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Life Cycle Cost Analysis of an Electrified Inland Waterway Vessel Concept

Master's thesis in Mechanics and Maritime Science

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Mobilizing small waterway solutions

Interreg
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Department of Mechanics and Maritime Sciences
Division of Maritime Studies
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Cover picture:
A visualisation of the Electrified concept vessel developed by SSPA (Sjöling et al., 2020)

Abstract

Present and future environmental regulations are re-shaping the shipping industry and pushing it to heavily reduce all their emissions. As a result, new technology is emerging in the market along with new strategies like retrofitting vessels or switching fuels and routes.

In this thesis, the life cycle costs (LCC), including the costs associated with the construction and operation, of a fully electric concept vessel are identified, modelled and analysed. The concept vessel, which is developed by SSPA, is a Vänermax (vessel size) and is intended to operate on Göta älv between the port of Gothenburg and the port of Trollhättan. In addition, the corresponding LCC of a traditional vessel running on marine gas oil (MGO), and the costs of a vessel running on liquefied natural gas (LNG) are estimated and compared to the fully electric concept vessel.

In order to perform the comparison between the three different propulsion systems, a Life Cycle Cost Analysis (LCCA) is conducted for the three alternative vessels with a focus on the costs that are different between the three propulsion options. The overall aim for this thesis is to provide relevant stakeholders with information to aid them when assessing the investment in a new propulsion system.

The costs that are different between the three propulsion systems are identified and summed up to the respective categories of construction, operational and total LCC for each alternative. A sensitivity analysis is also conducted for the parameters that are most important to the results and are vulnerable as well as expected to change in prices. The results show that the electric propulsion system at current prices is the most expensive, followed by the LNG and least expensive diesel alternative. The future scenarios, however, are more favourable to the electric propulsion regarding operational costs and make this option exceed.

Keywords: Inland Waterway Transportation, IWT, Life Cycle Cost, LCC, Life Cycle Cost Analysis, LCCA, Greenhouse Gas, GHG, Inland Waterway Vessel, Electric Vessel.

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Helena Svemark & Esmeralda Dervishllari, Gothenburg, June 2020

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Abbreviations

CH_4 - Methane
CO_2 – carbon dioxide
CSI – clean shipping index
DNV – Det Norske Veritas
DWT – deadweight tonnage
EU ETS – EU emissions trading system
IWTGHG – greenhouse gas
GWP – global warming potential
HFO – heavy fuel oil
HVAC – heating, ventilation and air conditioning
ICE – Internal combustion engine
IMO – International Maritime Organization
IWT – inland waterway transportation
IWV – inland waterway vessel
kn – knots
kW – kilowatt
kWh – kilowatt hour
LCA – life cycle assessment
LCC – life cycle costing
LCCA – life cycle cost analysis
LNG – liquefied natural gas
MGO – marine gas oil
NO_x – nitrous oxide
NSR – North-Sea Region
PM – particulate matter
SMA – Swedish Maritime Administration
SO_2 – sulphur dioxide
SO_x – sulphur oxide
TEU – twenty-foot equivalent unit
USD – United States dollars
WHO – World Health Organization

Symbol list

$\in_{fc}$ = fuel price (€)
C = cost/kWh based on fuel consumption and CO_2-tax
$C_{O,i}$ = operation costs
C_0 = cash flow at period 0
$C_{C,i}$ = construction costs (initial costs)
C_F = cost of fuel
C_i = compound interest
$C_{M,i}$ = maintenance costs
$C_{S,i}$ = Scrapping costs
Fc = fuel consumption
FV = future value
P_i = engine load (%)
r = annual fixed interest rate
T_i = time spent in each operating mode (years)

1. Introduction

The shipping industry has a long history and is widely operating in the transportation sector (Stopford, 2009). About 90% of international goods are transported by ships (ICS, 2020). On a national level, Sweden handled in 2018 a total amount of 179 million tons (a 2% increase from the previous year) of goods which is more than a quarter of the total annual 700 million ton goods flow in Sweden (Regeringskansliet, 2018). Out of the 179 million tons handled in port, 86% was imported or exported to Sweden, and 87 million tons in total was imported goods discharged in a Swedish port (Trafikanalys, 2019).

The development of vessels over a long period of time has gone from sails to steam power and to the internal combustion engine running on fossil fuels (Stopford, 2009). That development has resulted in releasing not only carbon dioxide (CO_2) into the atmosphere, but other greenhouse gases (GHGs), such as methane (CH_4) as well as nitrous oxide (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) (C2ES, 2020). Besides contributing to global warming, the burning of fossil fuels cause acidification and eutrophication of our lands and waters, and particulate matter have a serious impact on our health (Andersson et al., 2016). For example, in 2012 the World Health Organization attributed 7 million deaths to air pollution (WHO, 2014).

In an effort to combat the damaging effects of GHG emissions from the transport sector, the European Union has set a goal to cut GHGs by 60% below the levels of 1990 by 2050, and thereby creating an incentive for the transport industry to heavily reduce their emissions in only 30 years (European Commission, 2012). In 2018, the International Maritime Organization (IMO) set a goal to reduce GHG emissions by at least 50% by 2050 having 2008 as a baseline year (IMO, 2018). Many countries have also decided to implement measures on a national level, one example is Sweden. The Swedish government adopted a climate act which was enforced in January 2018, regulating how the climate work is to be done (The Swedish Government, 2017).

In the climate act, the government agreed on the following targets;

- No net emissions of GHGs to the atmosphere by 2045.
- Emissions from national transport lowered by 70% compared to 2010 levels, by 2030 (except emission from aviation which is regulated in the European Union emissions trading system, EU ETS).
- Emissions in Sweden that are not regulated by EU ETS to be 63% lower than 1990 levels by 2030, and 75% by 2040.

As for now, the conventional technology related to the ship power systems, that is widely available to the shipping industry and generates GHG emissions, cannot meet either the requirements of the Swedish climate law or future EU regulations (Zheng et al., 2017). Thus, a breakthrough in technology and new strategies to reduce the emissions are needed.

Rogerson identifies that shifting the transport of goods from the road to sea represents one key route to a sustainable transport sector (Rogerson et al., 2019). This would decrease the GHG intensity since shipping transportation is more energy efficient compared to other modes of transport, such as train, truck and aviation. The maritime industry, while carrying almost 90% of the transported goods worldwide, only emits 10.6 % of the total GHG emissions from the EU transport sector compared to the emissions from road transportation, including both goods and passengers, which amounts to 73.4% (European Commission, 2014).

Historically, inland waterways have been used to transport domestic goods all over the world, but in the last decades of the twentieth century, the overall trend in Europe has seen an increase in road transport and decrease in Inland Waterway Transport (IWT) (Wiegmans and Konings, 2016). Some countries, like the Netherlands, have a well-developed and utilized IWT network, and China have the largest IWT network in the world, in terms of both length and tonnage (The World Bank, 2009). In Sweden Though, IWT is considered a new market since out of the 3% domestic goods volume transported by sea in 2014, only 0.7% (or 79 000 tons) was on IWT (Trafikanalys, 2016).

In markets with high levels of IWT, ports and authorities promote the use of IWT's (Kotowska et al., 2018), as opposed in markets with low levels of IWT, promotions and policy measures to stimulate the modal shift might not exist at all (Macharis et al., 2009). Because of this, in a low level IWT market the goal is not only to improve present activities, but to initiate IWT activities and attract goods volumes. Therefore, there are additional barriers which need to be overcome in a new market to successfully implement and develop a well-functioning IWT network, such as transhipment costs and size of ships (Rogerson et al., 2019) while more research needs to be done around the means of this implementation.

Since 2000, the European Union has promoted cooperation in the North Sea Region (NSR) through the implementation of several projects in 49 regions within 7 countries; Sweden, Denmark, Germany, Norway, the UK, Belgium and the Netherlands (North Sea Region Programme, 2015b). Thanks to the geographical position, the NSR with its deep-water ports represents the international trade hub for most of Europe. The region contributes greatly to the economy, on the downside it also has an impact on the environment due to the dependency on fossil fuels. The programme of the NSR is working to develop innovations to reduce emissions, improve air quality and relieve congestion that threaten the efficient flow of goods and people around the region. The focus lies on shifting extensive goods volumes from long-distance road transport to inland waterways, and to improve the shipping industry's performance with zero carbon fuels, green technologies and developing more effective transport hubs (North Sea Region Programme, 2015c).

Part of this programme is the Inland Waterway Transport Solutions (IWTS) 2.0 project which for the Swedish region is coordinated by SSPA. The aim is to account for IWT benefits, identify and overcome barriers and encourage the shifting to IWT by developing innovative logistic concepts for inland shipping in Sweden (SSPA, n.d.). As a step towards a more environmentally friendly transportation of goods that fully utilizes the potential of Swedish inland waterways, SSPA has developed a fully electric concept vessel intended to traffic Göta Älv between the ports of Gothenburg and Trollhättan.

There are vessels operating on inland waterways today, but they are all diesel powered and thus release harmful emissions and particles to the atmosphere. The vessels operating on Göta Älv today are mostly general cargo vessels which connect inland ports with national and international destinations. However, there are no connections between the Port of Gothenburg and the Port of Trollhättan today, and there are no container vessels operating on this route. In order to attract new goods flows to inland waterways, such as container goods flows, electrified vessels are an interesting alternative for reducing emissions. The route between Gothenburg and Trollhättan is rather short, which makes the electric vessel a viable option that allows for decreased emissions in the area.

In long and complex projects, such as acquiring and operating a vessel, lifecycle management is as challenging as it is necessary to assess and manage the uncertainties when decisions need to be made from the very first step of a project conception. Especially when evaluating new technologies, which are more expensive when new on the market (Wang et al, 2017). For a shipping company, financial performance and control of its costs is key to surviving the market, especially in periods when the market is down, as there is a large volume of cash flow associated with the vessel (Stopford, 2009).

A Life Cycle Cost Analysis comparison on vessel's propulsion systems operating in inland waterways is performed in this report. With a focus on the electric concept vessel, the comparison is based on technologies that already exist for more accurate results while further assumptions that would occur in a comparison with new technologies that have not been fully developed yet, are avoided.

1.2. Aim of study

The aim of this report is to perform a comparative Life Cycle Cost Analysis (LCCA) on the propulsion system of a fully electric Vänermax concept vessel developed by SSPA, as well as on two traditional alternatives that run on diesel and LNG respectively. The cost elements that will be analysed are the ones that differ between the alternatives and represent the construction and operating[1] costs. The scrapping costs for the vessels are included in this thesis as well, they are however assumed to be the same for the vessels and are therefore not analysed further. The analysis on the differing cost elements is to provide a way for relevant stakeholders to assess and evaluate the financial impact of the different options when they invest in a new propulsion system.

