CHALMERS
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Techno-Economic and Environmental Assessment of Electrification Scenarios in Waterborne Public Transport

A Gothenburg Case Study

Master's thesis in Industrial Ecology

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Cover: Photo of one of the ferries crossing the Göta Älv, arriving to Stenpiren in Gothenburg by Mikael Svensson.

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Abstract

The shipping industry currently stands for around 3% of the world's greenhouse gas emissions (GHGs), and is predicted to increase its emissions significantly until 2050 unless mitigation efforts are made. For shorter routes and smaller vessels, electrification has been identified as a promising method of decarbonisation. In this study, a techno-economic and environmental assessment framework was used in order to analyze the cost and environmental effects of electrifying public transport ferries operating on the Göta Älv river in Gothenburg. Four different electrification scenarios were constructed based on information obtained from literature and interviews with relevant stakeholders. For these scenarios, the results suggest that three out of four would have lower costs than the baseline. The lowest cost of ownership was observed when optimizing the on-board battery capacity by deposition charging several times during the day, leading to around 8% lower costs than the baseline. As for the environmental calculations, the results indicate a possible decrease in GHGs of about 77-90% of greenhouse gas emissions in the electrification scenarios compared to the baseline, with zero emissions of NO_x, SO_2 and particulate matter (PM) on a local level compared to present case. The scenarios showing the largest mitigation potential utilized wireless opportunity charging which allows for a significant decrease in on-board battery capacity compared to the baseline, thereby reducing upstream emissions from battery production. Overall, the study shows that there are positive environmental and cost effects of fully electrifying the Göta Älv ferries, which could act as inspiration for decision makers within waterborne public transport.

Keywords: Waterborne Public Transport, Electrification, Electric Ferries, Case Study.

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Andrea Cedillo & Nils Jutblad, Gothenburg, June 2023.

List of Acronyms

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

BB	Big Battery Scenario
BCC	Battery Capacity Change
BS	Baseline Scenario
DoD	Depth of Discharge
EF	Emission Factor
EV	Electric Vehicle
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
MGO	Marine Gas Oil
OB	Optimized Battery Scenario
PM	Particulate Matter
SoC	State of Charge
WF	Wireless: Falling SoC Scenario
WS	Wireless: Steady SoC Scenario

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1
Introduction

It is estimated that the shipping industry contributes around 3% of the world's annual global greenhouse gas emissions (GHG) (SINAY, 2022). These emissions have continued to grow due to limited mitigation efforts, and could without further abatement actions grow between 50% - 250% by 2050 (IMO, 2018). Apart from GHG emissions, combustion of MGO results in the emission of nitrogen oxides (NO_x), sulfur oxides and dioxides (SO_x / SO_2) and particulate matter (PM) (Gössling et al., 2021). These pollutants are detrimental to the environment, causing effects such as acidification and eutrophication of land and water (Naturvårdsverket, n.d.). Emissions of $PM_{2.5}$, PM_{10} and NO_x also have an adverse effect on human health (Künzli et al., 2000; Andersson et al., 2009), and populations living near ports have been found to be exposed to higher levels of these pollutants (Saxe & Larsen, 2004). This is especially relevant in the case of Gothenburg, being a coastal city and having the largest port in Scandinavia.

Given that shipping was not included in the Paris Agreement, The International Maritime Organization (IMO) strove to complement the efforts to reduce global GHG emissions with the adoption of the "Initial IMO Strategy on Reduction of GHG Emissions from Ships" in 2018 (IMO, n.d.). In this strategy, IMO set the objective to reduce total annual GHG emissions by at least 50% by 2050 compared to 2008. However, only international shipping, and not national ships, are contemplated by IMO's regulations, leaving a gap for defining such ships' regulations for energy efficiency and GHG emissions (Trafikanalys, 2022). According to a public government investigation (SOU 2022:15), GHG emissions from domestic commercial shipping in Sweden have increased by about 37% from 1990 to 2020. Around half of these are caused by publicly procured transport, including e.g. public transport ferries. Acknowledging the importance of the topic, the reduction of domestic shipping emissions are included in the new Swedish regulatory climate framework which was adopted in 2017 (SFS 2017:720). One of its goals is that by 2030, the transport sector shall decrease its GHG emissions by 70% compared to 2010 levels. For this cause, Fossilfritt Sverige (2019) identify insufficient access to sustainable fuels, limited technical solutions, and disadvantageous economic factors as some key hindrances for decarbonisation. Their proposed technical measures include further development of ship-specific solutions, and securing access to high-voltage port side electricity for charging electric ferries. Other notable works in a Swedish context are *Koll på vatten* and *Fossilfri kollektivtrafik på vatten*, investigating the way forward for a sustainable shipping sector (Trafikverkat & Vattenbussen, (2015); Jivén et al., 2020). The latter identifies, along with several other studies (Al-falahi et al., 2018; Wang et al., 2021; Perčic et al., 2022), that full electrification is a viable solution for ferries traveling on shorter distances, which leads us to the overarching topic of this study.

1.1 Electrification of ferries

One way of reducing emissions from the shipping industry is via the adoption of battery technology. In 2015, the world's first battery electric car ferry, MV Ampere, was introduced in Norway with several more electric ferries coming in the following years (Ship Technology, 2015). Copenhagen's commuter ferries are another example. These ferries run for 17 hours per day and charge every hour for approximately 6-10 minutes to comply with their schedules (Echandia, n.d.). Overall it is mostly smaller ships which get electrified, but there are exceptions such as the Aurora, operating between Helsingör and Helsingborg, weighing 8 414 tonnes (SHIFT 2 Clean Energy, n.d.).

As for Sweden, the number of electric ferries has started to increase in the last few years. Västtrafik, the company responsible for public transport in the Västra Götaland region, launched its first electrical hybrid ferry in Gothenburg 2019, called Elvy. This was followed by the launch of Eloise in 2022, also a hybrid, and transiting the same route but with a bigger battery capacity. Completely electrified ferries are now also on the way. In the Southern archipelago there is MS Burö, which will be rebuilt to run on electricity and go between the islands Öckerö and Grötö starting in December 2023 (Västtrafik, 2023). On the other side of the country, Stockholm was involved with electrification early, operating the electric ferry E/S Sjövägen already in 2014 (Sjövägen, 2015). Currently, the company Green City Ferries is set to deploy electric ferries in the Stockholm peninsula by 2024 (Sjöfartstidningen, 2022). Furthermore, the Candela P-12, cited as "the world's fastest electric ship", is set to begin test runs in the inner city of Stockholm during the spring of 2023, being the time of writing (Dagens industri, 2022). These types of battery-driven ferries are a promising development due to the environmental and societal benefits that come from using electric propulsion, mainly the almost non-existent CO_2 and particle emissions. (Jiven et al., 2020). Electrification also has the benefit of reducing the demand for other alternative fuels, which may instead be used in cases where electric drive isn't feasible (Trafikanalys, 2022). In Gothenburg, electrification will be crucial if the city is to reach its target of a 90% reduction of GHGs within its geographical area by 2030 compared to 2010, being even more stringent than the national target (City of Gothenburg, 2019). This brings us to the purpose of this study.

1.2 Aim and purpose

The purpose of this thesis was to assess the economic and environmental performance of public transport ferries based on different *electrification scenarios*, which in this study are defined as a combination of the types of ferries used and the chosen charging strategy. For this end, Västtrafik's ferries operating in the Göta Älv are used as the basis for a case study. In this context, the research questions to be answered within this study are:

- What are possible electrification strategies for public transport ferries operating in Göta Älv?
- How do the electrification scenarios convey their associated costs?
- How do the environmental impacts differ between different electrification scenarios?

1.3 Scope of the case study

The scope of the case study is limited to the ferries that cross the Göta Älv under line 286, which are owned by Västtrafik and operated by a company called Styrsöbolaget. This line currently has four ferries (two hybrid-electric and two diesel-electric), of which a maximum of three are used at the same time, depending on demand. In the assessment of the electrification of these ferries, the following demarcations are put in place:

- The fact that the MGO used in the diesel ferries consists of 5-10% hydrogenated vegetable oil (HVO) is dismissed. Instead, the fuel is assumed to be 100% MK1 diesel.
- The electricity price is considered constant, meaning that the cost difference between daytime and nighttime charging is dismissed, as well as price fluctuations throughout the day.
- The pollutants considered are CO_2, NO_x, SO_2 and particulate matter (PM).
- The effect that the weight of the vessels has on their energy use was not accounted for. For example, a decrease in installed battery capacity would likely also decrease the electricity use due to the ship being lighter.
- This thesis does not contemplate the costs or emissions associated end of life stage of the vessels.
- No changes to the current time-table are made in this study.

1.4 Background on charging strategies

An important consideration for deciding the electrification is how the electric ferries should be charged. It is common to make a distinction between two different types of charging methods; *destination charging*, and *opportunity charging* (Thorburn, 2021). Destination charging involves taking the ferry out of traffic into a designated charging spot, often for overnight charging. Opportunity charging on the other hand means that the ferry is charged while it is docking and picking up passengers. An example of this

(a) MF Folgefonn Car-Ferry, Bergen - Photo: Wärtsilä

(b) Frederikstad's Passenger Ferry - Photo: IPT Technology ENRX

Figure 1.1: Wireless Chargers in Norway

is the aforementioned Aurora ferry. When it docks, a robotic arm automatically plugs the charging cable into the boat using (SHIFT 2 Clean Energy, n.d.). Such charging is often referred to as "fast charging". A benefit of using opportunity/fast charging is that it has the ability to decrease the on-board battery capacity, which will in turn reduce the total cost and weight of the vessel (Jivén et al., 2020). A similar effect could also be achieved by deposition charging several times during the day.

The technology used for charging can be broadly divided into cold ironing and wireless charging, as explained below:

Cold ironing / Cable:

Paul et al. (2014) define a cold ironing system as the method of connecting ships to shore power-supply systems during berthing at the port. For a diesel ferry, this on-shore power-supply allows all onboard diesel generators to be switched off during the docking period, reducing emissions. It is also used for charging the batteries in electric ferries and is the most common charging method.

Wireless charging:

Wireless charging, also known as Wireless Power Transfer (WPT), is a charging technology based on magnetic resonance coupling (Ning et al., 2013). It utilizes two coils, where one is connected to an electric current which generates a magnetic field that causes the second coil to resonate. Through this magnetic resonance, power is transferred between the coils. Its application in ferries uses pads, where one is stationary and located in the port, while one is placed on-board the ferry. When the ferry docks and the pads come close to each other, the power transfer starts automatically. Examples of applications can be found in Fredrikstad and Bergen in Norway, as shown in Figure 1.1 (Wärtsilä, n.d.; SF Marina, n.d.). Advantages of wireless charging include reduced maintenance and increased safety, and being able to charge while the vessel is moving (Wärtsilä, 2018; Ahmad et al., 2020).

2
Case Study Description

The current operating scenario for line 286 consists of a journey of approximately 6 minutes between Lindholmen and Stenpiren in both directions. Between these stops, two or three ferries are always running depending on the time of day. During peak hours, from 7 to 10 in the morning and from 1 to 6 in the afternoon, three ferries run simultaneously. Otherwise, only two are running. The current ferry fleet consists of two diesel ferries and two hybrid ferries, which are charged exclusively overnight in the yellow area indicated in Figure 2.1. During the day, they run using electricity for as long as possible and switch to diesel when needed.

Figure 2.1: Image illustrating the route of line 286 between Lindholmen and Stenpiren. At the ends of the red line are the spots where the ferries stop to pick up passengers and where potential opportunity charging station could be built. The yellow area marks where the ferries are situated when they are not operating, which is also where they charge overnight currently. This same position will be assumed for daytime deposition charging in some of the electrification scenarios.

The case study consists of a baseline scenario, based on the current operation as explained above, and four electrification scenarios that explore various future possibilities. All cases consist of different constellations of the following ferry types (see schematic details in Appendix D):

1. **Diesel-Electric Ferry.** Uses only marine gas oil (MGO) for propulsion.
2. **Hybrid-Electric Ferry.** Uses both MGO and on-board batteries.
3. **Electric Ferry.** Uses only on-board batteries for propulsion.

Another defining factor for the cases, apart from ferry types, is the charging strategy. Charging is first and foremost divided into deposition or opportunity charging. Beyond that, charging can be performed during the day, night, or both, and utilize either plug-in or wireless technology.
Figure 2.2 shows a visual summary of the five different scenarios, which will be further explained in the next section. The color scheme of grey for diesel, green for hybrid, and yellow for electric is used consistently throughout the study.

