs of the technical feasibility of the method for the alternative operation of Fredrika.

Looking at the economic implications, shown by the economic outputs of the excel sheet in Figure 5.14, we see that it is still not economically feasible. Due to the high estimated investment cost, which is greater than both the maximum investment based on 5 years of payback time and the maximum considering the environmental performance with *Klimatklivet*. However, the payback time is now significantly reduced from 49 to 8 years, which is just above half the lifetime of the investment.

So, still not low enough to be considered feasible for the general fisherman, but considering other benefits or converting to avoid expensive engine repairs, is financially viable.

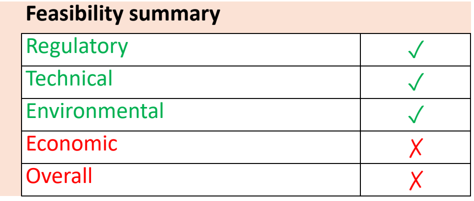


Operational costs	
Current yearly cost [kr]	337615
Yearly cost with electric [kr]	53140
Yearly surplus [kr]	284475

Investment	
Maximum investment cost klimatklivet [kr]	902042
Maximum investment cost with a payback time of 5 years [kr]	1266432
Estimated investment cost [kr]	1890336
Payback time of estimated investment [years]	8

Figure 5.14: Outputs of the economic feasibility of the method for the alternative operation of Fredrika.

The operational changes made it feasible from a technical perspective if the operational limitations are acceptable. That leaves the economic feasibility to be the limiting aspect for the overall feasibility as shown in Figure 5.15.



Feasibility summary	
Regulatory	✓
Technical	✓
Environmental	✓
Economic	✗
Overall	✗

Figure 5.15: Resulting overall feasibility from the method for the alternative operation of Fredrika.

5.4 Discussion

Throughout the development of the method, the trade off between simplicity and accuracy have been a constant consideration. Compared to the analysis done for Mira and Fredrika, our proposed method is simpler. That is by design since it is aimed at any owner of a fishing vessel for which documentation regarding the vessel, and data collection possibilities are limited. That is in line with what was also concluded by Kemp (2018). The main simplification which simplifies the method significantly is that it does not validate or fit the calculated fuel consumption with any measurements. Instead, the user is simply encouraged to compare the calculations of daily consumption or consumption at the transit speed.

Another aspect that was debated throughout the formulation of the method was the inclusion of the environmental feasibility. Today, the emissions from fishing vessels have no financial or operational implications. However, it was decided to keep it because of the political direction of reducing climate and environmental impact that seems to be growing. For example, if limitations on emissions were to be introduced in national parks or fishing vessels included in the EU Emissions Trading System (EU ETS), then the case for electrification would be much stronger.

The second reason for the inclusion of environmental feasibility is *Klimatklivet*. Which has the purpose of accelerating the green transition by providing funding. They stated that they see a potential for supporting the shipping sector and would like to see more applications (Naturvårdsverket, 2024a). However, we found that the chances of electrifying small fishing vessels with support from *Klimatklivet* to be very slim. That is mainly because of the balance between the environmental performance and the profitability of the investment. We found the investment to become profitable before the environmental performance was good enough.

Looking at the technical and economic aspect of feasibility of electrification, we would like to point out the dangers and possibilities with regards to overdimensioning the battery. In principle, the less operational variations the better because then the battery size can be kept down and optimized. For Fredrika, we found that to accommodate the current variations in operation a battery pack of 604 kWh but the same number of pots can be handled with a battery of 285 kWh according to the method. That is, if the operation would look the same every day. So it is a compromise between tailoring the system to be the most efficient technically and economically, and allowing for flexible operations.

The method was intended to be general enough to fit most small fishing vessels. However, throughout the project some assumptions and simplifications were made that limit the applicability of the method. That is primarily because of only having access and knowledge about the operation of two vessels that both use the same method of fishing. However, as seen in subsection 2.1.3, a clear majority of Swedish fishing vessels are shorter than 12 metres and fish using passive equipment like assumed in our method. The inclusion of other fishing kinds like trawling could be made by making additions to the operational profile and energy consumption model. Another big assumption which impacts most parts is that the vessel is Swedish. That impacts which regulations apply since it varies between countries. Moreover, the electricity mix for the environmental calculations is fixed in the method provided, which would lead to incorrect emission calculations in other countries.

6

Conclusion

The aim of the thesis was to develop a simple method for evaluating feasibility of electrifying small fishing vessels. The aim was also for it to be based on four criteria, regulatory, technical, environmental, and economic feasibility. The resulting method of the thesis fulfills all the set out objectives, but its the applicability that had to be slightly narrowed to keep the method simple.