More specifically the questions to answer are:

1. What are the cost elements included in a comparative Life Cycle Cost Analysis of an electrified propulsion system vs a diesel and an LNG propulsion system, applied on an inland waterway vessel?
2. How do the Life Cycle Costs of the ships differ on the two cost levels: investment and operation?
3. What cost elements included in the comparative analysis have the biggest impact on the Life Cycle Costs for the three propulsion alternatives?

1.3. Delimitations

This thesis will look at the potential of electrified inland waterway vessels for the transport route between Gothenburg and Trollhättan. The electrified vessel is expected to operate at normal levels with standard freight revenues that are to be the same for all alternatives during the lifespan.

In the Life Cycle Cost Analysis, only the cost elements related to the comparison will be included, meaning the costs that differ between the alternatives. Similar cost elements, revenue, external costs and value outcomes will not be included.

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[1] Included in the operating costs are the voyage costs and costs for maintenance and spare parts.

2. Background

2.1. Inland waterway transportation

Since the last decades of the twentieth century the European road transportation has seen an increase as opposed to the inland waterways (rivers, lakes and canals) (Wiegmans and Konings, 2016). However, environmental concerns, as well as congestion in the road transportation are nowadays shifting the transport industry's interest from road to inland waterways. The waterway network in all European countries amounts to 52 000 km of which 8 000 km is estimated to be of interest to freight transportation. Among the countries with an extensive activity of IWT the Netherlands and Germany account for more than 70 per cent of IWT performance (Wiegmans and Konings, 2016).

In an attempt to shift the trend from road to IWT, the emerging container transportation attracts the interest for inland waterways, due to that the increase in transported goods volume on roads brings problems such as congestion. In addition, inland waterways can offer a cheaper and more cost-effective alternative transportation due to their potential of large-scale transport, when compared to road transport (Wiegmans and Konings, 2016).

The NSR is a program, among others, promoted by the European Union to support the shift of transportation to inland waterways. All over the NSR there is a spider-web of inland waterways connecting land-locked nations and companies to many of the deep seaports in North-western Europe. Depending on the properties of the channel, a vessel can be up to 135 m long, with a cargo capacity of 5 300 t (Bremenports, 2020).

The inland waterway transport solution project 2.0 (IWTS 2.0) is a project cofounded by the NSR Programme of 2014-2020. The main purpose of the project is the promotion of inland navigation on the waterways of Europe. Switching over to IWT makes sense in more than one way. Transportation by ship is a more economical mode of transport, with ships being capable of transporting high volumes of goods in a single shipment. And with the higher goods volume being transported, the emissions per tonne-mile is significantly reduced compared to transport by truck or train, making ship transport a more eco-friendly alternative as well as a cheaper option (Bremenports, 2020).

Many waterways in Europe have been un- or under-used over the past decades (Interreg, 2020), the IWTS 2.0 project aims to deal with the challenges of IWT. Such as low awareness regarding transport potentials of inland waterways (IWW), few developments in smaller barge improvement and re-loading of goods, lack of skill in utilizing small waterway possibilities and lack of education contents, as well as devoted crews for small waterway navigation (Interreg, 2020). To address the challenges of IWT, the project partners join together and gather competences and capacity to move goods to the under-utilized waterways. This is done by facilitating a rapid modal shift through the introduction of new, proven logistic technologies and supporting managers in their decision, better use of the already existing waterways by modifying them for standardised vessels and updating IWT education and training with emphasis on sailing on smaller waterways (Interreg, 2020).

2.2. Inland waterway vessels

In 2016, Clarksons counted about 14,000 small ships operating on short international or national routes, most of which are coastal ships representing 22% of the global commercial fleet (Wu and Bucknall, 2016). Most of those vessels have the potential to operate in inland waterways.

However, among the variety of vessels that can sail through inland waterways, there are small vessels of only a few tons of capacity as well as large pushtows of tens of thousands of tons of cargo capacity that are depending on the water's properties, length and depth (Wiegmans and Konings, 2016).

In 2016 the European Parliament adopted a new Directive that sets technical requirements for inland waterway vessels operating in EU inland waterways. The Directive applies to vessels with a length of 20 meters or more, a volume of 100 m^3 or more, floating equipment, tugs, pushers and passenger vessels carrying more than 12 passengers. Its purpose is to ensure technical standards that will pursue a safe operation and will allow progress and innovation in the sector (European Parliament, 2016).

2.2.1. Vessel propulsion systems

There are several different propulsion systems used onboard vessels today, among others: diesel propulsion, LNG propulsion, electric propulsion and fuel cell propulsion, as well as hybrids and dual-fuel system combinations between the different propulsion systems (MAN ES, 2019). The adoption of a certain propulsion system for an inland waterway vessel (IWV) is motivated by goals that operators are trying to achieve. When choosing among alternative technologies, one purpose is to reduce the cost (both cost of acquisition and fuel costs) that form some of the main categories of the total cost of the vessel (Stopford, 2009).

Improvement of environmental performance is also a key driver for the inland waterway market, since the vessel's performance has a direct impact on the surrounding environment (Wiegmans and Konings, 2016). While trying to improve energy efficiency in order to reduce atmospheric emissions, the interest is currently shifting to battery power for small ships (Wu and Bucknall, 2016), following the previous interest in converting diesel to dual fuel (LNG) propulsion (Wiegmans and Konings, 2016). In addition, in order for a vessel to be seaworthy and remain competitive there is a need for adaptation to climate change and compliance with new regulations, such as emissions and technical standards set by governmental authorities (Wiegmans and Konings, 2016).

The three propulsion systems used for the comparison in this thesis, diesel, LNG and electric, are presented in the following sections 2.2.2., 2.2.3. and 2.2.4.

2.2.1.2. Diesel propulsion system

The most common propulsion system used today is the diesel propulsion system which utilizes internal combustion to produce mechanical energy (Sharda, 2019). An illustration of a marine diesel fuel system is presented in figure 1.

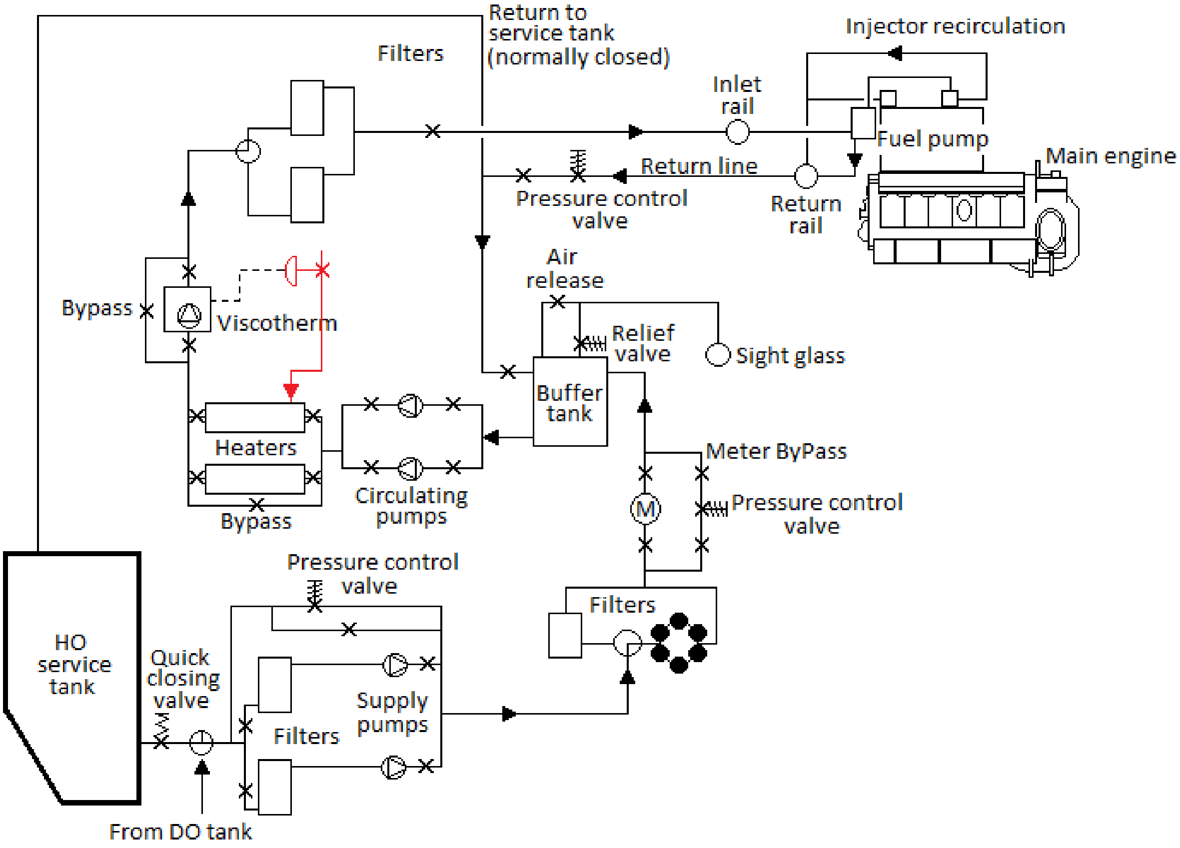

Figure 1. Marine diesel engine fuel oil supply schematic (based on MarineDiesels, 2005).

The reason why diesel engines have been so far most frequently used is that a diesel engine for large ships can run not only on marine gas oil (MGO), but also on heavy fuel oil. Heavy fuel oil is the residue obtained in petroleum distillation. It is the cheapest of fractions which is important in the shipping industry due to the huge quantities of fuel used. However, when it comes to inland waterways, the regulations regarding emissions and the use of fossil fuels are stricter than in the open sea. The European Commission has expressed its intentions to regulate the shipping emissions for the inland waterways in accordance with the limitations that apply for trucks since 2013 (Didier et al., 2017).

Additionally, a diesel engine generates high torque on relatively low RPM (Revolutions Per Minute) which is good not only for the fuel consumption, but it is also positive for the wear out of the engine, since it will allow it to operate longer. Moreover, diesel fuels have a higher flash point than other fuels, such as petrol. The high ignition point makes the fuel safer due to it minimizing the risk of fire incidents (Kuiken, 2008).

On the other hand, when burning diesel fuels, plenty of pollution is emitted in various ways. CO_2, SO_x, NO_x and particles are examples of air pollution, while potential oil spills can prove to be catastrophic for marine life as well as the fact that the diesel engine is loud and creates noise pollution (Fuglestvedt et al, 2009).