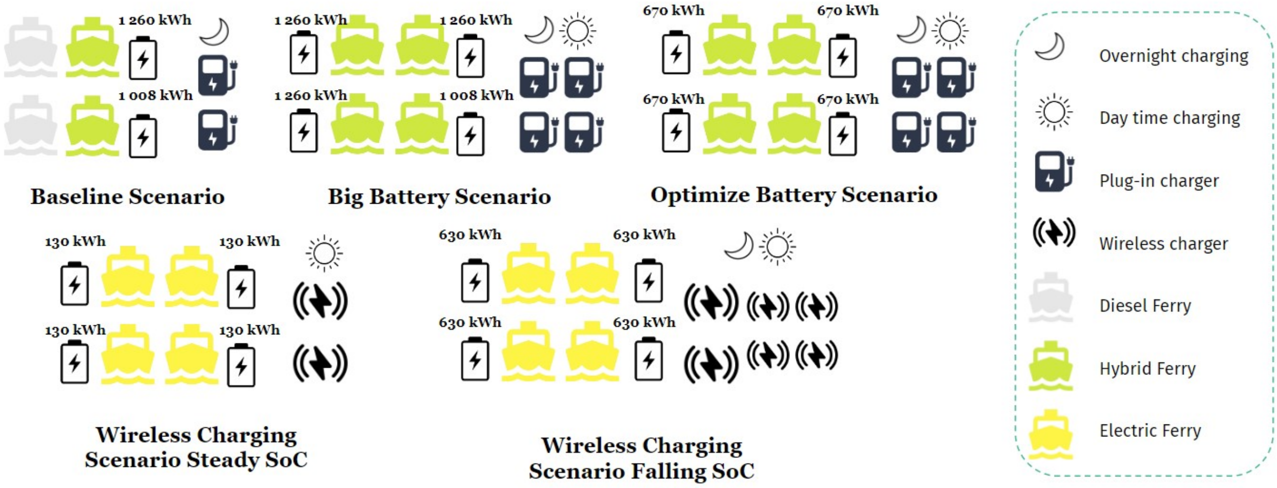


Figure 2.2: Visual summary of the case study scenarios, showing what ferry types they use, when the ferries charge, and how many plug-in or (stationary) wireless chargers are used.

2.1 Scenario Time-frames

This section presents the time-frames for the five scenarios included in the case study. They are represented in diagrams, showing when the ferries are acquired, how long they will operate etc. Deciding on time-frames was complicated due to the fact that the ferries were acquired at different points in time. Instead of opting for a set span of years for each scenario it was decided that for each ferry, costs and emissions should be accounted for from their point of acquisition and 25 years into the future, being their expected lifetime. Retrofits are also seen as points of acquisition at which a ferry's lifetime is "reset" to 25 years. What happens at the end of this lifetime is not considered. Furthermore, only one form of daily operation was evaluated for each scenario, while in practice the operation and scheduling would change over time. To summarize, the time-frames are dependent on these two main rules:

1. Retrofitted ferries have their time of acquisition set at the point of the retrofit.

2. The selected "Operational scenario", representing each scenario's main concept, is the basis for the cost and emission calculations. In the conditions of this time window, operational costs and emissions for each ferry are calculated on a daily basis. These daily values are then thought of as being valid for 25 years, representing the ferries' lifetime.

The method for how each scenario's costs and emissions are calculated is given later in the explanation of the techno-economic and environmental assessment framework (see Section 3.3).

2.1.1 Baseline Scenario

The baseline scenario examines the current operation. There are four ferries that regularly run on the Älvsnabbare line. Three run simultaneously at most, while one is always at quay. Two of them are hybrid ferries (Elvy and Eloise) and two are diesel ferries (Älvfrida and Älveli). The operational scenario spans the years 2022-2040 when all four ferries are available simultaneously.

Scenario's main characteristics:

- Two hybrid ferries fitted with 1 260 kWh and 1 008 kWh battery capacity respectively and two diesel ferries.
- Two 200 kW 3-phase chargers at quay in Lindholmen.
- Only overnight charging.

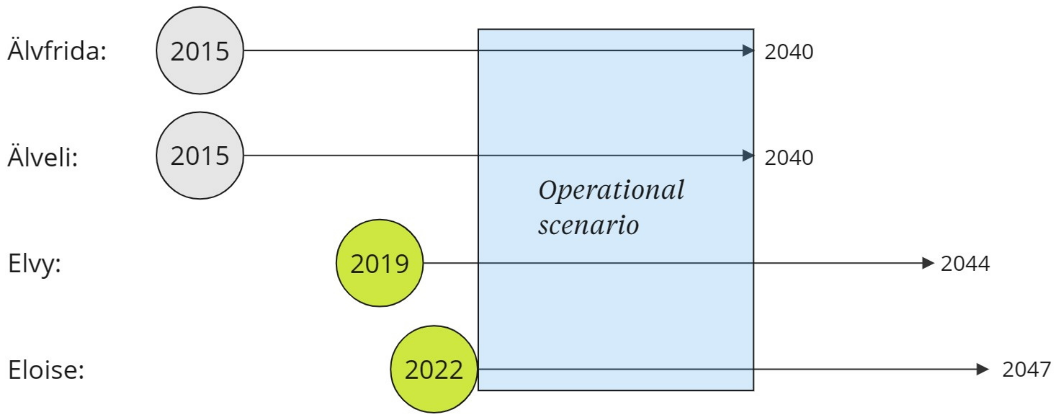


Figure 2.3: The time frame of the Baseline Scenario.
Black arrows: Lifetime of ferry, for which costs are accounted for.
Blue box: Time window during which the simulation takes place.

2.1.2 Big Battery Scenario

This scenario investigates what might happen in the near future in Gothenburg. Älvfrida and Älveli are here assumed to be retrofitted into hybrid ferries, as Västtrafik has shown interest in doing in the near future (Andersson & Rydenskog, 2023). This is arguably better than opting for full electrification since the ferries' diesel engines and other compartments are relatively new. Let us assume that this happens in 2025. The battery capacity of the retrofitted ferries will be assumed to be 1 260 kWh, while Elvy will continue to operate with 1 008 kWh. In total, there will be three ferries with 1 260 kWh capacity, and one with 1 008 kW. The retrofitted ferries are denoted as H1 and H2, and the operational scenario starts after their point of retrofit, spanning the years 2025-2044.

Scenario's main characteristics:

- Four hybrid ferries. Three with 1 260 kWh of battery capacity and one with 1 008 kWh.
- Four 200 kW 3-phase chargers at quay in Lindholmen.
- Deposition charging in intervals + Overnight charging.

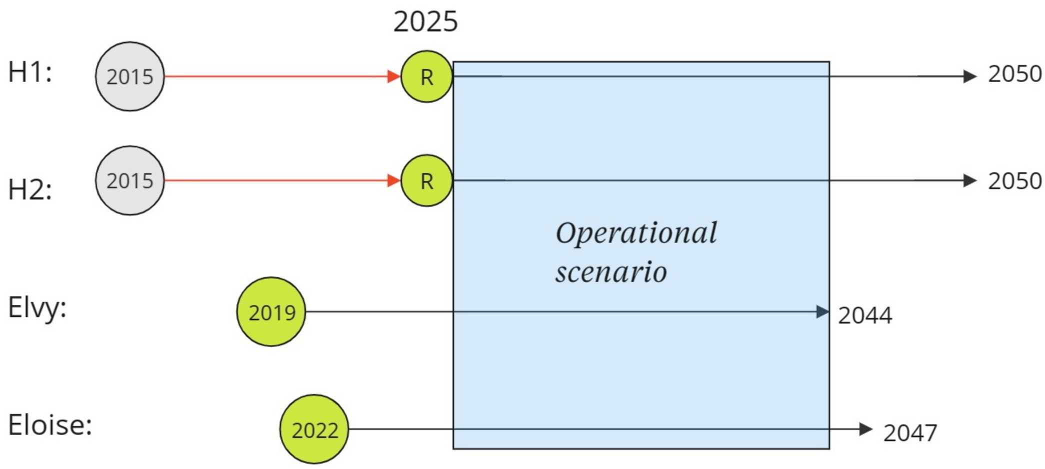


Figure 2.4: The time-frame of the Big Battery Scenario.
R: Time of retrofit.
Red arrows: Time before acquisition.
Black arrows: Lifetime of ferry, for which costs are accounted for.
Blue box: Time window during which the simulation takes place.

2.1.3 Optimize Battery Scenario

In essence, this scenario is similar to the Big Battery (BB) scenario since both consider the implementation of four hybrid ferries in 2025. However, this scenario investigates how much the battery size can be decreased by taking turns to charge several times during the day. The minimum battery capacity which all ferries could have simultaneously was calculated to be 670 kWh (using the Excel tool, see Section B.0.1), and the operational scenario would only start after all ferries acquire this capacity. For the diesel ferries, this could happen when they are retrofitted in 2025. The old hybrid ferries, on the other hand, would have to utilize their point of battery replacement for inputting a smaller capacity. With an assumed battery life of 10 years, Eloise would have its batteries replaced in 2032. From this point onward, all ferries could have 670 kWh capacity, and the operational scenario would span the years 2032-2044.

Scenario's main characteristics:
- Four hybrid ferries with 670 kWh battery capacity.
- Four 200 kW 3-phase chargers at quay in Lindholmen.
- Deposition charging in intervals + Overnight charging.

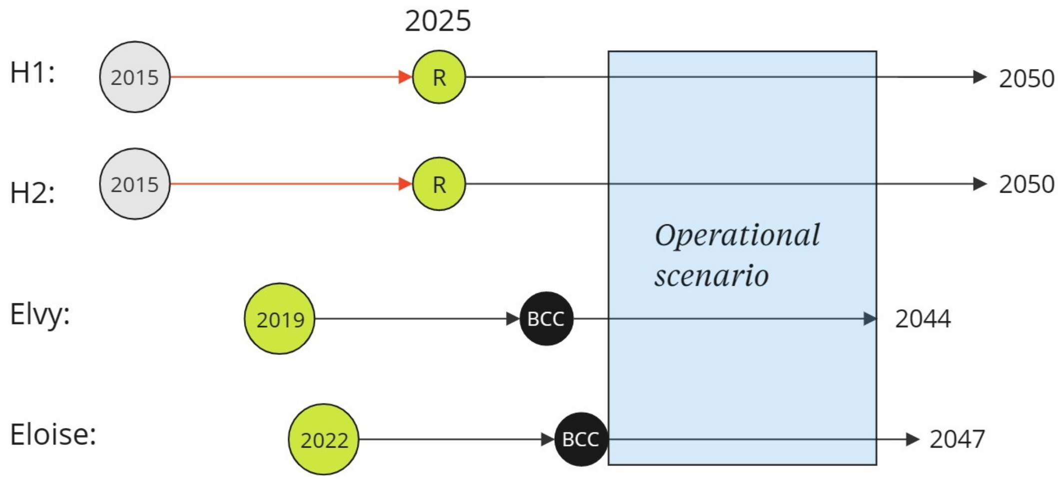


Figure 2.5: The time-frame of the Optimize Battery Scenario.
R: Time of retrofit.
BCC: Time of battery capacity change.
Red arrows: Time before acquisition.
Black arrows: Lifetime of ferry, for which costs are accounted for.
Blue box: Time window during which the simulation takes place.

2.1.4 Wireless Scenarios

These scenarios utilize wireless opportunity charging, taking advantage of the time when the ferries stop to pick up passengers at Lindholmen and Stenpiren. Based on interviews with Styrsöbolaget and Västtrafik, it is important to keep charging times low so that the schedule is not compromised (Cederberg, 2023; Andersson & Rydenskog, 2023). Wireless charging is a suitable solution for scenarios such as this where the vehicle performs several short stops (Ahmad et al., 2028). The four ferries (denoted as W1, W2, W3 and W4) are assumed to be fully electric ferries and newly purchased at an unknown time in the future. Also, the operational scenario is the same as the time-frame, which lasts for 25 years from some year X. The two separate wireless scenarios are called *Steady SoC* and *Falling SoC*. They are explained further in Section 3.2.1, but have the following main characteristics:

Steady SoC charging:
- Four fully electric ferries with 130 kWh battery capacity.
- Two stationary 700 kW units installed at the docking sites, four mobile 700 kW units installed in each ferry.
- Opportunity charging

Falling SoC charging:
- Four fully electric ferries with 630 kWh battery capacity.
- Two stationary 470 kW units installed at the docking sites, four stationary 50 kW units at quay , four mobile 470 kW units installed in each ferry.
- Opportunity charging + Overnight charging.

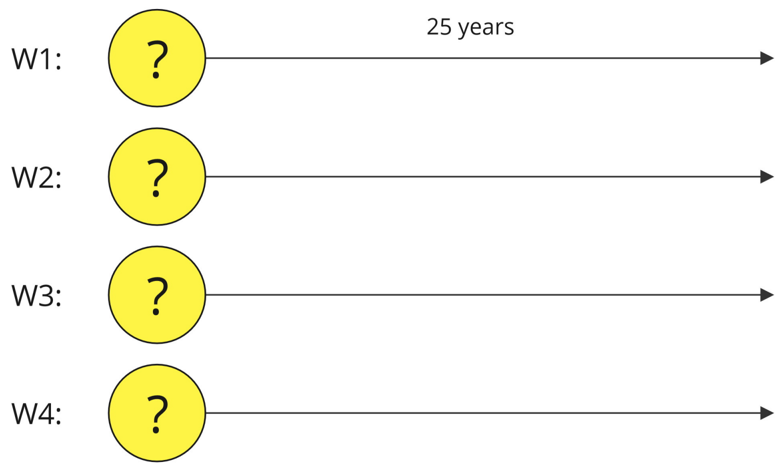


Figure 2.6: The time-frame of the Wireless Charging scenario.

3
Method

The various methods used to address the research questions are explained in this section. A literature review was the first method employed to acquire a broad overview of the subject, and using this data, interview questionnaires were created. The evaluated scenarios were built when the data collection was complete, which determined the parameters for the subsequent cost and emission calculations and needed additional analyses. Figure 3.1 shows a visual representation of the methods overview.