From our work we can conclude that electrification will play an important part in the transition from traditional fuels to aid the green transition. The emission reduction when going electric has been clearly established and with the right operational profile, electrification can be a great fit. However, there are some issues with electrifying small fishing vessels. First, the business case is currently weak because of the high investment cost which is a big gatekeeper for small fishing vessels run by small companies. Secondly, the regulatory implications are not clear. The rules are functional and technology independent which in theory opens the path for electrification. However, as there have been no electrification project of small fishing vessels in Sweden yet, there is no standard procedure.

Existing literature mainly looked at one or two aspects of the feasibility of electrifying small fishing vessels. What we add with this thesis, is a complete method which takes all aspects of the feasibility into consideration and makes it available and accessible to anyone interested in electrification of small fishing vessels. However, that means that the method is not detailed enough to act as guidance or how to go about the conversions. This is left for the owner or future projects. Instead, it can contribute to identify key parameters and thresholds that have to be met for electrification to be feasible.

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A

A method for determining feasibility of electrification of small fishing vessels

Our method stands on four pillars, regulatory, technical, environmental, and economic feasibility. A schematic overview of the method is shown in Figure A.1. The main principle of the method is that all four pillars must be feasible under the same operational assumptions for the electrification to be considered feasible. The method is implemented as an excel document so that any interested stakeholder can evaluate the feasibility of electrification of their fishing vessel of interest.

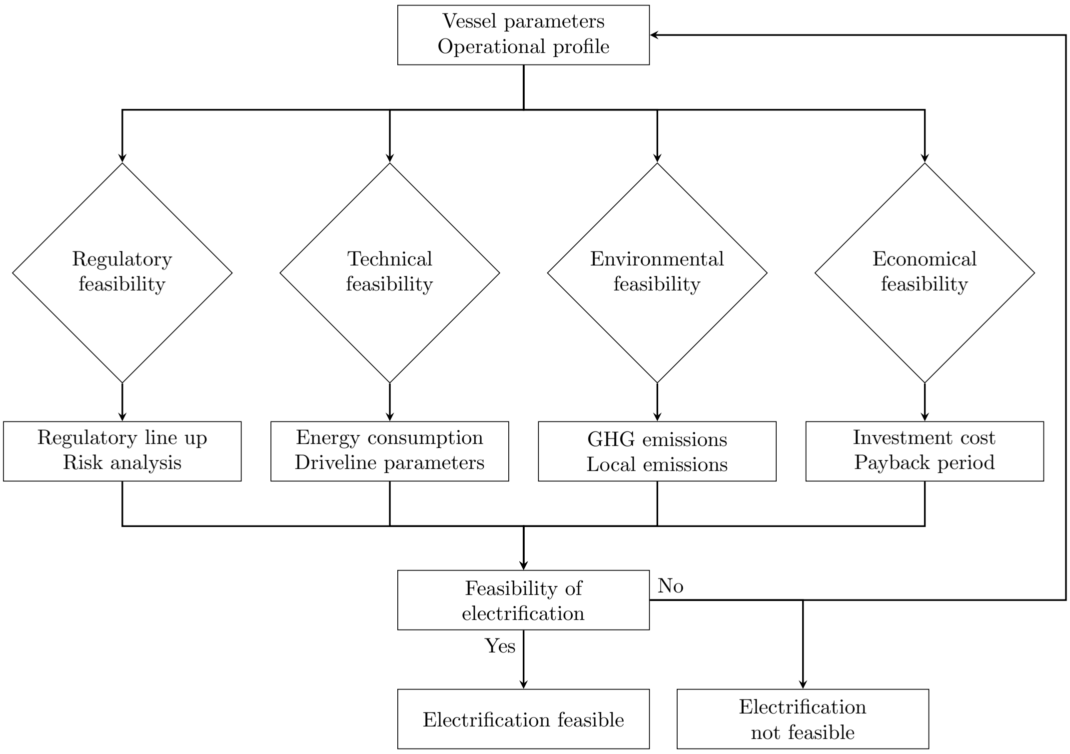
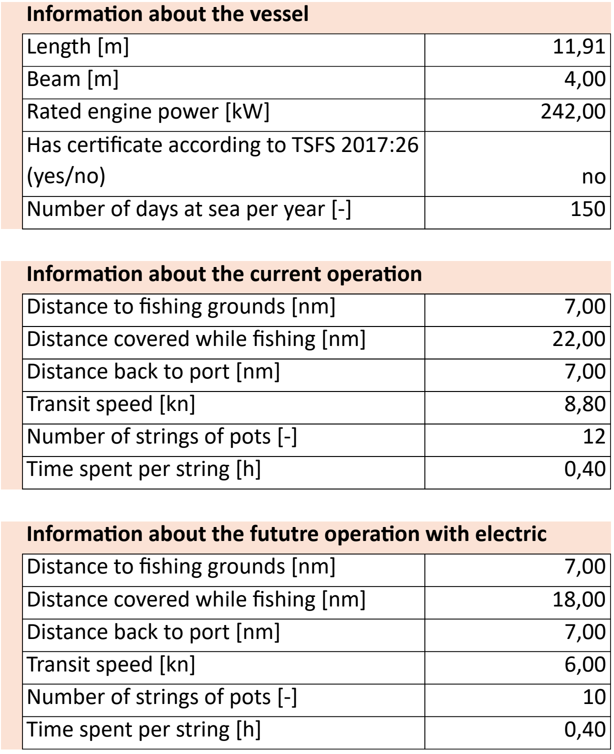


Figure A.1: Overview of our suggested method for evaluating feasibility of electrification of small fishing vessels.