2.2.1.3. LNG propulsion system

For an LNG propulsion system, where natural gas is liquified and used as fuel, the biggest difference is associated with the fuel system. Figure 2 illustrates the different parts of an LNG fuelling system.

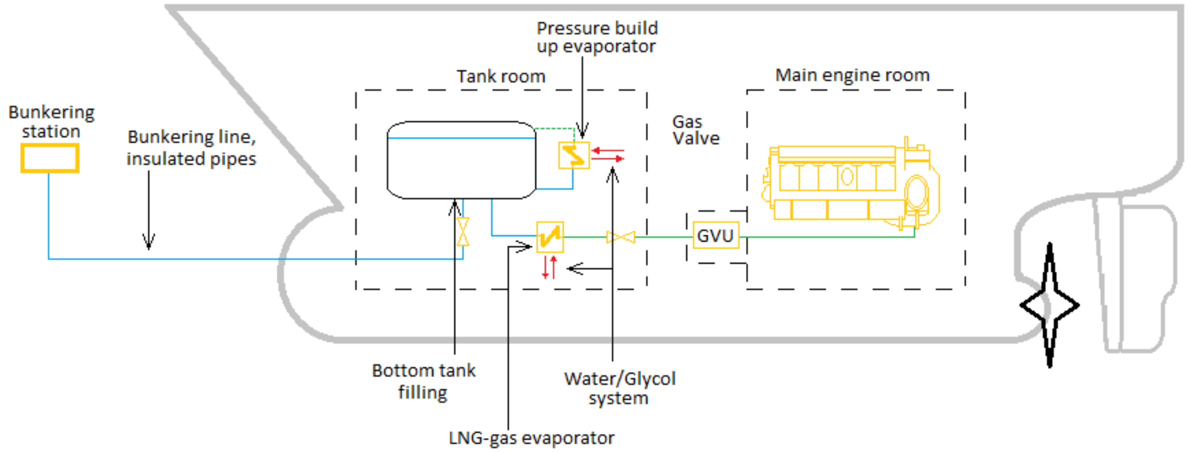

Figure 2. LNG fuel system schematic (based on TRB, 2013).

LNG has a lower density than diesel and marine gas oil which requires pressurized containers of a certain design. Due to the properties of the fuel itself, the tanks must be pressurised at about three times the ambient pressure and kept at a low temperature (-160°C) to keep the fuel in a liquid state when stored onboard the ship (Linde Engineering, 2020).

The biggest gain from using LNG over diesel as a fuel, is the lower emissions that are produced. LNG has become a trend in the maritime industry mainly because of its extreme low sulphur content but also for its reduced emissions of particular matters (PM) and NO_x. (Bengtsson, 2011). In addition, it is often available at a competitive price in comparison to fuel oils (Ellis and Tanneberger, 2015). However, what makes it less attractive from the traditional way of bunkering ships is the lack of infrastructure for LNG, the increased storage requirements and high investment costs (Wiegmans and Konings, 2016). Experiences from LNG ferries in operation suggest that about 2.5 – 4 times as much space is needed for storing LNG compared to fossil fuels (Martz, 2011).

2.2.1.4. Electric propulsion system

In a battery-electric propulsion system, the propellers are connected to electric propulsion motors that are supplying power for both propulsion and electrical requirements on board (Kyunghwa et al., 2016). Those motors are driven by the energy stored in the battery system that is typically charged from shore. An illustration of that system is presented in figure 3. In some battery-electric systems, a smaller diesel generator is sometimes included to ensure operation if the batteries fail to charge or to enable longer voyages (MAN ES, 2019).

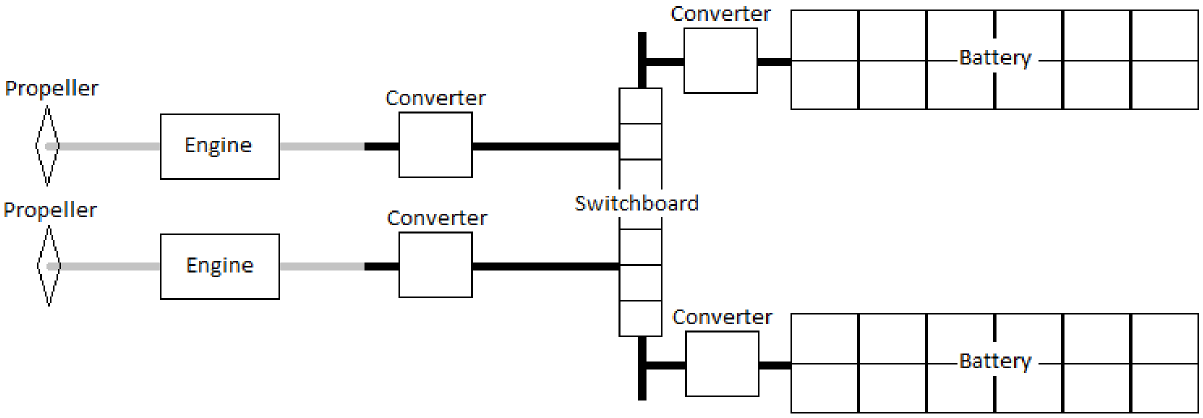

Figure 3. Battery propulsion system engine schematic (based on Editor, M., 2020).

For a fully battery electric vessel there is no need for fuel tanks, fuel processing, exhaust and air trunking, a diesel engine and its gearbox. In addition, auxiliary requirements change to some extent since the higher efficiency reduces the cooling load requirement (Zheng et al., 2004). There is also no need for regular maintenance, or the maintenance requirements are lower as for the diesel engine since the system is more reliable (Wu and Bucknall, 2016).

Considering the propulsion chain and all its components for a diesel and a battery propulsion system, Wu and Bucknall (2016) in their study proved the overall efficiency (energy source to thrust) of the battery system to be 67.8% against the diesel-mechanical option which is 31.4%, assuming that the efficiency of the propeller is in both cases 72%.

In addition, the system produces significantly less local pollution since it is not emitting any pollutants as compared to the combustion activity of conventional marine propulsion systems. However, the vessel still needs to use energy that charges the batteries. Electricity consumption from shore is essential, especially for container vessels, as they typically operate in a liner schedule with fixed ports of call, while they can carry reefer containers that require a large amount of energy at quay. Another way to charge the batteries is by using Power Take Off on a generator where the engine uses fuel combustion (MAN ES, 2019).

The drawback of using batteries onboard ships, compared to a traditional engine, is the energy density which is the volume needed in the ship to achieve reasonable speed and range. The heavy weight of the batteries, the high costs associated with the replacement of aged batteries and the installation of a recharging infrastructure on shore, require a high investment cost for the battery powered propulsion system. In addition, batteries have technical limitations that include energy density, power density and lifetime. At the moment, the batteries have a short lifetime compared to the whole lifetime of a ship, which means they may have to be replaced several times throughout the ship's lifetime. The battery replacement cost together with the cost of electricity consumed from the local grid are the major operating costs of the propulsion system. (Kyunghwa et al., 2016).

Compared to ships powered by liquid fuels, battery power will most often impact the vessel’s speed and range, due to the power density, meaning longer voyage time, which is automatically affecting the vessel’s size, operating profile, speed, routes, etc. (Wu and Bucknall, 2016). Those limitations will respectively have an impact on the economic scenario of the vessel’s case and limit the profitability.

2.3. Life cycle cost analysis

A life cycle cost analysis (LCCA) is an economic process to assess and evaluate the cost of an item over its life cycle. It identifies and quantifies all the important costs related to the lifespan of an item (Woodward, 1997). A short but concrete definition of life cycle cost (LCC) is: "The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life” (White and Ostwald, 1976).

Tangible and intangible expenses are included in the analysis, but not revenues and value outcomes. The LCCA typically includes cost of acquisition, operating costs, maintenance costs and cost of disposal at the end of the item’s functional life (IEC, 2017). However, despite those categories, the detailed costs in the cost breakdown stage will depend on the item to be analysed and the objective for the analysis (Woodward, 1997). When deciding to lease or own an asset, an

LCCA is one of the factors to take into account. It provides information for decision makers of a company in order to minimize the total cost of ownership of an item, including acquisition and operation (IEC, 2017). More specifically the objectives of LCCA include (Woodward, 1997):

1. More effective evaluation of investment options.
2. Consideration of all costs and their impact, rather than only initial construction cost.
3. Assistance in the effective management of overall projects.
4. Facilitating the choice when more alternative options are competing.

The LCCA is conducted at an early stage of conceptualizing an idea and it provides important information to develop budget estimates that will also influence future costs (IEC, 2017). The results of an LCCA can then be used for a financial analysis where revenues are also considered. When life cycle costing is conducted for financial purposes, the process and data collected should be extensive and accurate (Woodward, 1997). When the purpose is to evaluate alternatives, the data to be analysed will only be the data relevant to the comparison (IEC, 2017).

2.3.1. Previous work

Since the last decades, lifecycle approaches have become popular in the shipping industry. Previous studies in the area have mostly been looking into the LCCA of a vessel in relation to a Life Cycle Assessment (LCA) that mainly assesses environmental aspects. In those cases, the main focus has been to identify the environmental impact of the vessel with the costs being an associated aspect as opposed to the main aspect. The European Union has carried several projects with the consideration of LCA and LCCA. One of those being the Eco-REFITEC which focuses on the development of green power on board vessels by retrofitting options (Davis-Blanco and Zhou, 2014).

Another EU project is the SHIPLYS that suggests a framework for LCA and LCCA aiming to select optimal propulsion systems (Wang et al., 2018). Wang et al. have applied the LCC assessment framework to select optimum propulsion system among hybrid and diesel propulsion for a short-route ferry. Their results show that even though the construction costs for the hybrid alternative were higher, they compensate with the lower operating and maintenance cost ending to the hybrid alternative being €662 000 lower in overall costs. More specifically the construction costs for the hybrid alternative was 3.5 times the diesel alternative while the total operational costs for the diesel was 1.5 times more expensive. Regarding operational phase, they concluded that minimum cost is achieved with the maximum use of the batteries and when instead of charging the batteries onboard, the batteries are charged on shore during night-time when the electricity price is lower. Researchers from Italy have also developed a life cycle cost model to assess costs and environmental impact of different maritime vessels (Germani et al., 2017). More specifically, they present three phases, manufacturing, use and end-of-life, where input and output data of the model are measured.