3.1 Interviews

Interviews were selected as method of data collection from different stakeholders involved in the operation or with relevant knowledge in the field. These interviews were conducted as structured interviews for the most part. Data collected with these method was both quantitative and qualitative as the practicality of implementation and any other elements judged significant from the interviewees' perspective were also deemed useful information to collect.
A list of the interviewees, information on the interviews' methodology and questionnaires can be found on Appendix C

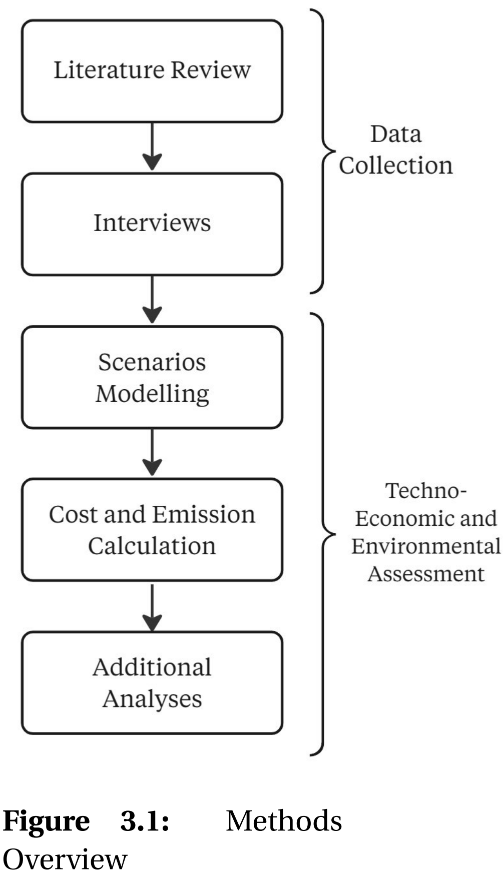


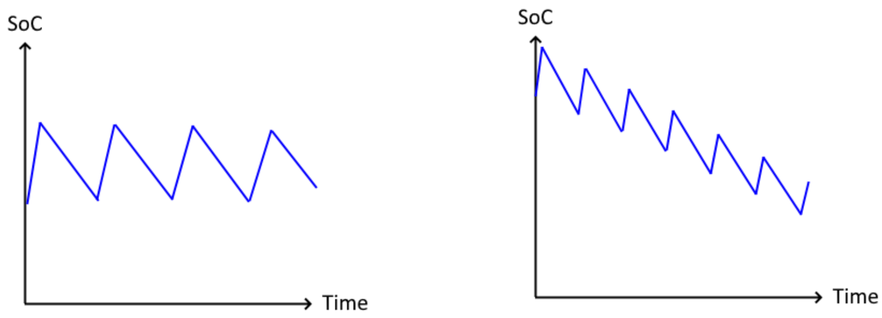
Figure 3.1: Methods Overview

3.2 Scenario Modeling

With the aim of modeling different scenarios, testing variations in different parameters such as the size of the batteries, the number of charging stations needed, charging times, etc., an Excel worksheet was built, which provides information on the operational statistics of each selected scenario that will be used later in the calculations of costs and emissions. The worksheet is divided in two sections, the first one is the input of technical data of the ferries used for each scenario. The second part allows you to try different configurations of how the ferries will take turns to operate and charge. Using this Excel tool, it is possible to see for how long the ferries can operate before running out of battery power. Thereby, it could be used for confirming that a fully electric operation would be possible in the *Big Battery Scenario*, as well as for dimensioning the battery capacity in the *Optimize Battery Scenario*. The tool also provided a visualization of when and of how long the different ferries would have to go into deposition charging. This was done under the constraint that three ferries should run during rush hour, and two ferries should run otherwise. As for the charger, it is simply dimensioned to have its current power output of 200 kW in the *Baseline*, *Big Battery*, and *Optimize Battery* scenarios (Cederberg, 2023). The wireless scenarios are modeled differently. They don't use the Excel tool, and the dimensioning of their battery capacity and chargers is provided in the next section. Detailed information on the construction and functioning of the Excel tool can be found in Appendix B.

3.2.1 Modeling for the wireless charging scenario

Two different strategies that may be used for modeling a fast charging are shown in Figure 3.2. The first is keeping a steady SoC throughout the day. This option would place a high demand on the charger, but have the benefit of allowing for a small battery. Conversely, the falling SoC strategy puts a lesser demand on the charger but would require a larger battery. Both methods will be evaluated.



(a) Steady SoC strategy. (b) Falling SoC strategy.

Figure 3.2: Opportunity charging strategies.

Assuming a Steady SoC approach, the following equation needs to be fulfilled:

$$t_{trip} \cdot P_{cons} = t_{char} \cdot (P_{char} - P_{cons}) \tag{3.1}$$

The time between charging stops (t_{trip}) multiplied by the power consumption (P_{cons}) gives the energy used for a trip, which needs to be matched by the energy received while charging. Since the ferry will be running and consuming energy while it is charging, P_{cons} needs to be subtracted from the power output of the charger P_{char} on the right hand side. The remaining power goes into charging the battery, which multiplied by the time charging (t_{char}) gives the energy received for one charging stop. If the SoC is instead allowed to fall throughout the day, a more general equation can be formed, indicating the net energy use after N trips:

$$\text{Net energy use} = N \cdot (t_{trip} \cdot P_{cons} - t_{char} \cdot (P_{char} - P_{cons}))\ \text{kWh} \tag{3.2}$$

In order to dimension the battery, a base capacity was first assumed based on the energy required to perform one trip. The trip time from one side to the other is around 6 minutes according to the schedule. Assuming the same performance as Västtrafik's current hybrid ships, the DoD is limited to 70% and the maximum power consumption is 140 kW (see Appendix A.1 for a data summary). Also, a buffer of 110 kWh is used through the study, representing one hour of operation with the median power consumption of 110 kW. This yielded the following base capacity:

$$B_{base} = \frac{P_{cons} \cdot t_{trip}}{\text{DoD}} + \text{Buffer} = \frac{140 \cdot (6/60)}{0,7} + 110 = 130 \text{ kWh}$$

Using the Steady SoC strategy, the battery does not need to be bigger than this. For the Falling SoC strategy, however, increasing additional capacity reduces the restraints on the charging time and charger power. Or, seeing it the other way, increased charging time and charger power allows for a smaller battery capacity. An expression for the additional capacity was derived by considering the daily net energy use in, which needs to be matched by installing extra capacity apart from B_{base}. Dividing Equation 3.2 with the DoD gave the following expression:

$$\text{Additional capacity} = \frac{N \cdot (t_{trip} \cdot P_{cons} - t_{char} \cdot (P_{char} - P_{cons}))}{0,7} \tag{3.3}$$

Additionally, the area of the charging pads was sized based on the recently developed high power inductive charging system from Chalmers University of Technology, providing 500 kW per two square meters when there is a 15 cm gap between the pads (Liu, 2023). The required size of the charging pads could therefore be simply estimated using equation 3.4.

$$A = \frac{P_{char}}{250} \text{ m}^2 \tag{3.4}$$

The four ferries together run approximately 120 trips in a day, or 240 counting both ways. Dividing by four gives N = 60 for each ferry. With P_{cons} = 140 kW and t_{trip} = 6 minutes being set, the additional capacity could thus be visualized, depending on the charging time and charging power:

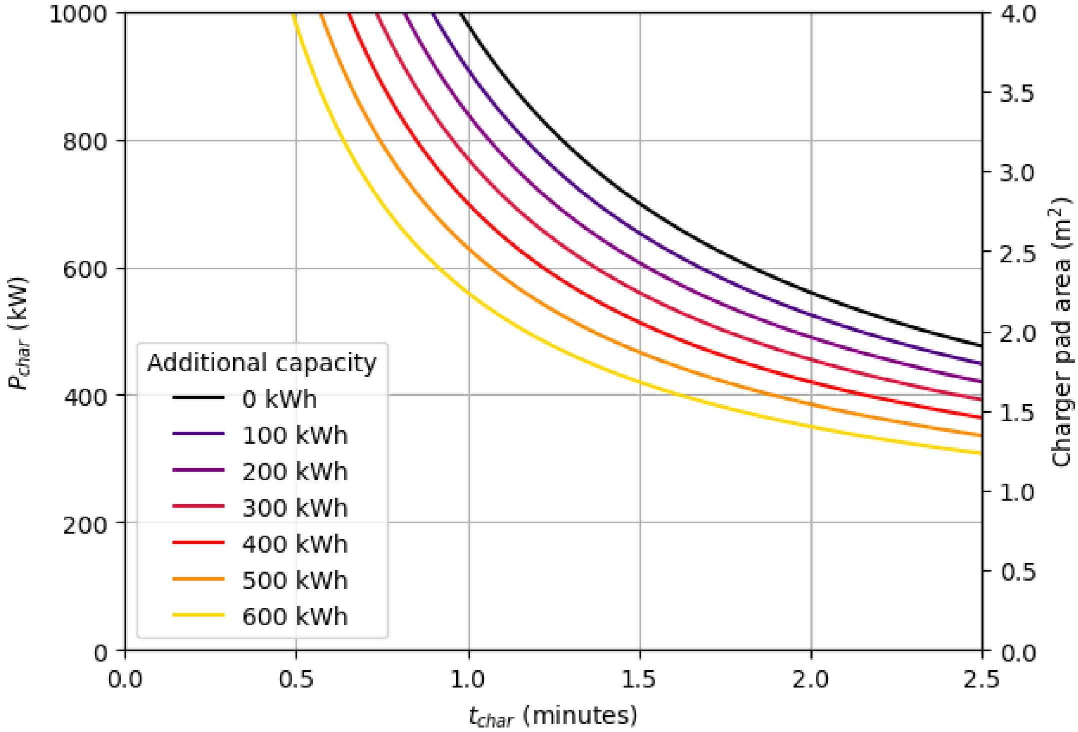


Figure 3.3: Correlation between the charging time, charger power, charger pad area, and additional battery capacity. Notice that the 0 kWh line in the above figure represents the Steady SoC case.

Two different scenarios were then constructed using Figure 3.3, one for steady SoC and one for falling SoC. Since Andersson & Rydenskog (2023) claimed that fast charging could be interesting for Gothenburg if a charging time of less than two minutes is achieved, $t_{char} = 1{,}5$ was chosen for both scenarios. The steady SoC scenario requires no additional capacity and is represented by the black line in the figure, yielding $B_{tot} = 130$ kWh and $P_{char} = 700$ kW. A potential issue with these values is that the C-rate may be too high. The batteries currently used have a listed max charge rate of 1C, while this scenario implies a rate of $P_{char}/B_{tot} \approx 5{,}4$C. But, since it is taking place in the future where there will have been developments in battery technology, it may still be feasible. On the other hand, the falling SoC scenario allowed the battery to be dimensioned for C-rate below 1. Choosing an additional capacity of 500 kWh gave $P_{char} \approx 470$ and a C-rate of $470/500 = 0{,}94$C. And so, total battery capacity for the falling SoC scenario is: $B_{tot} = B_{base} + B_{additional} = 130 + 500 = 630$ kWh.

The new vessel cost was approximated by subtracting the price of the 1 260 kWH installed in Eloise from its total cost, and then adding the price of the new batteries.

$$F_{cost} = 77.5 \cdot 10^6 + (B_{tot} - 1260) \cdot B_{cost} \text{ SEK} \tag{3.5}$$

For wireless charging, both the stationary and on-board part of the charger need to be considered. The cost ratio between stationary/on-board is 6:4 (Liu, 2023). In the steady SoC scenario, there is no need for overnight charging since the battery doesn't deplete during the day. Therefore, only two stationary parts for opportunity charging and four on-board parts (one in each ferry) are needed. In the falling SoC scenario however, overnight charging is required. Four additional 50 kW deposition chargers were therefore considered.

Finally, the wireless ferries were modeled to share the operational time evenly, and since the total daily operational time assumed for all scenarios is 33,5 hours, each wireless ferry would operate for 8,375 hours per day.

3.2.1.1 Operational statistics for wireless charging

In order to calculate the average SoC and the DoD, as was also done for the other scenarios, an equation for the DoD in the wireless scenarios was constructed. Since the ferries only ever pass from one side to the other, the DoD of performing one trip should always be the same. It is expressed by dividing the energy of performing a trip with the total battery capacity:

$$\text{DoD} = \frac{t_{trip} \cdot P_{cons}}{B_{tot}} \tag{3.6}$$

For the Steady SoC scenario, the average SoC should be in between the ferries' reoccurring min and max SoCs as shown in Figure 3.2a. This can be expressed in the following way:

$$\text{(Steady) SoC}_{avg} = \frac{\text{SoC}_{max} + (\text{SoC}_{max} - \text{DoD})}{2} \tag{3.7}$$

What values to use for the min and max SoC is left as a decision for the operator. As for the Falling SoC scenario, it is assumed that the ferries start the day fully charged and end the day with the battery depleted (within the determined DoD interval). For the batteries currently used, this interval is 20-90%, and the average SoC could then be approximated as the in between value of 55%. Generally, it can simply be expressed as:

$$\text{(Falling) SoC}_{avg} = \frac{\text{SoC}_{max} + \text{SoC}_{min}}{2} \tag{3.8}$$

3.3 Techno-economic and environmental assessment

This thesis uses a simplified techno-economic and environmental assessment framework consisting of the following steps:

1. Scope and system boundaries.
2. Economic analysis.
3. Environmental analysis.
4. Additional analyses.

The framework is based mainly on the one presented by Thomassen et al. (2019), with some alterations. For example, a market study was outside of the scope and was not performed. Also, while the original framework is based on the idea of analyzing an "industrial process", this study was centered around the "use-phase" of products (the ferries). In fact, many such frameworks focus on industrial processes along with a focus on emerging technologies (Wunderlich et al., 2020; Mahmud et al., 2021 & Schoubroeck et al., 2021). The Thomassen framework also expects an LCA to be performed, which was not the case in this study. However, data on upstream emissions from battery, engine, and electric motor production from earlier studies were used. As for the economic analysis, it had the "investor's" perspective, as was recommended. This approach is different from for example Life Cycle Costing (LCC) which looks at costs occurring during the entire life cycle. A further minor alteration in this study is the fact that the costs for the "operator" (Styrsöbolaget) were also accounted for, since they handle the scenario's main costs along with the "investor" (Västtrafik). Essentially, these two companies are seen as one from a cost perspective.