Below, the main inputs to the method are showcased. Furthermore, the main considerations and recommended steps are described for each pillar, and how it has been implemented in the excel version. It is intended to be performed by any owner of a small fishing vessel interested in an indication of the feasibility of electrification.

A.1 Inputs to the method

The inputs are split into two main groups, information about the vessels, its current, and future electric propulsion, as well as advanced settings for fine tuning the method. Figure A.2 shows the first group with the information together with some example values. Figure A.3 shows the advanced settings available and their default values. How the can be changed and why one should want to is explained in the explainations of each pillar below.

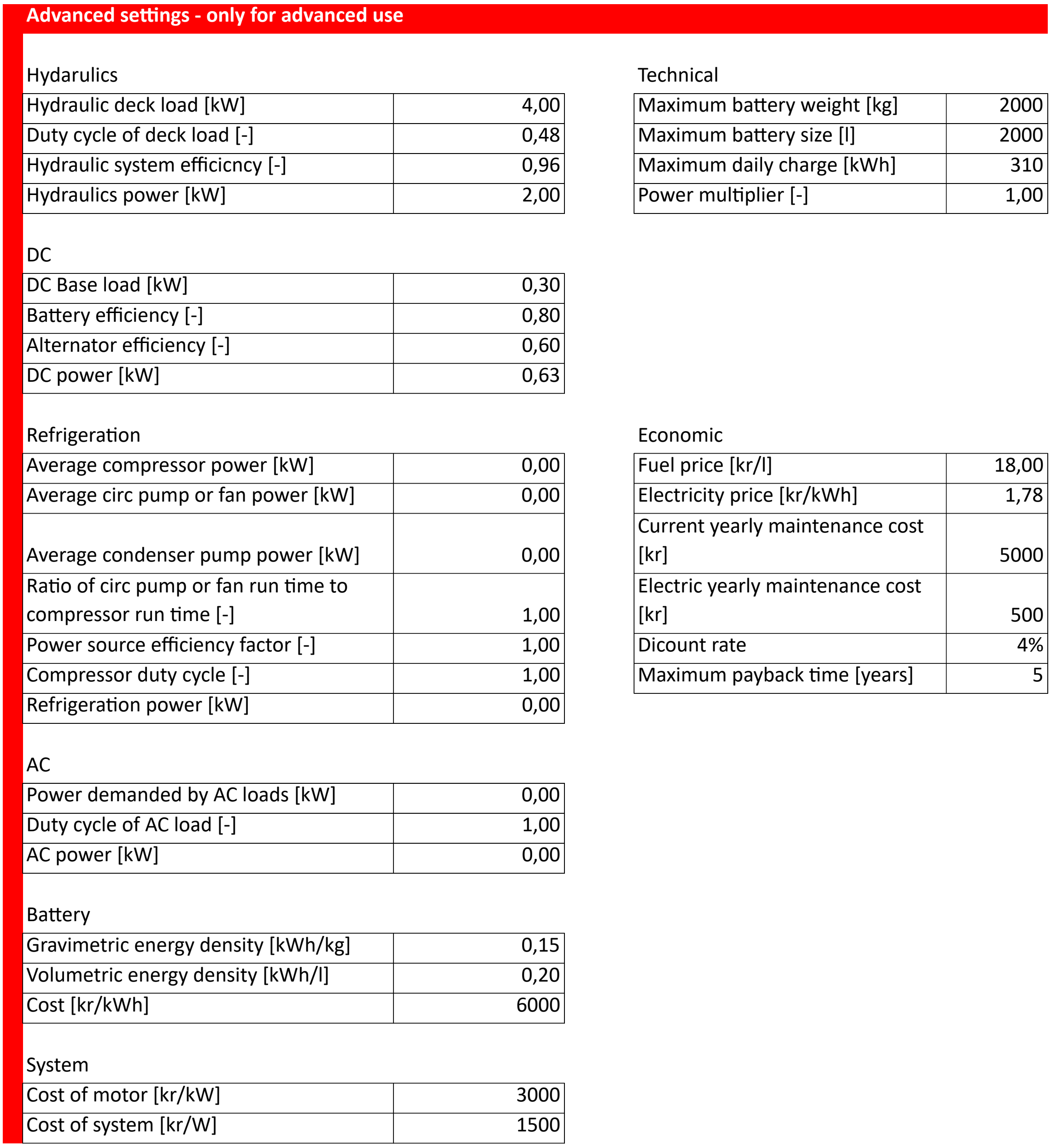


Information about the vessel	
Length [m]	11,91
Beam [m]	4,00
Rated engine power [kW]	242,00
Has certificate according to TSFS 2017:26 (yes/no)	no
Number of days at sea per year [-]	150