Many comparative analyses have been done for the assessment of different options when investing in a newly built vessel. Recently, more comparative analyses of different fuels and propulsion systems have been performed, but most are looking at the environmental aspect of the systems, as opposed to mainly the financial aspect of the propulsion systems (Alkaner and Zhou, 2006), (Schmidt and Watson ,2013). Such projects include Alkaner and Zhou’s investigation on fuel cells and diesel engines for marine application as a comparative study on life cycle analysis (Alkaner and Zhou, 2006). Schmidt and Watson (2013) have done a comparative LCCA on two different ferries to investigate the potential for economic and environmentally friendly lightweight ferries in Sweden and Denmark, basing the comparison on the vessel’s structure and hull components.

The company MAN Engine Solutions has done a study on the perspective of batteries on board vessels, where they estimate the construction cost for applying electric propulsion system on ocean going vessels of 50 000 dwt and 2 500 TEU minimum capacity (MAN, 2019). They compare the electric propulsion system to a typical two-stroke diesel propulsion system where they assume that the price of the power electronics and the electric motor is roughly the same as the price of the two-stroke main engine. Their results show that when the cargo transport rate is the same for both alternatives the total construction costs for the electric vessel compared to the traditional propulsion system will be three times more expensive, without including any battery change during the vessel's lifetime. One reason for further increasing the cost of the electric propulsion in that study was the applied service speed and the storage space in order to keep an equivalent transport rate.

2.4. Costs in the shipping industry

The term cost is explained by several definitions, one of which being: “a measurement in monetary terms, of the amount of resources used for the purpose of production of goods or rendering services” (Arora, 2009). The scope of the term cost is extremely general and thus is normally followed by an adjective like actual cost, marginal cost, standard cost, direct, fixed, and so on (Arora, 2009). However, there are other ways to categorize costs according to the scope.

Stopford in his book, Maritime Economics, identifies five cost categories related to a shipping company: capital costs, operating costs, periodic maintenance costs, voyage costs and cargo handling costs (Stopford, 2009). Each category consists of different cost items to which costs are assigned and are being separately measured (Arora, 2009). When conducting an LCCA, the common practice of categorizing the costs for the item under study is construction cost (or capital cost), operational costs and scrapping costs (Wang et al., 2019).

2.4.1. Construction costs

The capital costs refer more to the way a ship is financed and the acquisition cost (Stopford, 2009). These costs depend on the size of the loan, the interest rate applied and for how many years the loan lasts. The acquisition costs also depend on which currency the loan is at, this because of future fluctuations in the currency market that can have a major impact on the end value of the loan. In this category the building cost of the ship is included, since capital costs are defined as a one-time expense incurred in the stage of purchase (Stopford, 2009).

The construction cost of a ship is part of the capital cost category and commonly analysed according to the main building entities that the ship consists of; the steel structure, the machinery and outfitting.

In order to assign the cost to an item, it should be clear how the costs are occurring thus a breakdown of the workload and the resources used for the item is needed for more accurate results (Arora, 2009). Thomas Lamb, in the Ship Design and Construction book, separates the process of acquisition in four phases (Lamb, 2003):

1. planning
2. design
3. commercial activities

4. production

In the planning process, first a strategic plan is conducted, where the whole organization is involved, and an environmental analysis and strategy development is included. Second, the business plans, (a set of concrete plans including a marketing plan, competitor plan, financial plan, technology plan, organization plan and corporate development plan) are executed. Also included in this stage are the mission statements to control the economic feasibility of the acquisition process (Lamb, 2003).

The design phase in the ship acquisition process includes technical models, drawings, calculations, specifications and the required testing (Lamb, 2003). It demonstrates the configurations of the ship and includes the concept design, preliminary design, contract design and detailed design. The concept design defines some of the principle characteristics of the ship and requires a small number of creative engineers. In the next process, the preliminary design, much greater details are defined with features that will determine the main characteristics of the ship, like more accurate calculations on the hull strength, weight, draft, deadweight capacity and stability of the ship. The contract design is a set of documents that include contract specifications and drawings and accurately describe the ship to be built. In the detailed design, the contract design is developed even further, and all details are completed.

In the commercial activities stage, selection of yard, ship financing, negotiations and contracting between the shipyard and the shipowner as well as classification costs are pursued (Lamb, 2003).

The production phase begins with the signing of the contract and even though the initiatives shift directly to the shipyard, the shipowner continues to be involved in this stage with activities like contract management, inspection and quality control, approval of plans and ship delivery (Lamb, 2003).

One way to base a cost estimating method is by the ship’s technical characteristics like major dimensions and power. When estimating the costs of production, the ship is divided in parts and analysed respectively as individual parts. In that case the common base of a unit cost is on weight (Papanikolaou, 2014).

For the shipyard to estimate their production cost, it follows the work breakdown structure. These categories are:

- hull structure
- propulsion plant
- major equipment items
- distributed Systems (electrical, piping,heating ventilation and air condition)
- cleaning and paint
- manufacturing and assembly operations that can be easily identified by task (discrete work production work orders)
- production support activities (level of effort work such as shipyard services)
- technical services (design and engineering)
- subcontracted services
- material and equipment
- shipyard services (design and engineering)
- technical services (shipyard support)

2.4.2. Operational costs

The second category consists of the operating costs, the cost associated with the everyday expenses of running a ship. This category includes costs that will occur no matter the type of the trade the ship is involved in. Some cost elements related to this category are crew wages, stores, lubricants, repairs, maintenance, insurance and administration (Stopford, 2009). These costs depend much on the management approach of each company. For example, the insurance costs will be affected not only by calculated risks and ship's value but also from the operational history of the operators, since they may get bonuses or penalties for loss experiences (Pocuca, 2006).

When calculating the operating costs of a ship, the normal practice is to calculate the yearly operating costs for the number of years the ship will be functional and deduct that number to a present value (Pocuca, 2006). During a voyage the ship is to be under operation all 24 hours, normally in an agreed-on speed that will determine an established fuel consumption amount for the days it is set to fulfil the transport. While berthed at port the ship continues to consume energy to sustain systems that include heating, ventilation and air conditioning (HVAC system), while cargo handling costs and port dues occur as well. However, when the ship is under maintenance and repair in a shipyard, those hours will be deducted from the operating cost calculations (Pocuca, 2006).

2.4.2.1. Personnel costs

The crew wages form one of the most important and larger cost items in the operating phase (Stopford, 2009). These costs can vary even on the same type of ships since, for example, operators employ crew members from different countries which results in a significant difference in the crew wages. Stopford renders 17.4 per cent of the total operating costs to the subcategory of personnel costs (Stopford, 2009). This cost category can additionally differ among different types of ships. Labor costs on merchant vessels under 1500 tons have an average of 45 to 50 percent of monthly vessel operating costs, while on vessels larger than 7000 tons that percentage ranges between 17 to 25 (US Office of Federal Coordinator of Transportation, 1936).

2.4.2.2. Maintenance costs

One way of identifying the maintenance costs is by looking at the cost drivers for these costs. Important factors are the initial costs and suitability and durability of the materials from earlier on in the design phase of the building costs (Pocuca, 2006). The maintenance cost is calculated in accordance to the type of material and the maintenance activity. The operational maintenance policy of the operator will also affect to a large extent the cost of maintenance through the number of repairs and maintenance that is made. The maintenance activity can be further broken down according to frequency and responsibility (SPAR Associates, 2011). In table 1 the personnel responsible for specific maintenance activities and the frequency of the activities are presented.

Table 1. Maintenance activity frequency (SPAR Associates, 2011).

Position	**Daily**	**Weekly**	**Monthly**	**Annually**
Ship master	X	X	X	X
Designated crew	X	X	X	X
Deck mechanic	X	X	X	X
Engine mechanic	X	X	X	X
During evening lay-up	X			

Besides the maintenance performed on a daily, weekly, monthly and annual basis presented in Table 1, there are activities which have to be performed with less frequency, such as:

- Bi-annual dry-dockings
- Machinery maintenance - specified by equipment manufacturer
- Mid-life modernization and upgrades
- Expected unscheduled maintenance

In addition, there are costs associated with periodic maintenance that occur when the ship is in dry dock for surveys and repairs (Stopford, 2009). At this stage, high costs can be incurred, especially if the ship is old and significant repairs needs to be done. What affects this category is the age of the ship, the maintenance policy of the shipowner/operator, the special survey cycle and regulations. The quality of previous maintenance and day to day operational practices are variables that cannot be determined but will largely affect the costs of this category.

2.4.2.3. Voyage costs

Included here are variable costs related to a specific voyage or route. Voyage costs and elements that affect those costs include fuel consumption, main engine, auxiliary engines, fuel price, speed, port charges, canal dues, tugs etc (Stopford, 2009). The biggest part of this category is fuel costs (Stopford, 2009), which will largely depend on the price of the fuel, but also the specific fuel consumption of the vessel. Fuel consumption can differ between the same type of ships since it is dependent on the age of the ship and the condition on hull and machinery. The fuel prices depend largely on availability and market parameters like supply and demand, location etc (Stopford, 2009).

However, the shipyard is trying to manage the consumption of fuels by changing technical characteristics on ships like engines with better utilization of fuel and hulls that render better propulsion and lower the need for fuel through lower resistance and, more recently, developing new propulsion systems like battery driven ships. Operators can also control the consumption through voyage optimization, speed adjustments and antifouling measures (Pocuca, 2006).

2.4.2.4. Cargo handling costs

These costs are important in the shipping industry, particularly in liner trades. They refer to the costs for loading, stowing and discharging cargo, and they depend on the type of cargo (i.e. general cargo, container, bulk cargo or packaged cargo), ship design (container, bulk, barge), cargo handling gear (cranes, derricks, trucks, shore cranes etc.), unitization of cargo (container, pallets, packages etc.), organization of the cargo handling process and stevedore costs (Stopford, 2009).

2.4.3. Scrapping costs

In the scrapping phase the costs of the system's disassembly at the ship dock are included, along with transportation, recycling and scrapping at respective facilities. The energy required for the implementation of the scrapping process is an important part of those costs. During this process, some components of the ship's materials will be recycled while some will end up in a landfill (Jeong et.al, 2018).

2.5. Codification system

To identify and break down the costs for constructing a ship, the SFI (which stands for "skipsteknisk forskningsinstitutt", the ship research institute of Norway) codification system has been used as a base and is complemented with Watson's specification format of merchant ship types (Watson, 1998).[2] The SFI system was first developed by the Ship Research Institute of Norway in 1972, to form a standard for shipbuilding. The system is hierarchy-based, where each cost for constructing a ship is identified and given a unique code depending on its function, and then sorted into main groups, groups and sub-groups (SpecTec, 2020).