3.3.1 Scope for the economic analysis:

The overall goal of the economic analysis was to map the capital expenditures and operational costs for the various operating scenarios. Some costs were more interesting than others, such as the costs related to the propulsion systems themselves, since the costs for e.g. the hull were the same for the different systems. The scope spans from the acquisition of the vessels up until the end of the operational phase. Following the investor's perspective (in this case, Västtrafik), means that costs occurring to any actor before the acquisition phase are not interesting. Neither were costs or profits during end-of-life considered, as they would likely be minuscule compared to other costs. Figure 3.4 summarizes the cost categories for the three types of propulsion system that will be considered.

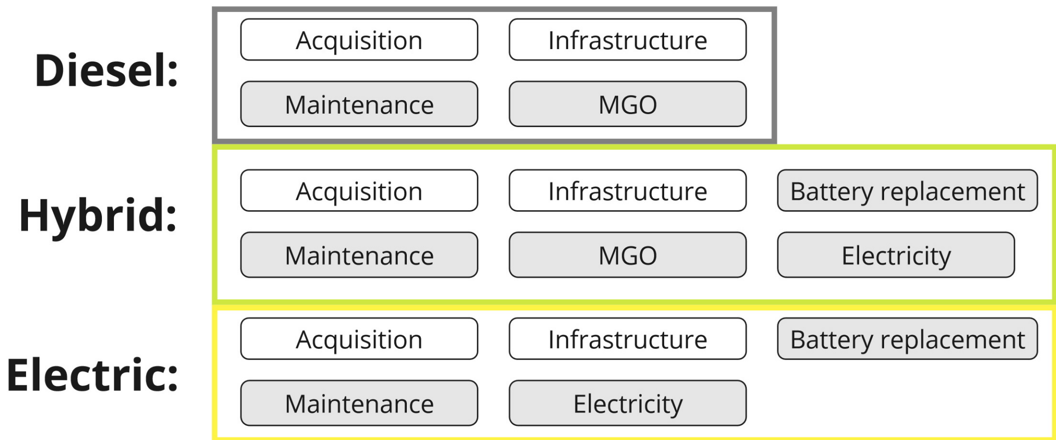


Figure 3.4: Cost categories for each type of propulsion system

3.3.2 Scope for the environmental analysis:

For each propulsion system, emissions were accounted for its respective energy storage, energy conversion, and energy carrier. The energy storage in the ships exists in the form of either batteries or a fuel tank. Emissions from production of the fuel tank were dismissed since they were thought to be negligible compared to the emissions from battery production, which are accounted for. The means of energy conversion are internal combustion engines (ICEs) and electric motors, which had their upstream production emissions estimated using previous LCA results. Finally, the energy carrier is either MGO or electricity, for which both tailpipe and upstream production emissions are considered (note that tailpipe emissions from electricity use are zero). Only GHGs were considered for the upstream emissions, since accounting for several pollutants was deemed too complex and not as relevant for the case study. For the fuel use, however, it was decided that not only GHGs, but also SO_2, NO_x, and PM emissions should be included in order to account for local pollution due to the burning of MGO.

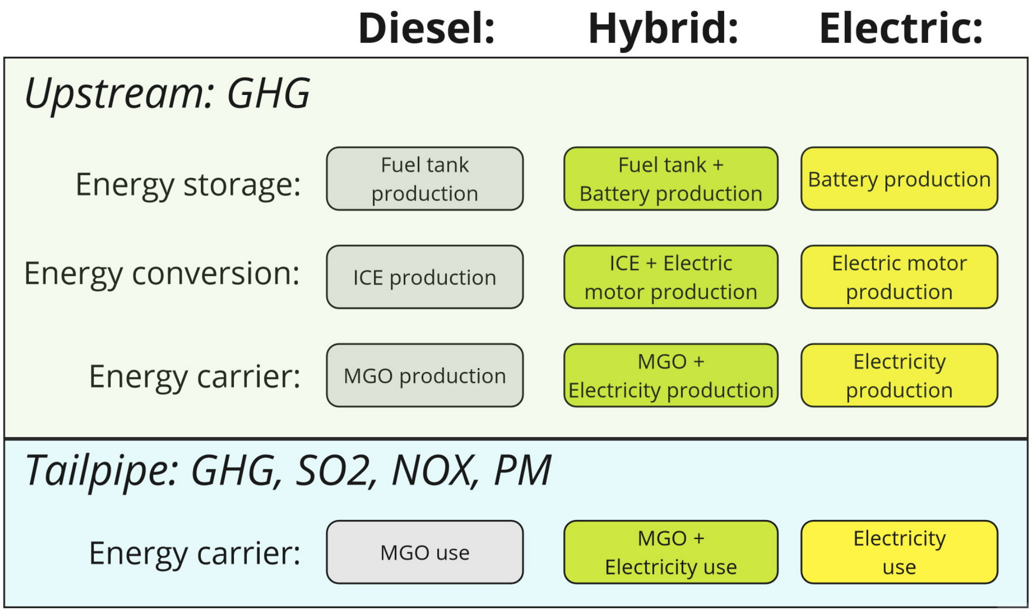


Figure 3.5: Components included in the environmental calculations.

3.3.3 Economic analysis

This section presents the equations for calculating each cost category. Except for the infrastructure cost, the equations are applied to each ferry individually. See Appendix A.2 for a summary of the parameters used.

e-factor (e_f)
e_f represents the share of time a ferry uses electric each day, where 1 equals 100% electric and 0 equals 100% diesel drive. It is calculated using the Excel simulator.

Capital recovery factor (CRF):

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.9}$$

A CRF was considered for the acquisition, infrastructure, and retrofitting costs, with an interest rate of i = 3%.

Depreciation formula for ferries:

The decrease in value of the ferriers is calculated with the following formula:

$$F_{cost} = F_{cost_0}(1-r)^N \tag{3.10}$$

where F_{cost_0} is the purchasing price, and F_{cost} is the value of the ferry after N years with depreciation rate $r = 0.073$, based on a lower bound value for used cars (iSeeCars, 2022).

Acquisition cost:
For a new ferry, the acquisition cost simply depends on the purchasing price:

$$C_a = \frac{F_{cost_0} \cdot CRF}{365} \tag{3.11}$$

For a retrofitted ferry, the acquisition is seen as happening at the point of the retrofit, with the cost being the depreciated value of the ferry at that moment + the retrofit cost:

$$C_a = \frac{(F_{cost_0}(1-r)^N + R_{cost}) \cdot CRF}{365} \tag{3.12}$$

Infrastructure cost:
The infrastructure cost only concerns the cost of the chargers. It can be generalized in the following way, where S_{tot} is the total amount of charger parts, S is the amount of a certain charger part, P_{char} is the charger power, C_{cost} is the cost per installed kW, and r scales the price based on if it is an on-board or off-board part (0,6 for wireless off-board, 0,4 for wireless on-board, and always 1 for plug-in):

$$C_i = \frac{(\sum_i^{S_{tot}} S_i \cdot P_{char} \cdot C_{cost} \cdot r_i) \cdot CRF}{365} \tag{3.13}$$

Maintenance cost:
The maintenance cost per day is simply calculated as follows, where M_{cost} is the yearly maintenance cost:

$$C_m = \frac{M_{cost}}{365} \tag{3.14}$$

Battery replacement cost:
The cost for replacing the batteries depends on the lifetime of the ferry (t_F), the lifetime of the batteries (t_B), the cost per installed kWh (B_{cost}) and the total amount of installed battery capacity in a ferry (B_{tot}):

$$C_r = \frac{\left(\frac{t_f}{t_b}\right) \cdot (B_{cost} \cdot B_{tot}) \cdot CRF}{365} \tag{3.15}$$

Note that since this cost is paid on more than one occasion, the use of CRF is dependent on the simplifying assumption that the battery price does not change during the ferry's lifetime.

Fuel cost:

For a hybrid ferry, this calculation needs for how long of a duration the ferry operates using the diesel engines as opposed to the batteries. e_f represents the amount of time spent in "electric drive", and the equation consists of a diesel and an electricity part:

$$C_f = (E_{cost} \cdot P_{cons} \cdot e_f \cdot t_{op}) + (D_{cost} \cdot D_{cons} \cdot (1 - e_f) \cdot t_{op}) \tag{3.16}$$

where E_{cost}/D_{cost} is the diesel/electricity cost, and P_{cons}/D_{cons} is the electricity/MGO consumption. For diesel and fully electric ferries the equation reduces to $C_f = D_{cost} \cdot D_{cons} \cdot t_{op}$ and $C_f = E_{cost} \cdot P_{cons} \cdot t_{op}$ respectively.

3.3.4 Environmental analysis

This section presents the equations used for calculating the scenarios' emissions. All equations are applied to the ferries individually. See Table A.2 for a summary of the parameters used, and Table A.3 for engine and electric motor specifications.

Emissions from MGO combustion:
All emissions can be said to be upstream except for those caused by MGO combustion, which is also the only process where pollutants other than CO_2 are considered. The SO_x and PM emissions can be calculated using the following equation:

$$\text{EM}_{SOx/PM}\ [\text{kg/day}] = \text{EF}_{SOx/PM} \cdot D_{cons} \cdot \frac{\text{MK1}_{hv}}{10^6} \cdot t_{op} \cdot (1 - e_f) \tag{3.17}$$

where EF is the emission factor, D_{cons} is the fuel consumption per hour, MK1_{hv} is the heat value for MK1 diesel, t_{op} is the amount of daily operating hours, and e_f is the "e-factor" which determines how many of these hours are spent using diesel drive. CO_2 is calculated similarly but does not utilize the heat value and instead only considers the daily fuel consumption in liters:

$$\text{EM}_{CO2}\ [\text{kg/day}] = \text{EF}_{CO2} \cdot D_{cons} \cdot t_{op} \cdot (1 - e_f) \tag{3.18}$$

Calculating NO_x emissions is more complicated, and utilizes equations provided by IMO (n.d.) in *Regulation 13*. First of all, NO_x emissions are dependent on the power output at the engine and not the propeller (see Appendix D). The amount of emissions also depend on the ship engine's "Tier", which can be either I, II or III, where Tier I causes the most emissions and Tier III causes the least. Lastly, different equations apply depending on the engines' Tier and rpm (revolutions per minute). It is known that the ships analysed in this thesis have either Tier II or Tier III engines with an rpm range of 1 500-1 800, which lets us choose the correct equations (Skärgårdsbåtar, n.d.-a; Skärgårdsbåtar, n.d.-b; Cederberg, 2023). They can then be altered slightly in order to calculate daily emissions:

$$\text{Tier II emissions [g NO}x\text{/day]} = [44 \cdot \text{rpm}^{-0.23}] \cdot P_{consICE} \cdot t_{op} \cdot (1 - e_f) \tag{3.19}$$

$$\text{Tier III emissions [g NO}x\text{/day]} = [9 \cdot \text{rpm}^{-0.2}] \cdot P_{consICE} \cdot t_{op} \cdot (1 - e_f) \tag{3.20}$$

where the [bracketed] terms are taken from IMO and represent the "total weighted cycle emissions limit" (unit: g/kWh), $P_{consICE}$ is the power output at the engine shaft, and t_{op} and e_f function the same as in equation 3.3.4. Note that the formulas are based on regulated emission limits and that the amount of emissions could be lower in reality.

Upstream electricity production emissions:
Similarly to equation 3.3.4, the emissions from electricity use can be calculated as following:

$$\text{EM}_{ElecProd}\ [\text{kg CO}_2\ \text{eq./day}] = \text{EF}_{Elec} \cdot P_{cons} \cdot t_{op} \cdot e_f \tag{3.21}$$

Upstream battery production emissions:
As in equation 3.3.3, the calculation is based on determining the battery capacity across the ferry's lifetime:

$$\text{EM}_{BatteryProd}\ [\text{kg CO}_2\ \text{eq./day}] = \frac{\text{EF}_{Battery} \cdot (B_{tot_0} + (B_{tot} \cdot \frac{t_F}{t_B}))}{t_F \cdot 365} \tag{3.22}$$

Here B_{tot_0} is the initial battery capacity as opposed to B_{tot} which is the capacity that is continually being replaced. This is only relevant for the optimize battery scenario where the hybrid ferries have their battery capacity changed within the time-frame.

Upstream ICE production emissions:
The emissions from ICE production depend only on the kW of the installed engines, as is also the case for equation 3.3.4 below.

$$\text{EM}_{ICEProd}\ [\text{kg CO}_2\ \text{eq./day}] = \frac{\text{EF}_{ICE} \cdot \text{kW}_{ICE}}{t_F \cdot 365} \tag{3.23}$$

Where kW_{ICE} is the total kW of the installed diesel engines.