Information about the current operation	
Distance to fishing grounds [nm]	7,00
Distance covered while fishing [nm]	22,00
Distance back to port [nm]	7,00
Transit speed [kn]	8,80
Number of strings of pots [-]	12
Time spent per string [h]	0,40

Information about the fututre operation with electric	
Distance to fishing grounds [nm]	7,00
Distance covered while fishing [nm]	18,00
Distance back to port [nm]	7,00
Transit speed [kn]	6,00
Number of strings of pots [-]	10
Time spent per string [h]	0,40

Figure A.2: Input section of the method excel sheet with some example values.



Advanced settings - only for advanced use

Hydarulics

Hydraulic deck load [kW]	4,00
Duty cycle of deck load [-]	0,48
Hydraulic system efficicncy [-]	0,96
Hydraulics power [kW]	2,00

DC

DC Base load [kW]	0,30
Battery efficiency [-]	0,80
Alternator efficiency [-]	0,60
DC power [kW]	0,63

Refrigeration

Average compressor power [kW]	0,00
Average circ pump or fan power [kW]	0,00
Average condenser pump power [kW]	0,00
Ratio of circ pump or fan run time to compressor run time [-]	1,00
Power source efficiency factor [-]	1,00
Compressor duty cycle [-]	1,00
Refrigeration power [kW]	0,00

AC

Power demanded by AC loads [kW]	0,00
Duty cycle of AC load [-]	1,00
AC power [kW]	0,00

Battery

Gravimetric energy density [kWh/kg]	0,15
Volumetric energy density [kWh/l]	0,20
Cost [kr/kWh]	6000

System

Cost of motor [kr/kW]	3000
Cost of system [kr/W]	1500

Technical

Maximum battery weight [kg]	2000
Maximum battery size [l]	2000
Maximum daily charge [kWh]	310
Power multiplier [-]	1,00

Economic

Fuel price [kr/l]	18,00
Electricity price [kr/kWh]	1,78
Current yearly maintenance cost [kr]	5000
Electric yearly maintenance cost [kr]	500
Dicount rate	4%
Maximum payback time [years]	5

Figure A.3: Advanced settings for the method and their default values.

A.2 Regulatory feasibility

The regulatory feasibility differs from the other pillars, in the sense that you can not calculate a set parameters and through comparison of those determine the feasibility. Instead, it is highly dependent on the individual case and the work effort put in by the owner. However, there are some principles one can follow to determine the feasibility more simply, which are presented further.

The main input, when looking at the regulatory feasibility of small fishing vessels, is whether it needs a certificate in accordance with TSFS (2017:26) or not. The process of updating and going through with renewing the certificate is at this stage, when the technologies are so new, assumed to be too work intense for it to be feasible. That means that vessels that carry more than 12 passengers or have a length of more than 15 metres should be disregarded according to our method.

For vessels without any certificate, the regulatory path is still not entirely clear cut. It is our recommendation to keep close contact with Transportstyrelsen in order to make sure the solution installed is in accordance to the regulations, as encouraged by the previous electrification projects Blich (2016), Squires (2023), and HM Coastguard (2023). From a regulatory point of view there are now two options, which are both feasible but depending on the effort and financial resources available to the owner. Both are in accordance with Transportstyrelsen (2023) and listed below.

1. Using marine approved and to the greatest extent certified parts for the electric driveline installed by professionals. This option requires the least regulatory investigation work by the owner and the only requirement is to document the new risks and setup plans and mitigating efforts in accordance with TSFS (2017:26). However, this is cost intense and limit the financial feasibility significantly.
2. Using cheaper parts like second hand batteries or automotive parts and parts of the installation being done by the owner. The cheaper but more work intense option as this requires a full risk analysis in accordance with MSC.1/Circ.1455 (IMO International Maritime Organization, 2013), which is a process developed by IMO to allow for alternative technologies by proving equivalent safety levels to current solutions. The full extent of this option has not been researched in the development of this method.