Both Watson's specification format and the SFI codification system are using a hierarchical system to divide the costs. By using a hierarchical system to divide the systems of a vessel, it is easier for the user (i.e. shipowner, shipyard or ship design company) to keep track of several different things; such as costs, maintenance and other information (ShipLab, 2014). Since the SFI codification system is a standardized system used worldwide, it provides a reliable breakdown structure of the cost elements for constructing a ship.

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[2] A full list of the combined cost elements in the SFI codification system and Watson's specification format for construction costs can be seen in appendix A.

3. Methodology

The methodology that is adopted throughout the LCCA is dependent on the fact that this is a comparative analysis and the data needed for the cost model should be as accurate as possible, although considering the long and complex life cycle of the vessel and thus the associated uncertainties. When planning the analysis, the scope is defined by identifying the elements of the study, such as the main objective of the analysis, the timeframe and the operating environment with the respective boundaries. Additional scoping statements are, the setting of financial decision criteria that can influence the outcome of a comparative analysis and are related to measures, definition of the cost breakdown structure and lifecycle stages, as well as identification of alternative options for comparison purposes (IEC, 2017).

In order to compare the LCCA of three alternative propulsion systems a cost model was developed. The costs of the three propulsion systems are collected, categorized, and compared on two levels: construction costs and operational costs. The scrapping costs of the vessels are categorized and broken down in the cost model as well. However, since they are assumed to be the same for all three vessels, they are not included in the comparative analysis of the vessels. A further breakdown of the construction and operational costs follows in the cost model performed on an excel spreadsheet, which consists of the costs that differ among the alternatives and is as detailed as necessary to provide accuracy.

3.1. Data Collection

To answer the research questions, a literature review of articles and material relevant for the scope of this thesis is performed, as well as data collection through interviews with appropriate stakeholders in the field, such as manufacturers, scrappers and operators.

A big part of the initial work for this report was to gain the necessary knowledge through theoretical studies. In the literature review, costs of the shipping industry, cost estimating methods, cost analysis tools and cost breakdown systems were identified. The most suitable tools and data that corresponds to the purpose of the study were chosen as reference. The literature studied includes books, e-books, academic reports, industry reports and websites. For access to books and e-books the Chalmers library website was used, while for further research on more relevant reports, articles and websites the google browser, google scholar, Scopus and similar databases have been used. Part of the data used in the report was also provided by SSPA.

Apart from the secondary data collected through the literature review, access to primary data was also provided through interviews conducted with stakeholders in the maritime industry, such as manufacturers, operators, scrappers and scientific institutions. The primary data of cost elements were used as inputs in the cost model of the analysis while secondary data were collected to supplement and validate primary data. The method used in the interviews was both structured and semi-structured. In a structured interview the questions are decided in advance and presented in a specific order to the interviewee while on the semi-structured interviews the subject and the questions are decided in advance, but the interviewer is also forming questions during the interview (Björklund and Paulsson, 2012).

The method used and the questions formed were adjusted according to the stakeholder's profession and the data that was expected to be given input on. The purpose of using a semi-structured interview is to equip the interviewer with new ideas acquired from what the interviewee says. On the other hand, a structured interview, using the exact same questions in the same order, is used to ensure that the data will be reliably aggregated and the comparison between the samples can be made with accuracy (Björklund and Paulsson, 2012). Presented in table 2 are the interviewed stakeholder companies, the interviewees position as well as type and length of the interview.

Table 2. Interviewed stakeholders, positions, type of and length of interview.

Stakeholder	**Position**	**Type of communication**	**Interview technique**	**Length**
Marine research institute	Head of the project department	Skype	Semi-structured	1 hour
Marine research institute	Director of the maritime academy	Skype	Semi-structured	1 hour
Insurance company – P&I and hull & machinery	Senior underwriter	Skype	Structured	1 hour
Ship design consultant firm	CEO	Skype	Structured	40 min
Ship building company	Sales manager, supervisory board member & business developer	Microsoft teams	Structured	1.5 hours
Engine propulsion manufacturer	Sales manager	Microsoft teams	Structured	1.5 hours
Engine propulsion manufacturer	Electric design manager	Microsoft teams	Structured	1.5 hours
Fuel supplier	Sales manager	Phone	Structured	20 min
Fuel supplier	Bunker trader	E-mail	Structured	
Fuel supplier	CEO	E-mail	Structured	
Fuel supplier	Sales manager	E-mail	Structured	
Port authority	Senior manager market intelligence and innovation	E-mail	Structured	
Port authority	Marketing and sales-manager	E-mail	Structured	
Ship operator	Technical inspector	E-mail	Structured	
Ship operator	Captain	Study visit onboard ferry	Semi-structured	1.5 hours
Maritime research institute	Maritime consultant	E-mail	Structured	
Maritime research institute	Maritime consultant	E-mail	Structured	
Electric propulsion manufacturer	Commercial director	Phone	Structured	10 min

The interviews with the relevant stakeholders were mainly conducted via skype. At first, semi-structured interviews were performed with people from marine research institutes and employees at SSPA in order to acquire a holistic view over the costs related to the life cycle of a vessel, as well as the differing costs between the three propulsion systems. When performing these semi-structured interviews, open ended as well as follow up questions were directed to the respondents in order to collect qualitative information corresponding to the subject of the thesis.

Later, more interviews with ship operators, manufacturers, scrappers, and people from insurance companies were carried out. In this process structured questions were asked, as well as specific questions that would provide direct answers to amounts of the cost elements included in the model. Moreover, selected specific questions were directed via email to bunker suppliers and port operators in order to collect current data on fuel prices and port fees.

Due to time and access limitations, some figures included in the model are actual, like the current fuel prices and port dues, but some costs are estimations given by the stakeholders through the interviews and are based on their experience. The data provided by the stakeholders in interviews were collected in an excel spreadsheet where the cost model was developed, and the results for the different propulsion systems were compared.

3.2. Case study

The LCCA is performed on the fully electric concept vessel of Vänermax size with the vessel's specifications provided in the report by Sjöling et al. (2020), which is described in table 3 along with the two alternative propulsion systems that the comparison is based on.

The operating time is assumed to be the same for the time period of the life cycle analysis and for all three vessels, following the schedule of the concept vessel, which is intended to execute a turnaround trip between Trollhättan and Gothenburg on a daily basis. The distance per one turn around trip is 90 nautical miles which the vessel will cover in 16 hours at an average speed of 8.27 knots. The 8 hours remaining the vessel shall spend in the port for loading and discharging cargo. The vessel is expected to be operating for 260 days per year, out of which 4 weeks (20 working days) are deducted for dry-docking and traffic implications.

The operational profile of the case is calculated for one year, and then the accumulated future value (FV) is calculated over the 30 years of operation for the three propulsion systems. Because of the vessel’s long lifetime, a long-term perspective was applied when collecting and evaluating data that is prone to changes in order to make accurate cost calculations and comparisons of the three alternatives. The designed service life of a vessel is 20 – 30 years, depending on various parameters, one of which is operational management (Dinu and Ilie, 2015).

The dimensions and characteristics of the electric concept vessel developed by SSPA and the two propulsion alternatives are presented in Table 3. The vessels are assumed to have the same dimensions in regard to length, width, draught and weight. There is a difference between the vessels in total cargo capacity due to the different fuel systems requiring different amounts of space, with a difference of 2 – 6 containers between the vessels.

Table 3. Vessel alternatives comparison.

	Electric	**Diesel**	**LNG**	Unit
Length over all	87.9	87.9	87.9	m
Beam	13.4	13.4	13.4	m
Draught	6.9	6.9	6.9	m

Air draught	6-15/18.7	6-15/18.7	6-15/18.7	m
Deadweight	3 475	3 475	3 475	t
Total cargo capacity	150	156	148	TEU
Gross tonnage	2 136	2 136	2 136	t
Net tonnage	1 310	1 310	1 310	t
Service speed	10	10	10	kn
Max speed	12	12	12	kn
Battery size	6 100			kWh
Controllable pitch propeller	2 x 3.0	2 x 3.0	2 x 3.0	m
Crew	3	3	3	
Ice class	1C	1C	1C	

3.2.1. Propulsion systems comparison

The electric concept vessel described above will be compared to two other propulsion systems, one running on diesel and one running on LNG. The diesel and LNG vessels are assumed to have the same length, beam and draught as the electric concept vessel described in Table 3, the difference will be related to the propulsion systems installed onboard.

In order to compare all three propulsion systems on the same level, the diesel and LNG engines will be of a similar size as the electric vessel's two 590 kW-engines. When interviewing an engine propulsion manufacturer, the best option for the diesel propulsion system was decided to be a set-up of two 634 kW-engines at €150 000 each, with a SFOC of 205.3g/kWh and unlimited operation time. The whole diesel propulsion system, with a twin-screw drivetrain layout, a 2-stage reduction gear box, hydraulics, stern tubes etc, amounts to a total of €850 000 - 1 million.[3]

The costs for an LNG engine of a similar size as the electric engines is not available, since there are no LNG engines of the same size as the electric engines on the market today. When interviewing both a shipyard and an engine propulsion manufacturer, the added extra cost for an LNG propulsion system, compared to a diesel propulsion system, was estimated to be €1.5 - 2 million,[4] where the cost for the LNG fuel tanks of €1.2 - 1.4 million is included.[5]

All three vessels would also need to be fitted with an emergency auxiliary engine and bow thrusters for manoeuvring. However, for the purpose of this thesis the costs for the auxiliary engines and bow thrusters are assumed to be the same for all three vessels.

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[3] The total cost for the diesel propulsion system is in this thesis calculated at €1 million.

[4] In this thesis, the extra cost for the LNG propulsion system compared to the diesel alternative, is calculated at €2 million.

[5] In this thesis, the cost for the LNG fuel tanks is calculated at €1.4 million.

3.2.2. Cargo capacity

In table 4 the space requirement for all three vessels is illustrated. For the electric vessel, the batteries onboard will require a space of 6 TEU (twenty-foot equivalent unit), and an additional 4 TEU for the engine room (Sjöling et al., 2020). The diesel and LNG vessel would not require the same space for batteries as the electric vessel, but they do need space for the engine at 4 TEU each. The LNG vessel will also need extra space for the added fuel tanks. Since the LNG fuel tanks are separate from the vessel's construction, in an interview with a maritime research institute, the required space for the additional LNG fuel tanks was estimated to be 8 TEU.

Table 4. Space requirement for engine room and fuel tanks.