Upstream electric motor production emissions:

$$\text{EM}_{MotorProd}\ [\text{kg CO}_2\ \text{eq./day}] = \frac{\text{EF}_{Motor} \cdot \text{kW}_{Motor}}{t_F \cdot 365} \tag{3.24}$$

Where kW_{Motor} is the total kW of the installed electric motors.

Upstream MGO production emissions:
The upstream emissions from producing MGO are calculated in same fashion as the tailpipe emissions (see equation 3.3.4)

$$\text{EM}_{MGOProd}\ [\text{kg CO}_2\ \text{eq./day}] = \text{EF}_{MGO} \cdot D_{cons} \cdot \text{MK1}_{hv} \cdot t_{op} \cdot (1 - e_f) \tag{3.25}$$

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3.3.5 Additional analyses

Monte Carlo analysis:

A Monte Carlo analysis of 10 000 runs was performed in order to determine the uncertainty of the cost and emissions results. Triangular distribution were used for all parameters, which are listed in Appendix A.1. The min and max values generally represent uncertainty ranges for the present day estimation of the parameters, with some exceptions. First are price of the chargers and the batteries, for which the minimum value is the estimated future cost. Second is electricity cost, whose uncertainty range is based on best/worst future scenarios as described in (**) of Table A.2. Finally, for the battery production EF, the min value is based on future giga-scale production of batteries. Note that the EF represents the production of *battery packs*, as investigated by Ellingsen et al. (2014), and not *battery cells* which was considered in the follow-up study by Chordia et al. (2021). The min value was deduced by modifying Chordia et al.'s result to represent battery pack production by using information from both studies. In conclusion, the analysis considers a mixture of current best/worst cases and future potential.

Sensitivity analysis:

A basic sensitivity analysis of the electricity mix's impact on the results was also performed. The results are shown in Section 4.4.

3.3.6 Producing cost and emission summaries

As part of the techno-economic and environmental analysis framework, Python was used for calculating the costs and emissions of the scenarios. Figure 3.6 shows how data for the calculation was acquired via the different parts of the method. The "various data" concerns all of the parameters laid out in Table A.1. Using the Excel Simulator specifically yields the e-factor (e_f) and ferry operational time (t_{op}) values for the non-wireless scenarios, as well as the battery capacity (B_{tot}) for the optimize battery scenario. For the wireless scenarios, these values are instead derived during the modeling step in section 3.2.1. Utilizing the theory laid out in the previous economic and environmental analysis sections, the code produces summaries of the daily costs and emissions for each scenario. After this step, Python was also used for performing the Monte Carlo and sensitivity analyses.

All Python code, as well as the Excel simulator, is available on GitHub. This includes the code for producing the plot in Figure 3.3.

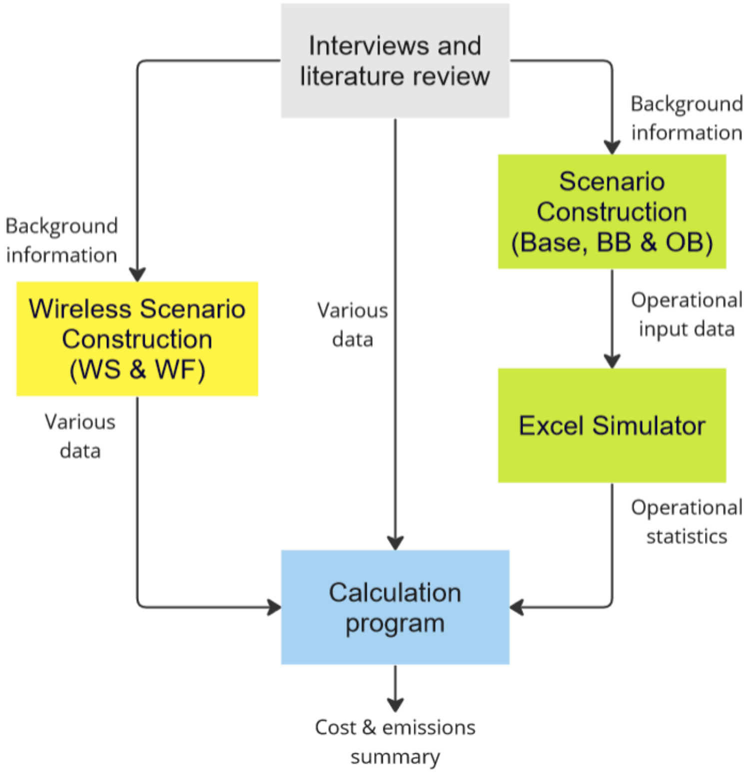

Figure 3.6: Flowchart showing how the collected data is used for producing the cost and emissions summaries.

4

Results

This section presents the results obtained by modeling the different scenarios, the cost calculations per scenario, the emissions inherent to the different operating setups of each scenario, as well as the sensitivity analysis.

4.1 Operational Statistics

After using the Excel simulator, various operational statistics were required. Note that these results are not necessarily "optimal", and that there are many different possibilities. One may use the simulator and search for other possible solutions themselves. What is consistent for all scenarios in the authors' simulations is that the diesel use is minimized.

Regarding the outputs, the first is the e-factor e_f which decides the ratio between MGO and electricity use in the baseline scenario. For the other scenarios it equals 1 for all ferries since they are modeled to only use electricity, even if they are hybrids. Second is t_{op}, the time of operation in hours for each ferry as it was modeled. This output is also used as a parameter in the calculations. Then there are the DoD's, showing how many daily battery cycles the ferries have and how big they are. This, along with the average SoC, gives an insight into how the battery may be affected by the given operational scenario. These values are not used for any further analysis in this thesis, however. As an added detail, the diesel ferries' specific fuel oil consumption (SFOC) is included in the baseline results, calculated for 110 kW power consumption and 35 liters / hour fuel consumption.

	Eloise	**Elvy**	**Älvfrida**	**Älveli**
e_f	0,6154	0,44	0	0
t_{op}	13	12,5	8	0
DoD	70%	61%	N/A	N/A
SoC$_{avg}$	51%	57%	N/A	N/A
SFOC (g/kWh) (*)	N/A	N/A	259	259

Table 4.1: Operational statistics - Baseline Scenario. (*): P_{cons} = 100 would give an SFOC of 285 for the diesel ferries.

	Eloise:	**Elvy:**	**E1:**	**E2:**
e_f	1	1	1	1
t_{op}	1	10,5	9	3
DoD_1	35%	39%	44%	33%
DoD_2	61%	52%	35%	N/A
SoC_{avg}	61%	62%	63%	57%

Table 4.2: Operational statistics - Big Battery Scenario.

	Eloise	**Elvy**	**H1**	**H2**
e_f	1	1	1	1
t_{op}	8	8,5	9	8
DoD_1	33%	41%	49%	33%
DoD_2	33%	16%	16%	16%
DoD_3	16%	33%	33%	49%
DoD_4	49%	49%	49%	33%
SoC_{avg}	61%	62%	63%	66%

Table 4.3: Operational Statistics - Optimize Battery Scenario.

	W1, W2, W3 & W4
e_f	1
t_{op}	8,375
DoD_{all}	8.5%
SoC_{avg}	Operational decision

Table 4.4: Operational Statistics - Wireless Steady SoC Scenario.

	W1, W2, W3 & W4
e_f	1
t_{op}	8,375
DoD_{all}	8.5%
SoC_{avg}	55%

Table 4.5: Operational Statistics - Wireless Falling SoC Scenario.

4.2 Costs

This section present the daily costs for each scenario, divided into the different cost categories. Table 4.6 presents the figures for the daily costs of operation for all five scenarios, subdivided by cost categories described previously in the scope of the study. This same information is presented and complemented with the graph in Figure 4.1. Assigning a color by cost category and separating initial battery cost from acquisition cost.

The main highlight that can be taken from Figure 4.1 is that costs between all five scenarios don't have a significant variation, which can be an indication that cost shouldn't be considered an obstacle for the implementation of electrification scenarios. Furthermore, the results show that the acquisition cost makes up the largest share of the costs for each scenario and that the infrastructure cost is minor, although bigger in the wireless scenarios given that the technology is newer and likely fundamentally more expensive. Fuel and maintenance cost are slightly lower in the electrification scenarios compared to the baseline, due to electricity being a cheaper fuel than MGO, and hybrid and electric ferries costing less to maintain than diesel ferries. It is shown that the batteries make up a solid portion of the overall cost, and that a significant amount of money can be save be reducing the on-board battery capacity. Finally, the diagram shows error bars for each case showing the 5th and 95th percentiles, based on the results of the previously described Monte Carlo simulation.

Costs	**Base**	**BB**	**OB**	**WS**	**WF**
Acquisition:	43 896	40 525	39 782	42 930	47 188
Infrastructure:	189	378	378	1 388	1 017
Battery replacement:	3 568	7 533	4 217	818	3 965
Maintenance:	8 219	7 671	7 671	7 671	7 671
Fuel:	9 175	7 370	7 370	7 370	7 370
Total:	**65 047**	**63 477**	**59 417**	**63 177**	**67 211**

Table 4.6: Summary of the daily costs for all scenarios (SEK / day).

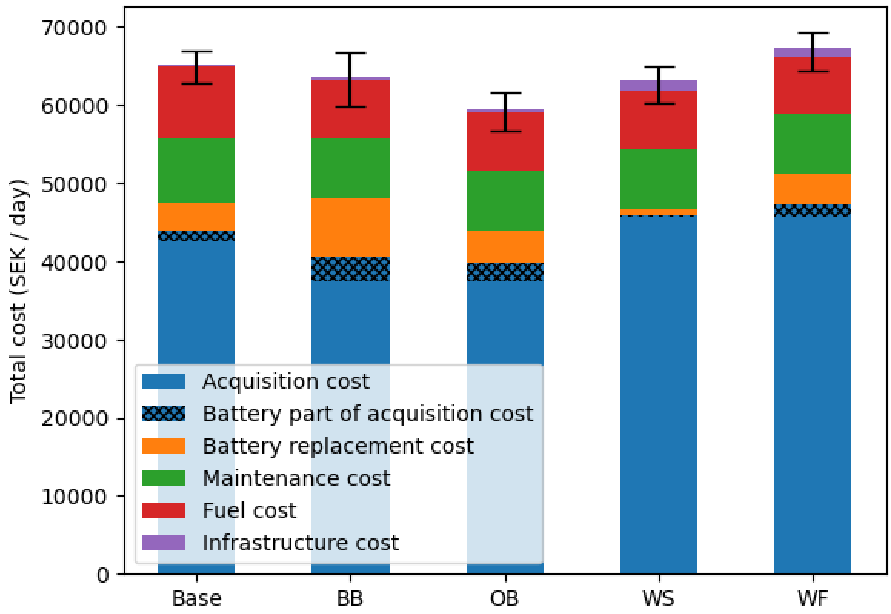

Figure 4.1: Summary of the total costs for each case. Base = Baseline, BB = Big Battery, OB = Optimize Battery, WS = Wireless Steady SoC, WF = Wireless Falling SoC. The error bars represent the 5th and 95th percentiles based on the Monte Carlo results.

4.3 Emissions

Table 4.7 and Figure 4.2 show the findings of the emission calculations for each scenario.

It can be observed that there is a significant difference between the electrification scenarios and the baseline, mainly due to the halt on diesel use and its associated emissions. Another aspect to observe in these results is that battery production makes up a large portion of the emissions, outweighing emission from electricity production in all cases but one (WS). The miscellaneous upstream emissions come from engine, electric motor, and MGO production, and make up a small share of the emissions in each case except for the baseline. This is due to the upstream emissions stemming from MGO production, which is zero for the other scenarios. Again, the error bars in Figure 4.2 represent the 5th and 95th percentiles based in Monte Carlo simulation.

Type of emission	**Base**	**BB**	**OB**	**WS**	**WF**
GHGs [kg CO_2 eq./day]	2 276,5	560,0	390,3	167,1	317,7
NO_x [kg/day]	10,6				
SO_2 [g/day]	5,1				
PM [g/day]	6,3				

Table 4.7: Daily emissions summary for all scenarios

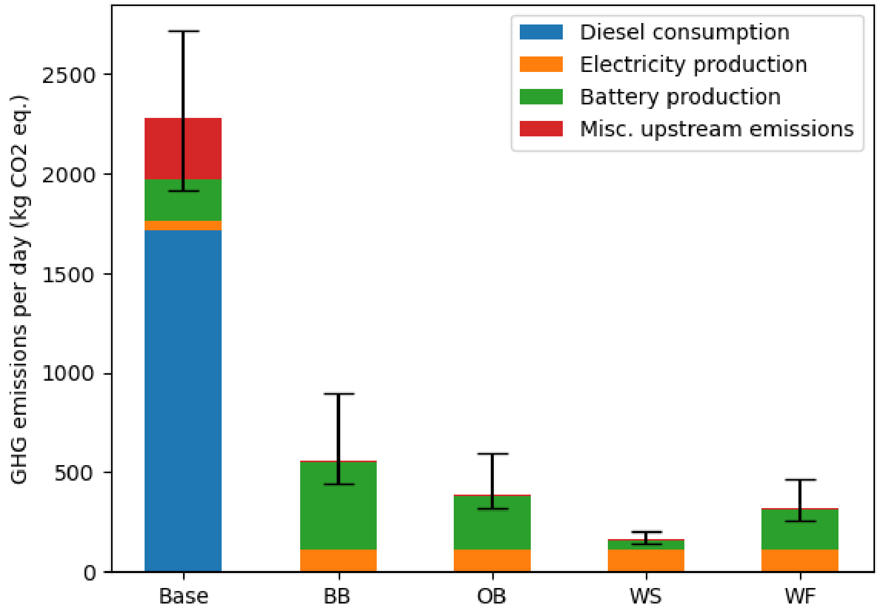

Figure 4.2: Summary of the daily GHG emissions for each scenario. Base = Baseline, BB = Big Battery, OB = Optimize Battery, WS = Wireless Steady SoC, WF = Wireless Falling SoC. The error bars represent the 5th and 95th percentiles based on the Monte Carlo results.