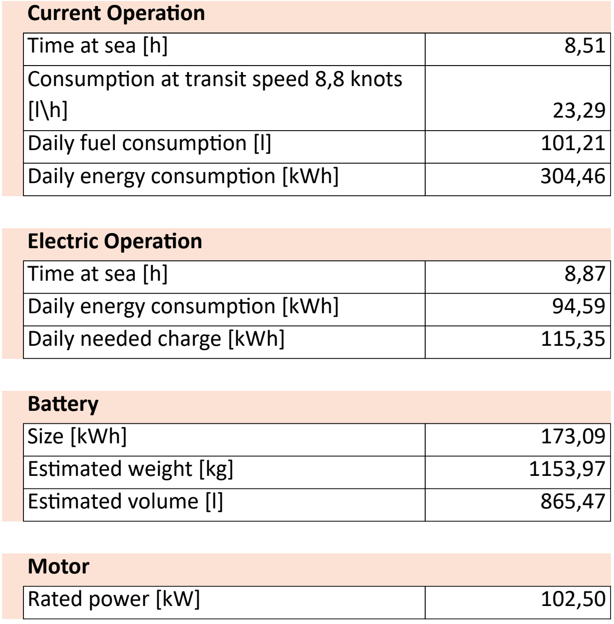
Any deviations from what is stated by the Transportstyrelsen guidelines for electrification (Transportstyrelsen, 2023) needs to be documented well in the form of a regulatory line up in combination with a risk analysis.

In the excel version the feasibility is simple determined by whether the vessel has a certificate or not which is submitted by the user in the section "Information about the vessel".

A.3 Technical feasibility

For evaluating the technical feasibility we use an implementation of the vessel energy analysis toll (VEAT) developed by Kemp (2018). It models 5 different load types, DC-electric, AC-electric, hydraulics, refrigeration, and propulsion. It also has an engine module for calculating the fuel consumption. All models are implemented in the excel sheet, but the refrigeration and AC-electric loads do not have default values and are therefore assumed to be zero, unless they are input in the advanced settings.

The technical feasibility section has a few outputs shown in Figure A.4. First, the time spent at sea, fuel consumption, and energy consumption is provided corresponding to the inputs given for the current operation earlier. Here one has the option to tune the propulsion model. If the consumption is known at the operating speed, the power multiplier in the technical section of the advanced settings can be adjusted until the consumption matches that of the vessel. The same can also be done if the daily consumption is known. However, that is less reliable since it also depends on the operational parameters. The second part of the output shows the time, delivered energy consumption, and the daily needed charge accounting for efficiencies, corresponding to the operation defined in the future operation with electric section of the inputs.



Current Operation

Time at sea [h]	8,51
Consumption at transit speed 8,8 knots [l\h]	23,29
Daily fuel consumption [l]	101,21
Daily energy consumption [kWh]	304,46

Electric Operation

Time at sea [h]	8,87
Daily energy consumption [kWh]	94,59
Daily needed charge [kWh]	115,35

Battery

Size [kWh]	173,09
Estimated weight [kg]	1153,97
Estimated volume [l]	865,47

Motor

Rated power [kW]	102,50

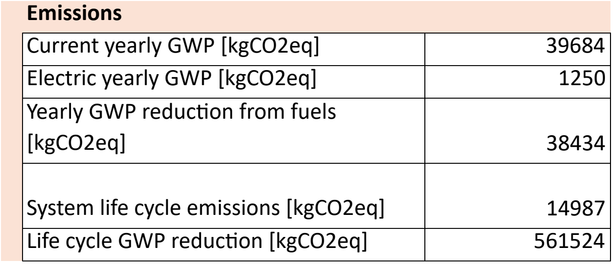
Figure A.4: Outputs of the technical feasibility section.

To evaluate the technical feasibility the daily needed charge, estimated battery weight, and estimated battery volume are compared against set thresholds in the advanced settings. The all need to be below the set threshold for electrification to be feasible from a technical perspective.

A.4 Environmental feasibility

The environmental feasibility is obtained by first estimating the global warming potential (GWP) from the conventional propulsion system. This is done by taking the annual fuel consumption by the vessel and a multiplier of 2.614 is used to estimate the annual greenhouse gas potential. The GWP for the electricity is calculated using the annual energy consumption and a multiplier of 0.027 which is the kgCO2 equivalent of production of 1 kWh of electricity in Sweden. Finally, the system GWP is estimated by using the rated motor power and the battery capacity installed on the vessel. While the multiplier varies depending on the type of chemistry used for the battery and power density of the motor, it is taken to be 86.036 for the motor and 9.07 for the motor.

Figure A.5 shows the outputs of the environmental assessment. The set requirement for the electric propulsion to be environmentally feasible, is that the total life emission reduction is greater than 50 %. The final life cycle GWP reduction is calculated by taking the difference between the emissions from combustion of the fuel and the GWP from the entire electric propulsion system.