	Electric	**Diesel**	**LNG**	Unit
Engine room	4	4	4	TEU
Battery room	6	-	-	TEU
Fuel tanks	-		8	TEU
Total space requirement	10	4	12	TEU

Deducted from the total container capacity of the concept vessel of 160 TEU, the electric vessel is left with a 150 TEU container cargo capacity, the diesel vessel has 156 TEU available and the LNG vessel 148 TEU of available cargo capacity.

3.3. Cost model

The proposed cost model is divided into three phases: "construction", "operation" and "scrapping". The LCCA is carried out in an excel spreadsheet where the collected data is gathered. The numbers are costs provided by relevant stakeholders operating in the shipping business through interviews and are based on their experience and knowledge of the business, as well as through research on market prices and literature review.

By using the SFI codification system, an overview of the costs related to construction and operation & maintenance of a ship is provided, as well as simplifying the analysis and interpretation of the LCCA results for the complex construction that a ship is. The breakdown structure also facilitates easier identification of costs when performing interviews, by allowing an easy switch between detailed and general information (Germani et al., 2017).

3.3.1. Cost model calculations

To calculate the LCC for a ship, first the individual parts, i, separated into construction costs, $C_{C,i}$, operational costs, $C_{O,i}$, maintenance cost, $C_{M,i}$, and $C_{S,i}$, scrapping costs, are identified and calculated. The total LCC was then calculated as the sum of all the separate costs for the ships in different stages of their lifetime as shown in equation 1 (Wang et. al, 2018).

$$LCC = \sum_{i=1}^{n} C_{C,i} + \sum_{i=1}^{n} C_{O,i} + \sum_{i=1}^{n} C_{M,i} + \sum_{i=1}^{n} C_{S,i} \qquad \text{Equation 1.}$$

When operating a ship, the overall biggest costs are the costs of the crew (wages, insurance, pension etc.) and fuel costs (Stopford, 2009). In this thesis, as only the differing costs will be analysed, the voyage costs that will be calculated in the cost model is the fuel cost, port fees and fairway dues. Since the analysis is performed on three ships with different propulsion systems, and therefore different fuels, the fuel costs between the three ships are expected to be different.

To calculate the fuel costs for the vessels, equations 2 and 3 (Wang et. al, 2018) are used in the cost model, where the fuel consumption of the diesel and LNG vessel is calculated by multiplying the sum of the specific fuel oil consumption with the engine load and time in years. This value is then multiplied with the fuel price for the respective fuels of the vessels.

$$F_C = \sum_{i=1}^{n} SFOC \times P_i \times T_i \qquad \text{Equation 2.}$$

$$C_F = \text{€}_{fc} \cdot F_C \qquad \text{Equation 3.}$$

Besides consuming a lot of fuel during operations, the vessels consume quite a lot of lubrication oil for the engines to run smoothly. According to stakeholders interviewed, the cost of lubrication oil will be negligible in difference between the diesel and LNG propulsion systems, and only a small amount will be needed for the electric vessel. The cost of lubrication oil is already included in the maintenance cost for the three propulsion systems provided in interviews and is therefore not calculated separately in this thesis.

Since the vessels are expected to operate over 30 years, the accumulated future value (FV) (Finance Formulas, n.d.) of the total operational costs for year one are calculated using equation 4, where C_0 represents the cash flow at period 0, r is the fixed annual interest rate applied each year and n is the number of periods the payment is made. The future value is calculated by using the FV function in excel, where the present value of total operational costs for the three vessels are calculated over 30 years, at an interest rate of 2%.

$$FV = C_0 \times (1 + r)^n \qquad \text{Equation 4}$$

3.3.2. Cost breakdown structure

To identify and break down the costs for constructing a ship, the SFI codification system described in section 2.8. have been used as a base, and then complemented with further cost items provided in a cost breakdown structure of shipbuilding costs developed by Watson in his book *“Practical Ship Design*” (Watson, 1998).

To break down the construction costs for a ship the cost items are categorized according to their respective area. The cost items are categorized into main groups, identified by one digit. The main groups are divided into groups, identified by two digits. Each group is then further divided into subgroups, identified by three digits. For example, in the SFI codification system, the main group number 2 is designated to the hull, group number 20 is hull materials and subgroup 200 is steel plates.

Since the SFI codification system is a standardized system, most of the costs for ship construction are provided through the SFI system. The system was adapted to the purpose of the electrified concept vessel by analysing all the cost items through interviews with stakeholders of maritime research institutes.

To identify the costs for operations and maintenance of the vessels, the cost items identified for the construction of the vessels have been used as a starting point for maintenance costs and spare parts, and voyage costs such as fuel and fairway dues have been identified through interviews with stakeholders in the academia, staff at SSPA and port authorities in Gothenburg and Trollhättan.

All costs that are the same or minor in difference for all three vessels are excluded from the full list of construction and operation & maintenance costs, and they are therefore not calculated. Only the cost items that are identified as being different between the three vessels are included in the cost model, this to highlight the difference in cost between the vessels. The costs included in the model are as detailed as necessary to provide an accurate and meaningful analysis.

4. Analysis

All the costs presented in the cost model have been converted to USD from their original currencies based on current foreign exchange rates from XE (2020), this to have a homogeneous currency all throughout the cost model for easier understanding and calculations throughout the cost model.

To be able to perform the necessary calculations for the analysis, some assumptions have been made in order to put all the prices and calculations on a level playing field (Barroso, 2018) and place the focus of the analysis on the three propulsion systems. The assumptions made for the purpose of this thesis are mostly based on facts provided in a report published by SSPA (Sjöling et al., 2020) of the electrified concept vessel.

The assumptions important to the case study are:

- All three vessels are assumed to have the same operational profile as presented in section 3.2.
- The vessels are assumed to discharge their waste, bilge water and sludge in the port of Trollhättan where the waste fee is already included in the port fees.
- The capital costs for all three vessels are the costs for a newly built ship.
- All costs associated with the scrapping of a vessel is in this analysis omitted.

4.1. Construction costs

To identify the costs that would be different between the three propulsion alternatives, the full list of construction costs using the SFI codification system and Watson’s specification format of merchant ships developed in section 2.5. was put forth to several stakeholders operating in the maritime industry, such as a maritime research institute, a ship building company, a maritime consultant company, an insurance company and a ship design consultant firm. From the full list of construction costs, the cost elements which would be the same for all three propulsion alternatives were deducted, and only the ones which would be different were left.

The following cost elements are identified as being different between the three propulsion system alternatives in this thesis:

Main machinery components

- Diesel propulsion system
    - Diesel engine
- LNG propulsion system
    - LNG engine
- Electric propulsion system
    - Electric engine
    - Batteries

Systems for main machinery components

- Fuel systems
    - Fuel tanks

Ship common systems

- Air sounding systems
- Electrical power supply
    - Shore power connection
- Electrical distribution common systems

    - Main switchboard
- Electrical cable installation

With a current retail price of €600-800/kWh, the initial cost for a 6 100-kWh battery alone is the total of €3 660 000 - €4 880 000. The batteries necessary to power a ship engine of the size needed for this vessel is much more expensive than regular batteries. When interviewing a ship owner in the Gothenburg area, it was stated that the cost for batteries is somewhat hard to define, when the price given is usually a total installation price where cooling, fire protection and control systems are included as well, besides the batteries themselves. The total cost of the related systems installed along with an electrical propulsion system is about ⅓ of the installed battery cost, and there is also necessary to deduct the equipment not necessary for the electric propulsion, which is small in comparison.

Because the vessels are running on different fuels, there are different storage facilities necessary to accommodate the specific properties of these fuels. The main difference between the fuel system of the diesel and LNG propulsion system, is the LNG fuel tanks which have to accommodate the LNG fuel. Usually, the fuel tanks on a diesel vessel are an integrated part of the vessel’s hull structure, and there is therefore no extra cost for the fuel tanks themselves for the diesel vessel. There might, however, be a difference in costs related to the hull structure itself for the diesel vessel, but this cost has not been provided. The LNG fuel tanks are not an integrated part of the vessel’s construction, because of this an extra 100% in cost for fuel tanks is added for the LNG propulsion vessel, making the LNG propulsion system about $2 million more expensive than a diesel propulsion system.

In interview with a ship building company, general figures were provided for the cost of electric, diesel and LNG propulsion. These costs have been assessed with the costs provided in interview with an engine propulsion manufacturer, where the cost of the engine has been deducted from the general figure provided by the ship building company.

Presented in Table 5 are all construction costs identified for the three vessels.

Table 5. Construction costs of the vessels.

	Electric	**Diesel**	**LNG**
Machinery main components			
Electric propulsion			
Electric engine[6]	101 600		
Batteries for propulsion (at $790/kWh)[7]	3 374 252		
Diesel propulsion			
Diesel engine		1 128 890	
LNG propulsion			
LNG engine			1 806 224
Systems for main machinery[8]			
Fuel systems			
Fuel tanks			1 580 446
Ship common systems	1 446 108	282 223	282 233
Sum construction costs	**4 921 960**	**1 411 113**	**3 668 893**

NOTE: All values in United State dollars, USD.

4.2. Operational costs

The operational costs have been identified using the construction costs as a starting point, and through interviews with various stakeholders, including port authorities, fuel suppliers, an engine propulsion manufacturer and an insurance company, the cost elements for all operational costs were identified, and the cost elements identified as being the same for all three propulsion alternatives were deducted from the cost model.

The cost elements identified as being different during operation are:

Voyage costs

- Fuel
  - Electricity
  - Diesel
  - LNG
- Fees and dues
  - Port fees
  - Fairway dues

Maintenance and spare parts

- New batteries

During the vessel's lifetime, several costs are incurred for the shipowner to keep the vessel going. The costs that are different between the alternatives are presented in table 6 and include the cost of fuel, port fees and fairway dues, as well as the cost of maintenance and spare parts.

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[6] Total cost for 2 x 590 kWh-engines á $50 800 each, provided in an interview with an electric propulsion manufacturer.

[7] The cost for the batteries in this table is calculated as 2/3 of the total cost for the whole propulsion system, as indicated in an interview with a ship operator in Gothenburg.

[8] Cost elements included under "ship common systems" are (among others) the costs for inverters, transformers, main switchboard, fire alarm, ventilation etc.

The single biggest cost for all three propulsion alternatives is the fees and dues. The port fees and fairway dues are mandatory for all vessels travelling on Swedish waterways and calling at a Swedish port and are based on the vessel's gross tonnage (GT), which is the same for all three vessels. The cost for the port fees and fairway dues are calculated by multiplying the number of port calls the vessels have in one year with the port fees and fairway dues as set by the Swedish Maritime Administration (SMA), Port of Gothenburg and the port of Trollhättan. From this figure, the environmental and frequency discount was then deducted, giving the total fees and dues for one year as presented in Table 6.