The complete baseline pollution results along with their uncertainty intervals are shown in Appendix E.

4.4 Sensitivity Analysis

A simple sensitivity analysis was performed on the impact of the electricity mix on the electrification scenarios. The current Swedish mix is 30 g CO_2 eq./kWh (European Commission, 2021). Varying it from 0-200 g CO_2 eq./kWh while keeping all other parameters fixed provided the result shown in Figure 4.3.

Since all cases use an equal amount of electricity, the daily emissions vary linearly with the same magnitude. An electricity mix with 0 g CO_2 eq./kWh gives a decrease of ≈50 kg CO_2 eq./day for the baseline and ≈115 kg CO_2 eq./day for the electrification scenarios. To get an indication of how the different scenarios would perform in other countries, one can turn to Jeong et at. (2022) who provide LCA results for electricity production in 31 different countries. India was calculated to have the worst electricity mix, with 188 g CO_2 eq./kWh. Applying this value to the electrification scenarios would lead to an increase of ≈580 kg CO_2 eq./day. However, as can be seen in Figure 4.3, all electrification scenarios are significantly better than the baseline even when considering the worst electricity mixes.

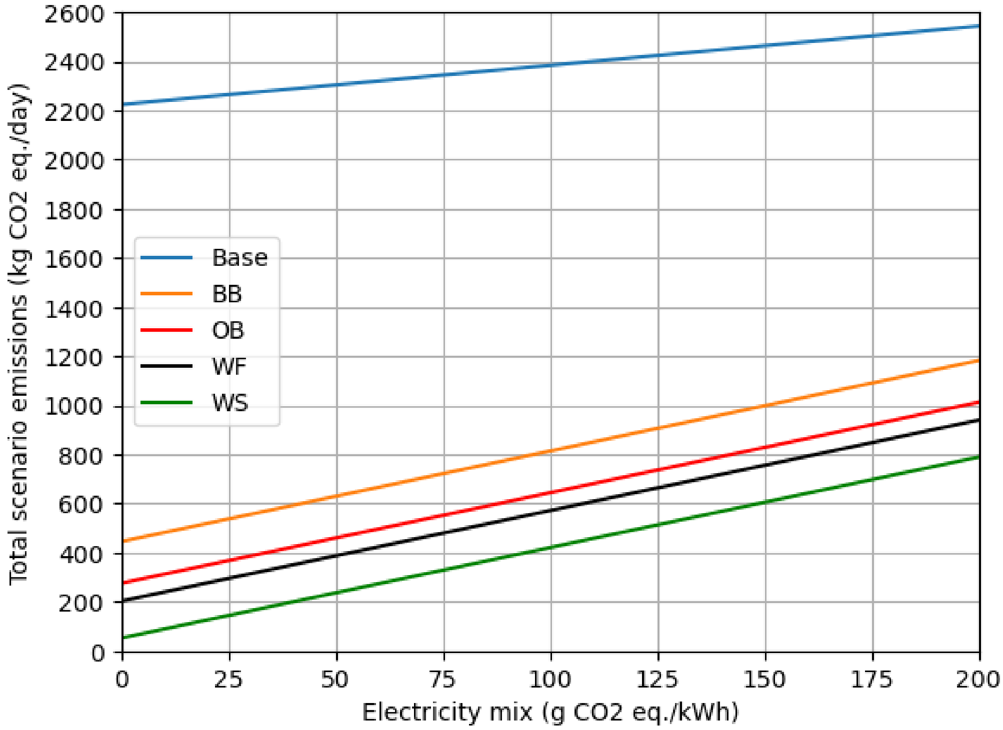

Figure 4.3: Sensitivity analysis of the electricity mix's effect on the total GHG emissions of the electrification scenarios.

5
Discussion

The purpose of this thesis was to assess the economic and environmental performance of different electrification scenarios modeled after the operation of the ferries crossing the Göta Älv in Gothenburg. Four different scenarios have been presented that, with modifications to factors such as battery size, charging strategy, infrastructure etc., can achieve full electrification with varying costs and emissions. These scenario results will now be discussed, as well the questions regarding the method and modeling modeling.

Costs:

The new scenarios all indicate similar costs as the baseline, with the largest decrease appearing in the Optimize Battery Scenario which has ≈8,7% lower daily costs. Between the Big Battery and baseline scenarios the difference in costs is minor, where the decreased acquisition is being compensated with large spending on batteries. Compared to the Big Battery Scenario, the wireless scenarios save money on batteries but have higher acquisition costs due to the assumption that the vessels are newly purchased.

Across all cases, the acquisition/retrofitting is shown to be the major cost item, which is in line with the observations made by Jivén et al. (2020). Because of the significance of the acquisition cost, its method of cost accounting plays a large role in determining the results. In the Big Battery and Optimize Battery scenarios, the depreciated value of the old diesel ferries (≈30 MSEK) is part of the vessel price. If you instead were to only consider the retrofit cost for these scenarios, their daily cost would decrease with ≈9 200 SEK. For the wireless scenarios, the decrease would be ≈34 600 SEK. Nonetheless, the electrification models appear to be cost viable alternatives.

It can be noted that previous works have also demonstrated the feasibility of converting ferries from diesel to battery power when they run on shorter routes. (Al-falahi et al., 2018; Wang et al., 2021; Perčić et al., 2022). For longer routes on the other hand, electric drive becomes disadvantageous due to high costs for the on-board batteries (Kanchiralla et al., 2022).

Emissions:

The GHG mitigation potential of the electrified scenarios compared to the baseline is in the range of ≈75-93%, indicating major benefits of substituting MGO for electricity as fuel. In comparison, the aforementioned works by Wang et al. (2021) and Perčić et al. (2022) showed a 30% GHG decrease and 47% CO_2 reduction *across the life-cycle* respectively. However, Jeong et al. (2022) note that these studies show such favorable results mainly because the electricity mixes used have a large renewable share, which is also the case for this study. They even found that electric drive could cause more emissions than diesel in some cases, which indicates battery ferries cannot be generally thought as a 'sustainable' alternative to diesel ferries on a global scale. However, the sensitivity analysis indicates that there is no risk for such an event in this study.

The aforementioned studies, along with Kanchiralla et al. (2022), notably identify electricity production as the main source of GHGs in electrified scenarios. Wang et al.'s study even estimates a possible GHG reduction of ≈99% if only renewable energy is used. This differs from the results of this study where the battery production generally caused the most emissions. The reason for this could likely be a high value for the battery production EF. Using the lower bound value (see bottom row of Table A.1) would heavily reduce the upstream emissions. Furthermore, the emissions associated with producing lithium-ion batteries for EV's are projected to continue decreasing significantly until 2050 (Xu et al, 2022).

Concerning NO_x, SO_2 and PM emission, all electrification models are preferable to the baseline since the local emissions of these pollutants would be zero. It is interesting to note, however, that Perčić et al. (2022) calculated an increase in life-cycle SO_x emissions for ferry using lithium-ion batteries instead of diesel.

Framework and modeling:

A limitation of this study is the scope of the method, which only takes the investor/-operator's cost perspective and uses second-hand LCA results. Most similar studies instead use LCCA and/or LCA for mapping the costs and environmental impacts across the life-cycle, as showcased in a thorough literature review by Guven et al. (2023) . In essence, the simplified techno-economic and environmental assessment framework used in this study has also acted as a miniature version of such LCCA/LCA studies. Developing the analysis into a full LCCA/LCA could be an interesting continuation of this study, especially considering the inclusion of wireless charging scenarios, which is missing from the current literature to the authors' knowledge.

Another caveat is that the effect that opportunity charging has on the battery life is dismissed. The wireless scenarios, and especially Wireless Falling SoC scenario, would have low DoD's which generally increase the cycle life (Zhang et al., 2017). How this would be offset by the batteries enduring several short cycles is complicated to determine. Cederberg (2023) shared the view that opportunity charging would be detrimental to the battery life in Västtrafik's ferries, however. Furthermore, the model does not consider the cost difference between charging daytime compared to nighttime. The electricity price is generally cheaper during the night, which could be accounted for by using different electricity prices based on during what time the charging takes place. Additional costs dependent on peak power are also not included in the model. In Gothenburg, for example, a tariff has to be paid based on the three hours with the highest average effect usage per month (Göteborg Energi, 2023). However, the peak power usage of the electrification scenarios do not necessarily differ much from the baseline.

Also not included in the modeling is the cost of diesel engine replacements, which in hindsight should have been calculated for the diesel ferries in similar fashion to the hybrid and electric ferries' battery replacement cost. Neither does the model account for staffing costs. While this may be seem like a minor issue due to the fact that the staffing cost could be assumed to be the same for all scenarios, it does alter how the scenarios' respective total costs relate to each other in terms of percentage. It is also important to note that one would get a more detailed picture if you were to consider variations in the power consumption of the vessels depending on the time of year etc., as this model considers only an average power consumption. Also, it is unclear how the power consumption would be affected by a lowered weight due to decreases in battery capacity or the installation of on-board wireless charging plates, which it was outside the scope of the study to determine.

6
Conclusion

In this study, four possible electrification scenarios for waterborne public transport in Göta Älv were constructed. They were based on using either diesel, hybrid, or electric ferries, and utilizing different charging strategies, such as deposition charging during the day using the current plug-in chargers, or by implementing a new wireless opportunity charging systems. These scenarios showcase different approaches for how the ferry traffic may be electrified, which may either use large amounts of on-board battery capacity, or decrease it significantly using the aforementioned charging strategies.

After their construction, the different scenarios were evaluated using a techno-economic and environmental assessment framework in order to deduce their economic and environmental performance. The results suggest that all electrification scenarios except for *Wireless: Falling SoC* cost less than the current operation, and that they all cause significantly less GHGs emissions than the baseline while also having zero local emissions of NO_x, SO_2 and PM. This is in line with previous research comparing electric and diesel ferries operation on short routes.

Furthermore, it is shown that deposition charging several times per day as done in the *Optimize Battery Scenario* allows the on-board battery capacity to be decreased compared to overnight charging while simultaneously reducing costs. It is also demonstrated that using wireless charging could be an economically viable option, which could help reduce the battery size even more. While the wireless scenarios showcase the lowest total emissions, the differences between the electrification scenarios are minor compared to the difference between the baseline and all electrification scenarios as a whole.

Based on these results, the authors' recommend that the electrification scenarios presented in this study are taken into account when planning future waterborne public transport. It is especially recommended that decision makers consider other charging strategies than overnight deposition charging, because of the potential for both economic and environmental gain.

As a final recommendation, there are to the authors' knowledge currently no LCCA/LCA analyses of wireless charging scenarios for ferries in the literature. Evaluating such scenarios with a more thorough methodology based on life-cycle analysis could give a more detailed perspective on the technology, and possibly raise awareness of it as a feasible option. More work could also go into estimating the effect that opportunity charging would have on the battery life, which was neglected in this study. The battery market should also be continually monitored for new developments, such as solid-state EV batteries which could improve charging time and energy density (MIT Technology Review, 2023). Other relevant topics not included in this study are: electrical grid expansion in response to increased energy demand, how to practically retrofit ferries for wireless charging, and finally, a general consideration of political hindrances such as conflicting interests between stakeholders, the acquisition of building permits etc.

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A

Supplementary information: Data

Parameter:	Values:	Sources
Maintenance cost, hybrid/electric (SEK/year)	700.000	(Cederberg, 2023)
Maintenance cost, diesel (SEK/year)	800.000	(Cederberg, 2023)
Plug-in charger power (kW)	200	(Cederberg, 2023)
Charger price, plug-in (SEK/kW) (*)	min: 1.000 base/max: 3.000	(Grauers et al., 2020)
Charger price, wireless (SEK/kW) (*)	min: 1.600 base/max: 4.500	(Liu, 2023) (Grauers et al., 2023)
Cost of diesel ferry (MSEK)	min: 60 base: 62.5 max: 65	(Cederberg, 2023) (Andersson & Rydenskog, 2023)
Cost of Eloise (MSEK)	min: 75 base: 77.5 max: 80	(Cederberg, 2023) (Andersson & Rydenskog, 2023)
Cost of retrofit, incl. 1260 kWh new battery capacity (MSEK)	min: 20 base: 22.5 max: 25	(Cederberg, 2023) (Larsson, 2023)
Battery life (years)	min: 8 base: 10 max: 12	(Cederberg, 2023) (Zakeri & Syri, 2014)
Battery price (SEK / kWh)	min: 2.000 base: 4.000 max: 6.000	(Cederberg, 2023) (Larsson, 2023) (Kanchiralla et al., 2022) (Perčić et al., 2022)
Electricity cost (SEK / kWh) (**)	min: 1.36 base: 2 max: 2.45	(Cederberg, 2023) (Energimyndigheten, 2021)
Diesel consumption (liter/hour)	min: 25 base: 35 max: 45	(Cederberg, 2023)
Power consumption (kWh/hour)	min: 80 base: 110 max: 140	(Cederberg, 2023)
Engine rpm	min: 1500 base: 1650 max: 1800	(Cederberg, 2023)

Engine production EF (kg CO_2 eq./kWh)	37.75	(Kanchiralla et al., 2022)
MGO production EF (g CO_2 eq./MJ)	12.5	(Kanchiralla et al., 2022)
Electricity production EF (g CO_2 eq./kWh)	30	(European Commission, 2021)
SO_2 EF (g/GJ)	36.0 ± 40%	(Fridell et al., 2021)
$PM_{2.5}$ & PM_{10} EF (g/GJ)	27.0 ± 40%	(Fridell et al., 2021)
Battery production EF (kg CO_2 eq./kWh)	min: 140 base: 240 max: 487	(Ellingsen et al., 2014) (Chordia et al, 2021)

Table A.1: Summary of input data and their sources.