Emissions

Current yearly GWP [kgCO2eq]	39684
Electric yearly GWP [kgCO2eq]	1250
Yearly GWP reduction from fuels [kgCO2eq]	38434
System life cycle emissions [kgCO2eq]	14987
Life cycle GWP reduction [kgCO2eq]	561524

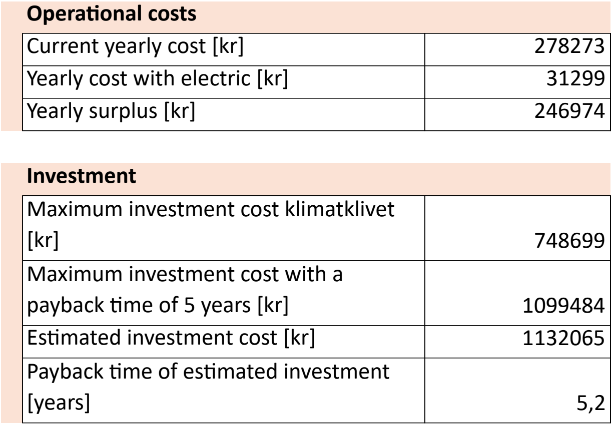
Figure A.5: Outputs of the environmental feasibility section.

A.5 Economic feasibility

The economic feasibility bases its inputs on the calculations from the technical part and a number of assumptions in the advanced settings. The settings include fuel and electricity price, maintenance costs, discount rate, and the maximum acceptable discounted payback period.

The economic conditions of the owner might differ greatly, as well as the prices of fuel and electricity. Therefore, it is recommended to set the current available prices in the advanced settings as well as the discounted payback period acceptable to the owner.

Figure A.6 shows the outputs of the economic section. These include the operational costs and the investments costs calculated from the estimated battery size, but also the maximum that is acceptable with the set payback time or by *Klimatklivet*. The default maximum payback time and discount rate are chosen to align with *Klimatklivet* at 5 years and 4 % respectively. The principle behind evaluating the economic feasibility is that it is feasible if the system can be purchased for less than the maximum investment costs calculated.



Operational costs

Current yearly cost [kr]	278273
Yearly cost with electric [kr]	31299
Yearly surplus [kr]	246974

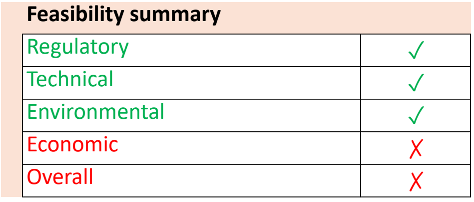
Investment

Maximum investment cost klimatklivet [kr]	748699
Maximum investment cost with a payback time of 5 years [kr]	1099484
Estimated investment cost [kr]	1132065
Payback time of estimated investment [years]	5,2

Figure A.6: Outputs of the economic feasibility section.

A.6 Summation

Electrification is considered feasible only if all four pillars are feasible under the same assumptions and operational profile. However, if any of the pillars fail the whole feasibility fails. Therefore, it might require some iteration between the different pillars to find an operation that works with electrification. The regulatory feasibility is the hardest to impact as either you have a certificate or not, but for all cases it is recommended to contact Transportstyrelsen for a discussion about the specific vessel. Regarding the environmental feasibility it does not strictly limit the feasibility of the electrification project as it has no financial or operational implications. However it is still included in the method, why is explained in section 5.4. The technical and economic feasibility might require some more effort with regards to input variables, but also for the owner to determine what operational profile and economic risks are acceptable. In Figure A.7 the feasibility summary from the excel sheet is shown. There one can see that all pillars need to be green in order for electrification to be feasible for the vessel.



Feasibility summary

Regulatory	✓
Technical	✓
Environmental	✓
Economic	✗
Overall	✗

Figure A.7: Summary of the feasibilities.

B

VEAT - Vessel Energy Analysis Tool

The Vessel Energy Analysis Tool (VEAT) was developed by Kemp (2018) so that the fuel consumption of the Alaskan fishing vessels could be analyzed more simply. It contains models for estimating energy consumption from five different load models. The loads considered are propulsion, refrigeration, hydraulics, AC-electric, and DC-electric. It also contains an engine model and a monetary model. Below, the main features of the different models used in this are presented. Note that the models are changed to the metric unit system compared to the imperial used by Kemp.

B.1 Propulsion

To predict propulsion loads, a cubic relationship between speed and shaft power is used up to 3 knots and above an exponential relation is used. The power is expressed as

$$P = \begin{cases} 0.0214L\sqrt{B}e^{0.57s} & \text{for } s \geq 3\,\text{kn}, \\ \left(\frac{s}{3}\right)^3 0.0214L\sqrt{B}e^{0.57\cdot 3} & \text{for } s < 3\,\text{kn}, \end{cases} \tag{B.1}$$

where s is the speed in knots and L, B are the length and beam of the ship in metres. Figure B.1 shows the delivered propulsion power as a function of speed as in Equation B.1 for a vessel with a length of 12.0 m and a beam of 4.0 m.