The fuel cost is also an unavoidable expense for the shipowner during the vessel’s lifetime, even though all three alternatives are assumed to have the same operational profile (time spent in each operating mode, speed and nm travelled) and energy consumption, there is a difference in fuel costs due to the different fuels being used, all having a different energy content and a different price.

The fuel cost for the three vessels was provided by using equations 2 and 3, where first the fuel consumption for one year for each of the three vessels was calculated by multiplying the SFOC of the engines, provided in interview with an engine propulsion manufacturer, with the energy consumption necessary for one year of operation. This figure was then multiplied by the average fuel price calculated from prices provided from several fuel suppliers in Sweden. The result is presented in total fuel cost over one year in table 6.

The cost of maintenance and spare parts presented in table 6 are estimates provided in an interview with a ship building company.

Table 6. Annual operational costs for the vessels.

	Electric	**Diesel**	**LNG**
Voyage costs			
● Fuel	70 501	91 355	92 111
● Fees and dues			
- Port fees	338 074	360 797	349 989
- Fairway dues	13 797	45 974	41 368
Maintenance and spare parts	90 311	169 334	112 889
Sum operational costs	**512 683**	**667 460**	**596 357**

NOTE: All values in United State dollars, USD

4.2.1. Fuel costs

The fuel prices used in the cost model are presented in Table 7. The prices used are based on current prices provided by several fuel suppliers operating in Sweden, from which an average was calculated. These averages were then multiplied by the annual energy consumption for each ship. The current prices used in the cost model are further analysed in the sensitivity analysis to account for future price fluctuations.

The price of electricity used in the cost model is the average stock price of electricity for 2019 provided by the consumer energy marketing agency (konsumenternas energimarknadsbyrå) at

$0.0432/kWh[9] (2020). Through interviews in March of 2020 with several fuel suppliers operating in Gothenburg, an average of the diesel prices at $325/t have been calculated and used in the cost model. For the price of LNG, only one fuel supplier was able to provide a price of LNG at $341/t. This cost was compared against price predictions for 2020 from 2015 by GloTram and DECC (Baresic et al., 2018), to make sure the price was within a reasonable range.

Table 7. Fuel prices used in the cost model.

Fuel	Price	Unit
Electricity	0.0432	$/kWh
Diesel	369	$/t
Liquefied natural gas	325	$/t

4.2.2. Port fees and fairway dues

All vessels travelling on Swedish inland waterways and calling at a Swedish port are subject to pay port and fairway dues set by the Swedish maritime administration (Sjöfartsverket). The port fees in the port of Gothenburg are based on the gross tonnage (GT) of a vessel, which for the three propulsion system alternatives is assumed to be the same. The difference in cost for the fairway dues and port fees between the three alternatives derive from the environmental discount the different propulsion systems are subject to.

The total port fees and fairway dues was calculated for all three vessels in the excel cost model and are presented in Table 6.

4.2.3. Environmental discount

In the port of Gothenburg all vessels with at least a Clean Shipping Index (CSI) class 4 are subject to an environmental discount of 10% on all port fees (Sjöfartsverket, 2018). To calculate the fairway dues owed by the vessels in our comparison, as well as the environmental discount, the CSI-score was calculated for each of the three propulsion systems. This was done by assessing the vessels according to the clean shipping index methodology and reporting guidelines which is available on their website (Clean Shipping Index, 2020). The fairway dues for vessels between 1 000-1 999 NT on Swedish waterways are presented in Table 8.

Table 8. Fairway dues on Swedish waterways (Sjöfartsverket, 2018).

Port call due, environmental class			
A	**B**	**C**	**D/E**
110	328	985	1 095

NOTE: All values in table 8 are in United State Dollars, USD.

In our calculations of the CSI-score for the three propulsion systems, only the electric propulsion system acquired a CSI-class 4, entirely credited to the electric propulsion system running on batteries which releases no emissions to the atmosphere. Therefore, only the electric propulsion system is subject to the environmental discount. But there is also a 10% LNG discount in the port of Gothenburg, resulting in a lower port fee for the LNG propulsion system as well. All vessels classified as inland waterway vessels are also subject to a 25% discount on all port fees in the port of Gothenburg.

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[9] Excluded from the electricity price is the yearly fee, cost of added services and tax.

The vessels are also subject to lower fairway dues based on their CSI-score which gives them an environmental class of either A, B, C or D/E. The CSI-score for the three vessels put the electric vessel in category B, the diesel propulsion vessel in category D/E, and the LNG propulsion vessel in category C. The price for each environmental class is presented in Table 7. Besides the environmental discount, there is also a frequency discount applicable on the three vessels. The percentage applied is the same for all three propulsion alternatives since they have the same operational profile. There is, however, a difference in the port fees cost for the vessels, due to the environmental class. In Table 9 the frequency and discount for each port call is presented.

Table 9. Environmental and frequency discount on Swedish waterways (Sjöfartsverket, 2018).

Frequency Discount	
Call/month	Reduction (%)
1	0
2	0
3	25
4	50
5	75
6+	100

4.3. Scrapping costs

At the end of the vessel's lifetime, if the shipowner decides to scrap the vessel instead of selling it on the second-hand market, there are some costs incurred during this phase. The cost elements connected to the scrapping process have been broken down and are presented in Table 10 to illustrate where the different cost drivers for each vessel are present.

However, due to access limitations to reliable data for the scrapping costs of this type of vessel, the scrapping costs have been excluded from the LCCA. Where the scrapping costs to be analysed further and included in the LCCA, it would have an impact on the overall LCC results.

Table 10. Cost elements of scrapping and their presence on the vessels (European Commission, 2007; Stopford, 2009).

Cost element	**Electric**	**Diesel**	**LNG**
Final voyage/towage	**X**	**X**	**X**
Pre-cleaning costs	**X**	**X**	**X**
• Manpower cost for safe removal of hazardous waste	**X**	**X**	**X**
• Hazardous waste disposal cost	**X**	**X**	**X**
• Construction costs for new equipment	**X**	**X**	**X**
Materials			
Equipment and machinery	**X**	**X**	**X**
Used steel material	**X**	**X**	**X**
Re-rollable steel material	**X**	**X**	**X**
Steel melting scrap	**X**	**X**	**X**
Cast iron	**X**	**X**	**X**
Forged steel	**X**	**X**	**X**
Non-ferrous steel	**X**	**X**	**X**
Batteries	**X**	**X**	**X**

4.3.1. Final voyage/towage

Presented in the European Commission’s Implementing Decision 2018/1906 which updates the European List of ship recycling facilities, No 1257/2013, are the current scrap yards in Europe. The closest scrap yard to port of Gothenburg, is a Danish scrap yard in Frederikshavn where they scrap vessels in a slipway of max dimension of 290m in length, 90m wide and 14m draught (European commission, 2018). The distance between Gothenburg and Frederikshavn is 50 nautical miles (Sea-distances, 2020), a trip that takes 4 hours at 12 knots speed.

Since the vessels would be classified as inland waterway vessels (IWV), there are restrictions to where they are allowed to sail. If the vessels are not allowed to sail over Kattegat using their own engines, towing is the only option and then the costs for towage are assumed to be the same for all three vessels.

4.3.2. Pre-cleaning costs

The European Commission (2007) explains the pre-cleaning concept as the removal of hazardous waste in the European Union before shipping the cleaned vessel to the scrap yard somewhere else in the world. Since the scrapping of the vessels included in this thesis is assumed to be performed in Denmark, the pre-cleaning of the vessels is assumed to be performed on site at the scrap yard.

The pre-cleaning cost is dependent on several ship specific factors, such as vessel size, vessel type, type of cargo, level of maintenance, repairs & refitting (EC, 2007). The vessels analysed in this thesis are assumed to be of the same size and have the same dimensions, therefore the factors that will have an impact on the pre-cleaning cost for the three vessel alternatives is associated with the level of maintenance, repair and refitting performed on the vessels during their lifetime.

Another factor that has an impact on the pre-cleaning costs, is the amount of hazardous material onboard. The amount of hazardous material will be different for the three vessel alternatives, due to the different fuels used onboard. Hazardous substances present on ships are, among others, fuel and gas oil, lubricating oils, sludge and waste lead batteries (EC, 2007). The hazardous substances exist in different quantities on the three vessels, for instance, the diesel and LNG vessels both have more lubricating oil than the electric vessel, and the electric vessel has more batteries onboard, albeit not lead batteries. Because the cost of removing hazardous material has a different cost driver for each vessel, there is a possibility that they cancel each other out.

4.3.3. Materials

It is assumed to be a difference in material cost when scrapping for the vessels. The vessels are all based on the same dimensions and characteristics, the difference in material cost does not derive from the hull structure, but from the engines installed onboard. This will have an impact on the scrapping cost regarding the materials for the vessels. How much that impact is, have not been investigated in this thesis.

4.3.4. Battery recycling fee

Another cost element that will be different between the vessels is the battery recycling fee. Onboard the electric vessel there are many more, and much more expensive batteries installed than on the diesle and LNG vessel. These batteries therefore result in the electric vessel incurring a larger scrapping cost due to the batteries.

In this analysis different cost elements are identified for the three propulsion options and the resulting cost of the scrapping phase would therefore be different, due to different amounts of various materials and hazardous substances on the propulsion systems.

4.4. Sensitivity analysis

In order to address the uncertainties that occur due to costs that are dependent on future, unknown events, a sensitivity analysis was conducted where necessary. The sensitivity analysis is related to costs that have been assumed and evaluates the accuracy (IEC, 2017) of the LCC model as well as the impact of uncertainty. In order to identify the cost elements that mostly affect the results of the LCCA, the operational phase is investigated further through a sensitivity analysis. Since the operational phase of the vessel’s lifetime spans over 30 years, this is where most variations are expected to occur.

Uncertainties arise from the difficulty to predict the costs that will occur in the future. For example, the fuel price in the LCC calculations is based on the current fuel price however, the fuel price might change in the future, as it is dependent on many unknown parameters such as supply & demand and technological advances. Therefore, different future scenarios are calculated with different approximations on these future costs. Another part of the operating costs that is hard to estimate is the maintenance costs, since it is dependent on future events during operation that cannot be predicted. Part of the maintenance cost in this model is the battery change costs where battery prices and battery lifespan is uncertain and will be therefore calculated in the sensitivity analysis.

The parameters that are presented in the previous chapter and are most important for the LCCA results due to their overall big impact on the LCCA and the risk they carry as they are more vulnerable to changes during the vessel’s lifespan are investigated further in this chapter with a sensitivity analysis.