(*) Apart from 3000 SEK/kWh which is taken from Grauers et al. (2020), these estimations come from e-mail correspondence with Liu and Grauers. The min values are very rough estimates of a future price where larger production volumes are considered. Note that a charger consists of both a stationary (off-board) and a mobile (on-board) part. For wireless charging, Liu estimates the cost ratio to be 6:4 between stationary/-mobile. The mobile cost is considered negligible for plug-in charging (1:0 ratio).

(**) The min and max values for the electricity price are calculated from Table 65 in Energimyndigheten (2021), using the ratios between the 2018 values and the cheapest and most expensive future scenarios:

$$\text{min} = (298/458) \cdot 2 = 1.30 \text{ SEK / kWh}$$

$$\text{max} = (561/458) \cdot 2 \approx 2.45 \text{ SEK / kWh}$$

Description	Nomenclature	Unit
Lifetime of ferry	t_F	year
Lifetime of batteries	t_B	year
Daily operating time	t_{op}	hour
Ferry cost	F_{cost}	SEK
Retrofit cost	R_{cost}	SEK
Battery cost	B_{cost}	SEK / kWh
Total battery capacity	B_{tot}	kWh
Maintenance cost	M_{cost}	SEK / year
Diesel cost	D_{cost}	SEK / liter
Diesel consumption	D_{cons}	liter / hour
Electricity cost	E_{cost}	SEK / kWh
Power consumption	P_{cons}	kW
ICE power output	$P_{consICE}$	kW
Charger power	P_{char}	kW
Charger cost per kW	C_{cost}	SEK/kW
Time spent charging each stop	t_{char}	hour
Amount of a certain charger type	S	Dimensionless
On-board/off-board multiplier	r	Dimensionless
Share of time in electric drive	e_f	Dimensionless
Emission factor for process X	EF_X	Varies
Heat value for MK1 diesel	$\mathrm{MK1}_{hv}$	MJ / liter
Total installed kW of ICE's	kW_{ICE}	kg CO_2 eq./kW
Total installed kW of electric motors	kW_{Motor}	kg CO_2 eq./kW

Table A.2: List of the parameters used in the economic and environmental analyses.

	Diesel:	**Hybrid:**	**Electric:**
ICE	2 x Scania DI09 257 kW	1 x Scania DI13 257 kW	N/A
Electric motor	2 x 257 kW	2 x 257 kW	2 x 257 kW

Table A.3: Engine and motor specifications, based on Västtrafik's ferries.

B
Supplementary Information: Methodology

A link to the Excel file can be found here.

B.0.1 Construction and functioning of Excel Simulation Tool.

Below is a description of how the Excel Simulation Tool was made.
First, observation of the timetable effective from 2022-12-11 until 2023-06-18 was carried out to get the number of ferries operating in the different time intervals. This is summarized in Table B1 .

Time Interval	Number of Ferries
06:00 - 07:00	2
07:00 - 08:00	3
08:00 - 09:00	3
09:00 - 10:00	3
10:00 - 11:00	2
11:00 - 12:00	2
12:00 - 13:00	2
13:00 - 14:00	3
14:00 - 15:00	3
15:00 - 16:00	3
16:00 - 17:00	3
17:00 - 18:00	3
18:00 - 19:00	2

Table B1: Number of ferries operating per service hour.

The tool allows the input of technical data from the vessels such as:
- Battery Capacity.
- Initial SOC (State of Charge).
- Final SOC (State of Charge).
- Charger Power Output.

The inputs are designated with a light blue shade, to show that the user must enter a value. Cells marked in yellow are calculated automatically by multiplying the battery capacity for each ferry by the agreed-upon initial and final SOC (State of Charge). The tool also requires input data for the energy consumption of the ferries and the power output of the charger. For the scenarios calculated in this thesis, 100 kWh is the energy consumption of the vessels, per hour of operation. The value used for the charger power is from the current charging infrastructure, 200 kW. Data was gathered from the interview conducted with Cederberg (2023).

Variables		
Number of electric ferries:	4	
Battery Capacity Ferry 1:	1260	kWh
Battery Capacity Ferry 2:	1260	kWh
Battery Capacity Ferry 3:	1260	kWh
Battery Capacity Ferry 4:	1000	kWh
Initial SOC:	90%	
Final SOC:	20%	
Initial Energy Available Ferry 1:	1134	kWh
Initial Energy Available Ferry 2:	1134	kWh
Initial Energy Available Ferry 3:	1134	kWh
Initial Energy Available Ferry 4:	900	kWh
Energy at Final SOC Ferry 1:	252	kWh
Energy at Final SOC Ferry 2:	252	kWh
Energy at Final SOC Ferry 3:	252	kWh
Energy at Final SOC Ferry 4:	200	kWh
Energy consumption:	100	kWh
Charger power:	200	kWh

Figure B1: Data Input for Simulation Tool.

The following section of the simulator allows to model different configurations for the ferries to take turns. Each subsection is explained below.

	Operating hours	11				Operating hours	10,5			
	Charging hours:	2				Charging hours:	2			
	Ferry 1					Ferry 2				
	Hours of operation [h]	Remaining kWh [kWh]	Flag	Time charging [h]	kWh charged [kWh]	Hours of operation [h]	Remaining kWh [kWh]	Flag	Time charging [h]	kWh charged [kWh]
06-07	1	1034				0,5	1084			
07-08	1	934				1	984			
08-09	1	834				1	884			
09-10	1	734				1	784			
10-11	X	934		1	200	1	684			
11-12	X	1134		1	200	X	884		1	200
12-13	1	1034				X	1084		1	200
13-14	1	934				1	984			
14-15	1	834				1	884			
15-16	1	734				1	784			
16-17	1	634				1	684			
17-18	1	534				1	584			
18-19	1	434				1	484			

	Operating hours	9				Operating hours	3			
	Charging hours:	1				Charging hours:	0			
	Ferry 3					Ferry 4				
	Hours of operation [h]	Remaining kWh [kWh]	Flag	Time charging [h]	kWh charged [kWh]	Hours of operation [h]	Remaining kWh [kWh]	Flag	Time charging [h]	kWh charged [kWh]
06-07		1134					900			
07-08	1	1034					900			
08-09	1	934					900			
09-10	1	834					900			
10-11		834				1	800			
11-12	1	734				1	700			
12-13	1	634					700			
13-14	X	834		1	200	1	600			
14-15	1	734					600			
15-16	1	634					600			
16-17	1	534					600			
17-18	1	434					600			
18-19		434					600			

	Ferry 1	Ferry 2	Ferry 3	Ferry 4
eF	100%	100%	100%	100%
top	11	10,5	9	3
DoD1	32%	36%	32%	30%
DoD2	56%	24%	32%	
DoD3				
SoCavg	66%	66%	59%	57%

Figure B2: Modelling Section Overview.

Operating hours

Counts the hours of operation of each ferry between 06:00 and 19:00.

Charging hours

Counts the hours the battery of each ferry is charged between 06:00 and 19:00.

Hours of Operation (Columns H, M, R and W)

Cells within these columns are meant to indicate the operational state of the ferry in each time interval.

- **Number 1 or 0,5** indicates the ferry is in operation for one hour or half an hour.

- **Letter X** indicates the ferry is out of commission and is being charged.
- **Blank** shows the ferry is out of commission.

Remaining kWh (Columns I, N, S and X)
Cells show remaining power after an hour of operation. In the case of charging, the column shows the available power after one hour of charging.

Flag (Columns J, O, T and Y)
Flag is a conditional based on the desired Final SOC for the battery of each ferry, it is green when the ferry can continue running and red when the remaining power falls below this constraint.

Time charging (Columns K, P, U and Z)
Cells automatically place a number 1 corresponding to one hour of charging if the value in "Hours of Operation" in the same row is letter X. For different scenarios, this value can also be a manual input.

kWh charged (Columns L, Q, V and AA)
Calculation of the total kWh charged during the time interval based on the time charging and the charger's power capacity.

e_f
Calculation of the share of time on electric drive of each ferry in each simulation.

DoD (Depth of Discharge)
These cells determine the battery's level of discharge from the time it starts to run until it receives its first charge of the day. The following DoDs calculations start with the SoC reached after charging until the next charge.

SoC_{avg} (Average State of Charge)
Calculates the average state of charge of the battery during the operational day.

C

Supplementary Information: Interview Methodology and Questionnaires

C.1 Methodology

Interviews were conducted following the series of steps proposed by George (2022):

- Step 1: Set goals and objectives.
  The main objective of the interviews was to gather relevant quantitative data to perform an environmental techno-economic assessment leading answer the previously stated research questions.
- Step 2: Design questions.
  The questions for these interviews were formulated based on the required data needed from each stakeholder to perform a techno-economic and environmental assessment
- Step 3: Participants Assemble
  Relevant stakeholders that were identified and interviewed.
- Step 4: Medium
  The interviews were conducted both in person and online, depending on the availability and geographical location of the interviewees.
- Step 5: Conduct interview.

The following questions were used when conducting the interviews with the different actors who provided quantitative and qualitative inputs. The insights gathered in these interviews helped the authors shape the different scenarios reviewed.

C.2 List of Interviewees

- City's Public Transport Responsibles
  - Västtrafik
  - Styrsöbolaget
- Background information (Technical)
  - Green City Ferries
  - METS Technology
- Wireless Charging (Technical)
  - Professor Yujing Liu (Head of Unit at Electrical Machines and Power electronics at Chalmers Tekniska Högskola)

C.3 Questionnaires

C.3.1 Styrsöbolaget - Tobjörn Cederberg (Technical Superintendent)

Eloise

1. What is the electricity consumption of Eloise? *[kWh / 100 km] or equivalent.*
2. When Eloise uses diesel for propulsion, what is the fuel consumption? Same as Älvfrida? *[liter diesel] / [100 km] or equivalent*
3. How much does Eloise run on electricity VS. diesel in a day? *[km]/[hours]/%*
4. How much battery capacity is installed in Eloise? *[kWh]*
5. How much is Eloise charged overnight? How many hours does it take, and at which time? *[MWh]/[kWh]/[hours]*
6. For how long will the batteries last? Any other major parts that will need replacement during the vessel's lifetime?
7. In what interval are the batteries' SOC kept? **[%]**

Eloise's costs

1. How much does it cost to charge on average? *[SEK / kWh] or equivalent*
2. What did it cost to build Eloise?
3. How much does it cost to do maintenance on Eloise? and how often is this needed?*[SEK/ year], [times per year]*

Älvfrida

1. What is the fuel consumption of Älvfrida? *[liters]/[100 km]*
2. What is the cost of the diesel used?
3. What's the maintenance cost of Älvfrida? And how often does it happen? *[SEK / year], [times / year]*
4. What did it cost to build Älvfrida? *[SEK]*
5. Precisely what type of fuel is used? Is it the same one used for Eloise?

General Questions

1. Proposition for implementing fast charging?
2. What are the staffing costs for the vessels? *[SEK/year]*
3. What is the carrying capacity of the ferries?
4. What is the total distance traveled in a day? *[km]*
5. Life time of the ferries?
6. Would fast charging require changing battery type? How would the battery lifetime be affected?
7. What's your estimate of what it would cost to build fast charging infrastructure in the port of Gothenburg? / What problems would there be?
8. How does the infrastructure for diesel supply look like? How much did it cost to build approximately?
9. Tell us about the current charging technology.
10. Power of the engines?

C.3.2 Västtrafik - Mats Andersson and Camilla Rydenskog

This interview was meant to have a double confirmation of the data previously gathered from the interview carried with Styrsöbolaget, so the first part of the interview followed the same questions described in the previous section. The second part of the interview provided a different point of view since Västtrafik is the investor in this Study Case.

1. What are your thoughts on the idea of purchasing a fourth ferry with the same characteristics as the current ones (Eloise and Elvy)?
2. Views on fast charging and timetable.
3. Is electrification of the ferries in Gothenburg the way forward?
4. What was the cost for the current charging infrastructure and how much of that was paid by Västtrafik?
5. If you were to retrofit Älveli and Älvfrida how many more charging points do you think would need to be built?
6. How will the current schedules be managed when the ferries are out of commission being retrofitted?
7. Do you have an approximate of the cost of the batteries?
8. What do you think would be a representative number of the average number of hours of operation?
9. In the future hypothetical case of purchasing a new electrical ferry, would the capacity be kept at 300 passengers?
10. Would there be a way to have only electrical drive in the ferries instead of having both a diesel and electrical drive?