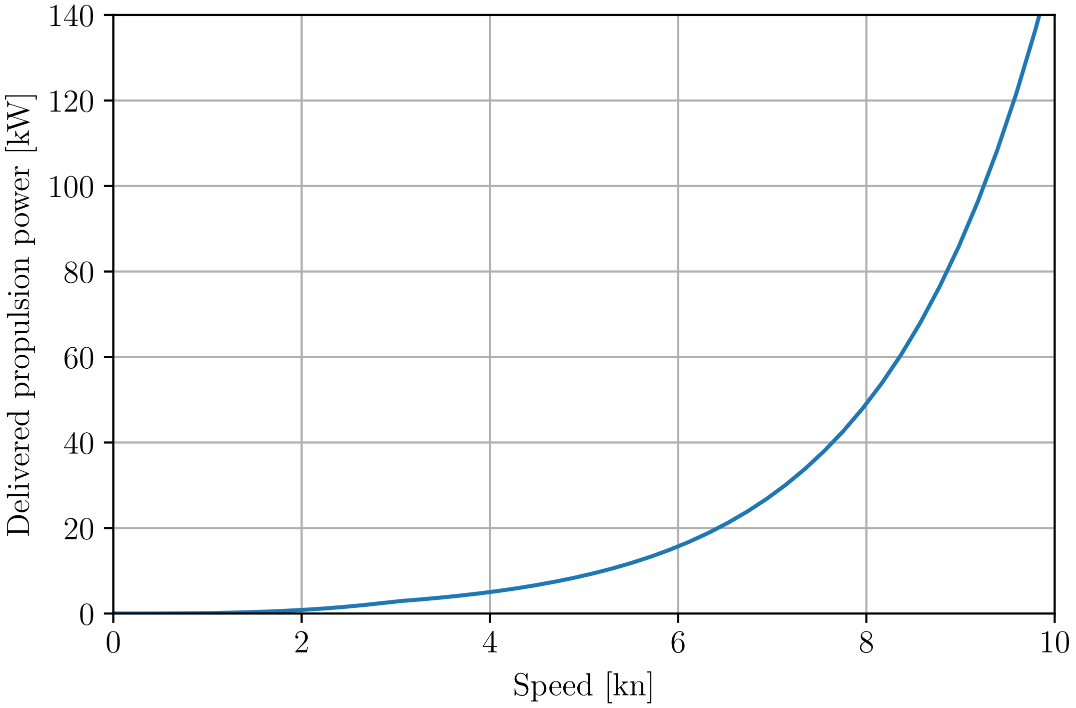


Figure B.1: Delivered propulsion power as a function of speed according to Equation B.1 for a vessel with a length of 12.0 m and a beam of 4.0 m.

B.2 Refrigeration

Energy consumed by refrigeration is calculated as

$$E = h f_{comp}(\bar{P}_{circ} f_{circ} + \bar{P}_{comp} + \bar{P}_{cond})/\eta_{ref}, \tag{B.2}$$

with variables defined in Table B.1. For the regrigeration, there are no default values. Instead, they have to be provided by the user.

Table B.1: Variables and default values of the refrigeration model.

Variable	Description	Units
$\bar{P}_{comp}$	Average compressor power	kW
$\bar{P}_{circ}$	Average circ pump or fan power	kW
$\bar{P}_{cond}$	Average condenser pump power	kW
f_{circ}	Ratio of circ pump or fan run time to compressor run time	
η_{ref}	Power source (hydraulic, electric or direct drive) efficiency factor	-
f_{comp}	Compressor duty cycle	-
E	Energy consumed for refrigeration	kWh

B.3 Hydraulic

Hydraulic energy consumption is calculated as

$$E = \rho P_{deck} h_{fish} / \eta_{hyd}, \tag{B.3}$$

with variables and their default values defined in Table B.2.

Table B.2: Variables and default values of the hydraulics model.

Variable	Description	Units	Default value
P_{deck}	Hydraulic deck load power	kW	4.0
ρ	Duty cycle of the deck load	-	0.48
h_{fish}	Time in fishing operating mode	hrs	-
η_{hyd}	Hydraulic system efficiency	-	0.96

B.4 AC-electric

AC-electric energy consumption is calculated as

$$E = \sum_{l \in AC} P_l \rho_l h, \tag{B.4}$$

with variables defined in Table B.3. There are no default values for the AC-electric model.

Table B.3: Variables and default values of the AC-electricity model.

Variable	Description	Units
AC	The set of all AC loads	-
l	Index of a specific AC load	-
P	Power demanded by an AC load when it is on	kW
ρ	Duty cycle of an AC load	-
h	Time in a particular operating and propulsion mode	hrs

B.5 DC-electric

DC-electric energy consumption is calculated as

$$E = \frac{P_{DC} h}{\eta_{batt} \eta_{alt}}, \tag{B.5}$$

with variables and their default values defined in Table B.4.

Table B.4: Variables and default values of the DC-electricity model.