C.3.3 Green City Ferries - Hans Thornell (Chairman and Founder)

General questions

1. Tell us about Green City Ferries. The company's purpose and vision.
2. What changes have you seen in the demand for the ferry solutions you offer?
3. Have you encountered any obstacles while commercializing your technology?
4. Is public transport your main market?
5. What obstacles have you found in that segment?
6. Do you have any current projects to implement your technology in public transport?
7. In the company's experience what are the greatest obstacles you identify for waterborne public transport to transition towards greener technologies?

Beluga 24

1. What is the battery capacity of the ferry?
2. What is the energy requirement per hour of operation?
3. What is the selected charging solution and why was it chosen?
4. How long does it take to charge the ferry's battery?
5. Is there enough charging facilities to operate this ferry a full day on electricity?
6. How long does it take to build this model of ferry?
7. What is the cost of this ferry?
8. Has it been decided which transport lines will operate with this ferry?
9. How near or far do you see waterborne public transport being fossil free in Sweden?

C.3.4 METS Technology - Per-Erik Larsson (Commercial Director)

Retrofitting of Diesel-Electric Ferries

1. Can you describe the process of retrofitting a diesel ferry to an electric ferry?
2. What are the technical challenges involved in retrofitting diesel ferries to electric propulsion?
3. How do you determine the appropriate battery size and charging options for an electric ferry?
4. How long does the retrofitting process take, and what factors influence this?
5. What kind of electric propulsion system do you install onboard the ferries, and how does it compare with traditional diesel systems in terms of energy efficiency?
6. Can you add battery capacity to a hybrid ferry?
7. What does it entail?
8. What is the investment needed for this? Cost per additional kWh for example.
9. Do you have any experience with wireless charging technology?
10. How difficult would it be to retrofit ferries for inductive charging compared to using cables?
11. What potential do you see in wireless charging moving forward?
12. Are there any limitations to retrofitting ferries to electric power, either in terms of the technology or the vessels themselves?
13. What advice would you give to other maritime organizations (Västtrafik for example) considering retrofitting their fleets to electric power?
14. What kind of investment is required for retrofitting diesel ferries to electric propulsion?
15. Are there any limitations to retrofitting ferries to electric power, either in terms of the technology or the vessels themselves?
16. With rising concerns about climate change and air pollution, how do you see the demand for electric ferries evolving in the future?

C.3.5 Chalmers Tekniska Högskola - Professor Yujing Liu (Head of Unit at Electrical Machines and Power Electronics)

1. How difficult do you think it would be to build a different type of charging system to the one already in place?
2. What are the pros and cons of 3-phase vs. DC, and what do you think of the possibilities of implementing DC charging in Gothenburg
3. How far into the future do you see the implementation of wireless charging becoming a common practice?
4. What's the feasibility of other more or less automatic charging solutions?
5. How could fast charging fit into Gothenburg's scenario (Retrofitting of the diesel ferries to have batteries as Eloise and maintain the timetable)?

D

Supplementary information: Powertrain schematics

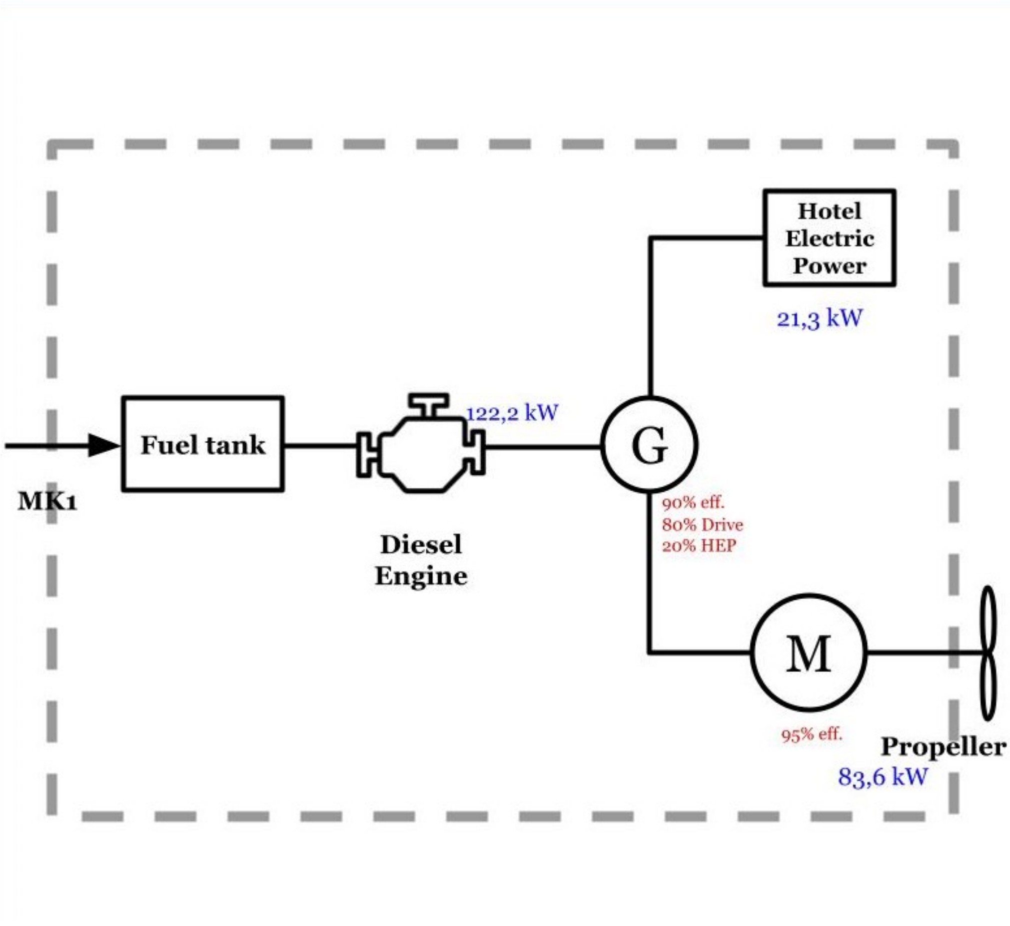

Figure B1: Powertrain schematic for a diesel-electric ferry, including the power outputs used in this thesis.

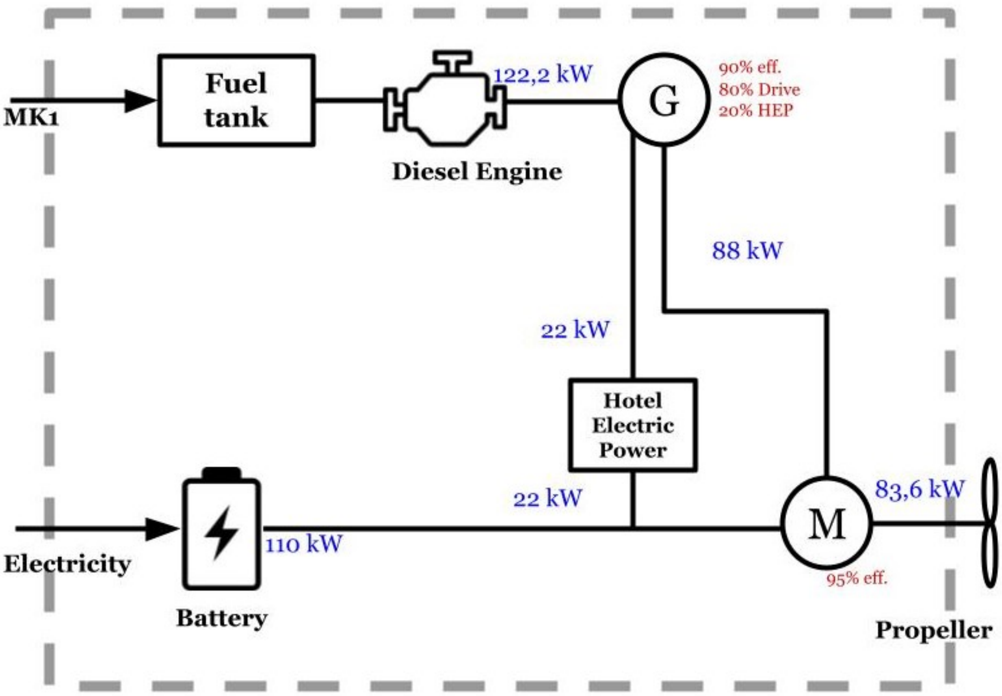

Figure B2: Powertrain schematic for a hybrid-electric ferry, including the power outputs used in this thesis.

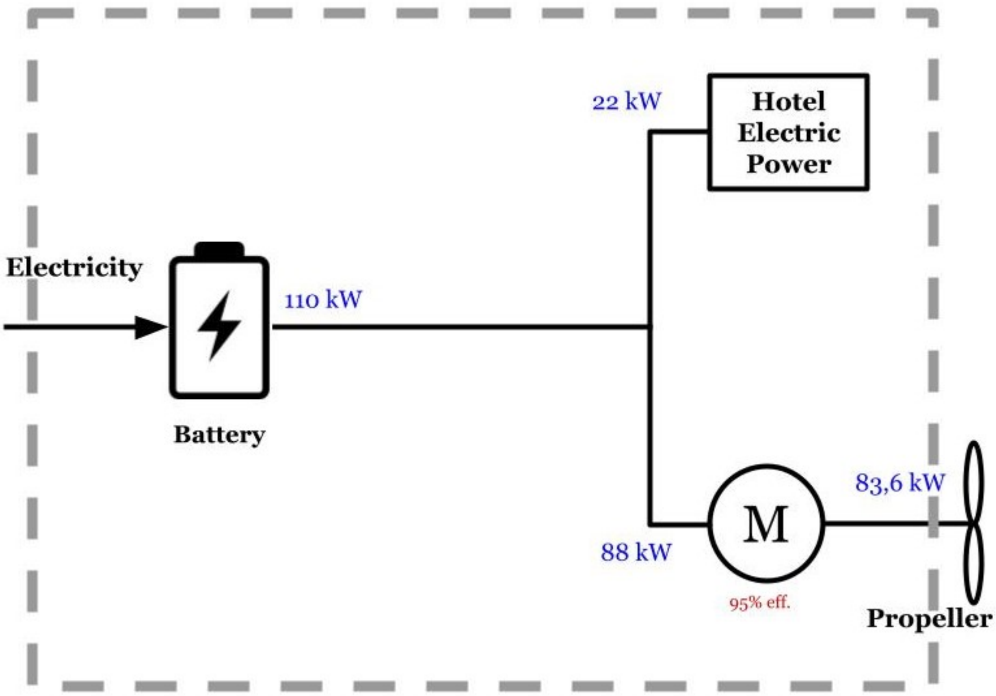

Figure B3: Powertrain schematic for an electric ferry, including the power outputs used in this thesis.

E

Supplementary Information: Baseline pollution results

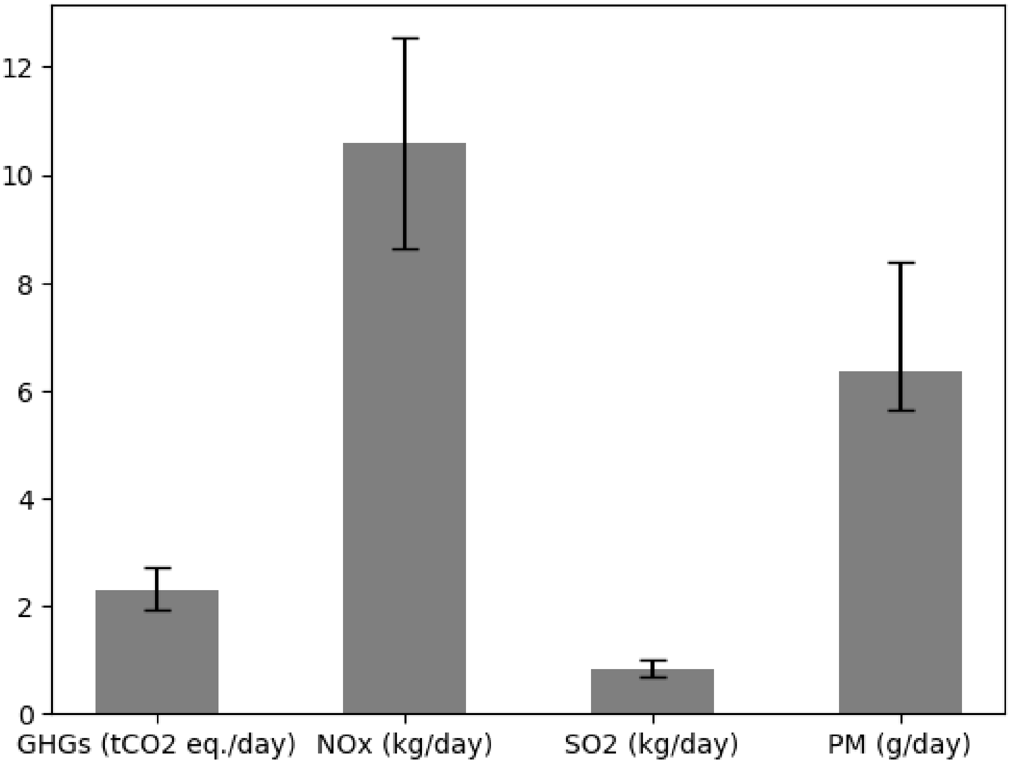

Figure B1: Daily GHG, NOx, SO2, and PM emissions for the baseline scenario. The error bars represent the 5th and 95th percentiles based on the Monte Carlo results.

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