Variable	Description	Units	Default value
P_{DC}	DC base load	kW	0.3
h	Time in operation	hrs	-
η_{batt}	Battery efficiency	-	0.8
η_{alt}	Alternator efficiency	-	0.6

B.6 Engine

For the engine model a linear relationship is assumed between the delivered power and fuel consumption. This gives the fuel consumption as

$$F = \alpha + \beta P, \tag{B.6}$$

with variables defined in Table B.5.

Table B.5: Variables of the engine model.

Variable	Description	Units
F	Fuel consumption	l/hr
P	Delivered power	kW
α	Idle fuel consumption	l/hr
β	Brake Specific Fuel Consumption (BSFC)	l/hr-kW

The coefficients α and β are calculated from the rated engine power R as

$$\alpha = c_0 + c_1 R, \tag{B.7}$$

and

$$\beta = c_2 + c_3 R, \tag{B.8}$$

using the engine coefficients in Table B.6.

Table B.6: Engine module coefficients

c_0 l/hr	c_1 l/hr-kW	c_2 l/hr-kW	c_3 l/hr-hp-kW
0.984	0.0041	0.303	$-1.066 \cdot 10^{-4}$

For Fredrika

$$\alpha = 0.984 + 0.0041 \cdot 242 = 1.9762\,\mathrm{l/hr} \tag{B.9}$$
$$\beta = 0.303 - 1.066 \cdot 10^{-4} \cdot 242 = 0.2772\,\mathrm{l/hr-kW} \tag{B.10}$$

For Mira

$$\alpha = 0.984 + 0.0041 \cdot 167 = 1.6687\,\mathrm{l/hr} \tag{B.11}$$
$$\beta = 0.303 - 1.066 \cdot 10^{-4} \cdot 167 = 0.2852\,\mathrm{l/hr-kW} \tag{B.12}$$

C

Regulatory analysis

C.1 TSFS 2017:26

Transportstyrelsen provide an excellent website for the rules in TSFS (2017:26) available at (Transportstyrelsen, 2024). It contains the regulations as well as supplementary information and general recommendations. Below an English summary of the chapters is given together with whether they need to be considered when electrifying fishing vessels and how they could be verified.

Chapter 1. General framework - Gives the general framework and definitions needed for the regulation. It can be considered unchanged during an electrification project.

Chapter 2. Design and use of ships - States main principles to follow for safe operations. Can be considered unchanged.

Chapter 3. Construction and stability - Regulates what must be considered for the vessel regarding strength of the hull, water ingress, and stability. The first two parts can be considered unchanged but the stability part 6-10 § would need to be reconsidered. Because, the centre of gravity and displacement changes with the added weight from batteries. It is most commonly verified using a set of rules like *Nordisk Båtstandard* (Nordisk teknisk arbeidsgruppe, 1990), Eurofins - Work Boat Guidelines (Eurofins, 2021), or regulations from a respected classification society.

Chapter 4. Machinery, propulsion, and manoeuvring - Regulates what must be considered regarding the machinery, where extra care should be given to fire and explosions. It is mentioned in the supplementary information to TSFS (2017:26) that this chapter is expected to be a bit difficult because of the ongoing developments and challenging new technologies, i.e. batteries and alternative fuels. Since, this chapter is traditionally verified using a coherent regulatory framework which there are few of that cover new technologies. However, for a fully electric driveline this chapter could be considered covered if chapters 5 and 6 are covered since the maneuverability stays the same with an electric driveline like we propose, and there is no further machinery on the vessel. Therefore, this chapter could be verified using a risk analysis.

Chapter 5. Electrical equipment and installations - Contains rules regarding power distribution to crucial equipment and how electrical installations should be done. Transportstyrelsen has published guidelines on electrification of ships (Transportstyrelsen, 2023). They mention three paths available for an electrification project in line with TSFS (2017:26), using a coherent regulatory framework, comparative and risk analysis, or empirical data. The most simple path forward is for everything to be done according to regulations by a classification society. However, that comes with a cost and limits the available solutions significantly. The option of using empirical data is deemed to difficult as there is very little experience so far using these systems onboard vessels. Instead, a more likely path is the risk analysis. Here there are two paths one could take. Either all equipment is intended for marine use and up to standard according to the guidelines for electrification (Transportstyrelsen, 2023), which would allow for a more simple risk analysis. If the equipment is not up to the standards or for example cheaper second hand batteries are used a full risk analysis according to MSC.1/Circ.1455 has to be made.

Chapter 6. Fire safety - Regulates the fire protection on board. Just like chapter 5 the most likely path to verify conversion is using equipment intended for marine use according to the electrification guidelines together with a simple risk analysis.

Chapters 7-14. Contains rules about living and work environment, life saving equipment, communication, navigation, transport of cargo, environmental protection, medical care and pharmacy, and availability for passengers with disabilities. All of which can be considered unchanged when electrifying a fishing vessel unless there are other modifications made to the vessel or its equipment.

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