4.4.1. Fuel prices

Historically, fuel prices are mainly increasing and expected to increase in the future. However, due to regulation restrictions related to environmental pollution and due to technological advances, that are emerging in recent years, whether there will be an increase or a decrease and the exact amount of it is impossible to estimate accurately. Therefore, in this part different scenarios of expected fuel prices are analysed. The predictions are based on the fuel price fluctuation in the last years and the expectation of changes on parameters that are affecting the price, like technology advancement, supply & demand. The different scenarios under analysis are presented in Table 11.

Table 11. Fuel price sensitivity analysis scenarios.

	Current price	**Scenario 1**	**Scenario 2**	**Frequency**
Electricity	$0.0432/kWh	+2.42%	+1.41%	Annually
Marine Gas Oil	$369/t	-3%	+3%	Annually
Liquified Natural Gas	$325/t	-1.50%	+1.50%	Annually

According to the state energy authority (statens energimyndighet), the electricity prices in Sweden are projected to almost double by the year 2050 (2017). Applying this on the average stock price of electricity for 2019 presented in 3.4.1., the electricity price for 2050 is projected to be $0.0838/kWh. Since there is no indication that the electricity prices are going down in the future, the sensitivity analysis on the electricity price in this thesis is made with an annual increase in electricity price of 2.42% in scenario 1, and 1.41% in scenario 2.

The oil price has a long history of fluctuating up and down due to several factors. Over the past 40 years the oil price have fluctuated by almost 400% from $3/bbl to $12 during the oil crisis of 1973 - 1974, in the 1979 - 1980 crisis the price increased again by 160% from less than €15/bbl to almost $40, just to crash in the early to mid-1980's. In December of 1998 the oil price was at its weakest in recent history, at a price of $11/bbl, when just two years earlier the oil was trading at $25/bbl. Then during the early 2000's the prices started to rise again, from $28/bbl to $134, only to drop during the next financial crisis in 2008 to $39/bbl. The price stabilised during 2009 at 2007 levels of $100/bbl with minor fluctuations of $3 - 13/bbl in 2011 and $0 - 9/bbl in 2012, just to drop again in 2014-2015 from $112/bbl to $47 (Baumeister and Kilian, 2016).

The price for oil can also suddenly drop to negative values because of several factors such as supply and demand, derivatives and reports, natural disasters, politics, production cost and interest rates. During natural disasters and pandemics, importing countries have stockpiled oil at cheap prices, whereas producing countries are storing crude oil at offshore facilities instead, using overpriced tankers to do so. At the beginning of 2020, the oil price/bbl was at $63.65, in April the price was down to $18.38/bbl and on May 24th: $27.43/bbl (Country Economy, 2020). On average, the oil price has increased by 3.91% annually in the past 47 years, from the oil crisis of 1973-1974 to April of 2020.

On the other hand, researchers estimate that beyond 2040, MGO/MDO are expected to be the only oil-based fuels used for propulsion (ABS, 2020). Along the path to clean and renewable energy, the adoption of biodiesel or renewable diesel is expected to displace part of the HFO and MGO/MDO share as well (ABS, 2020). Due to the fluctuating nature of oil and oil-based products, a sensitivity analysis has been performed with both a decrease and increase in fuel price for the MGO used on the diesel propulsion vessel, at an annual rate of 3% over 30 years lifetime.

As mentioned in the previous paragraph, one factor that has an impact on fuel price, is supply and demand. LNG is not as widely used today as oil-based petroleum products, there is, however, expected to be an increase in the demand of LNG in the next 15-20 years, based on its expanding infrastructure, trade volumes and lower carbon intensity than oil-based fuels. However, the adoption of LNG is not sufficient to meet the long-term IMO targets, therefore it is expected that it will be replaced by bio-derived natural gas and, eventually, by hydrogen (ABS, 2020).

As opposed to the oil price, where we have a long history of supply & demand and price fluctuations to look back on to base future projections on, LNG as a fuel is more unpredictable, but is in general considered to be more stable (SEA\LNG ltd, 2020). Therefore, a lower percentage of 1.5 has been applied in the sensitivity analysis when calculating the increase and decrease in fuel price for the LNG.

4.4.2. Battery prices

Maintenance cost is part of the operational costs, and in the cost model the cost of battery changes for the electric vessel is included, making the cost of batteries the single biggest cost in this category. Besides the size of this cost, there are also additional uncertainties regarding the lifespan of the batteries and the cost of acquisition.

According to current marine industry standards, the expected lifetime of the Lithium-ion batteries suitable for powering an electric vessel is 10 years long (MAN ES, 2019), with some variations depending on type and charging profile. This means that the batteries will have to be changed at least twice during the electrified vessel's lifetime to stay operational, and with a cost of €600-800/kWh this cost will have a large impact on the operational costs for the vessel.

However, the price for these heavy-duty marine batteries is expected to drop in the future. When looking at the prices for battery packs for electric cars, these have dropped from $1 000/kWh in 2010 to $210/kWh at the end of 2017 (MAN ES, 2019). With a drop of almost 80% in battery prices for battery packs for electric cars over the course of only 7 years, a 50% drop in prices for the next 30 years for marine battery packs seems a reasonable, very cautious, estimation to make.

There are also indications that the lifetime of the marine batteries could be longer than the industry standard is today, due to efficient usage and technological development. If the battery's lifetime were prolonged by 5 years, there would only be necessary to change them once during the vessel's lifetime, severely cutting costs in half by the time the vessel is taken out of operations.

Calculated at the median value of current prices at $790/kWh, the new batteries bought in year 11 and 21 each cost the same as the first fitted batteries during construction, $4 820 360. Totalling at $9 640 721 for both changes over the vessel's lifetime. If the battery's lifetime is prolonged with five years, there is only one battery change needed, the battery cost will be only half, $4 820 360, at year 16.

If the battery prices were to drop by 50% to $395/kWh but remain at the current industry standard of 10 years, the cost of the new batteries installed during the 30 years of operation would be half of the current prices, $4 820 360. If both the prices drop and the lifetime of the batteries is prolonged to 15 years, the total cost for new batteries during the 30 years of operation would be reduced even more, totalling at $2 410 180.

The results of the sensitivity analysis done on the batteries for the electric vessel is illustrated in figure 14.

4.4.3. Future carbon tax implementation

Carbon taxes have been often recommended as a cost-effective measure to reduce emissions (Baranzini et al., 2000). By applying a price to carbon emissions, the charge for the damage is shifted to those responsible and the pollution becomes less attractive to the industry shifting the interest to renewable energy. The typical tax rates amount from 5 to 30 euros per tonne of CO_2 (Parry et al., 2018), however the carbon tax does not yet apply in the shipping industry.

In Europe, the carbon tax prices have been relatively low for the past years leading to an emission reduction pathway that cannot meet the target of reduced emissions by 40% by 2030 (Rooney et al., 2018). The EU has recognized that further changes need to be made. The carbon price averaged to 30 euros per ton in 2019 which is four times that of 2016 and there are expectations that the price will continue to increase (Mathew, 2020).

In addition, there are indications of a future carbon tax being implemented in the shipping industry. Parry et al. have done a study on the possibilities of how the carbon tax could be implemented in the shipping industry (Parry et al., 2018). One possible implementation of the carbon tax could take place as part of port fees and fairway dues. In that case, the carbon tax costs would strongly affect the vessels running on fossil fuels, with the diesel propulsion vessel's operational costs increasing. An increase of 50% and a 100% to port fees and fairway dues was further applied to the sensitivity analysis along with the possibility of the tax expanded to include GHGs as well, thus the same increase also implemented in the LNG propulsion.

4.4.4. Combined future scenario

By combining all possible future scenarios, a combined future scenario was developed to illustrate a holistic overview of the future possibilities. In this scenario the battery prices are decreased by 50% compared to current prices, the lifetime of the batteries is expanded to 15 years meaning only one battery change will be required for the electric propulsion system during the vessel’s lifetime.

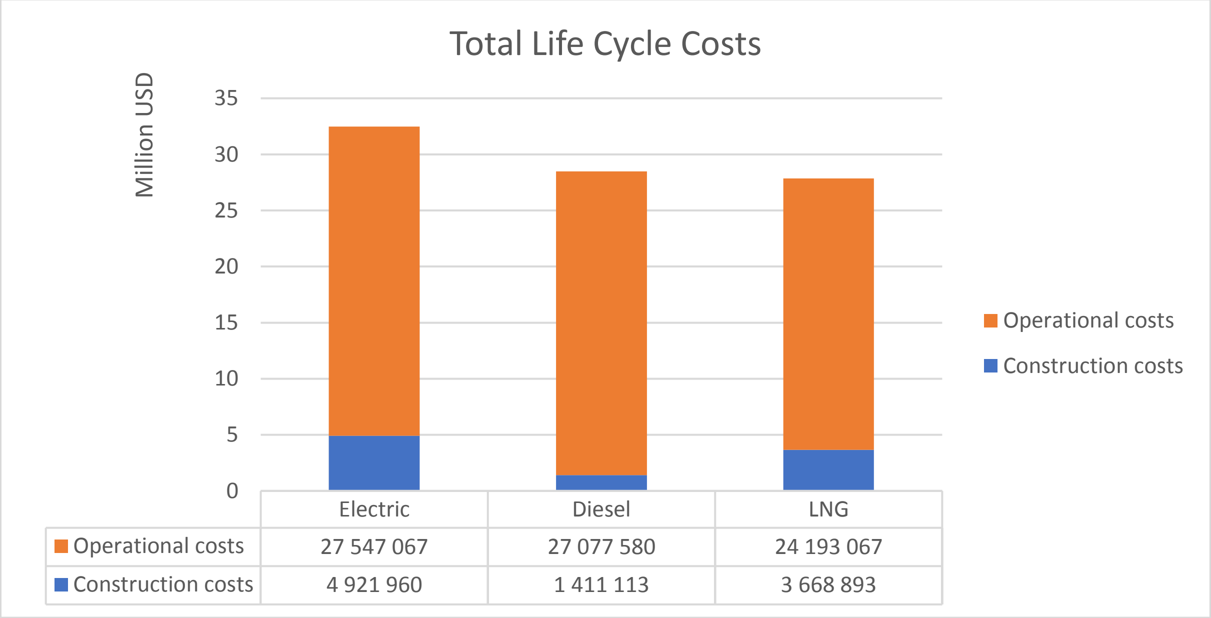
In addition, the carbon tax is assumed to be implemented which leads to additional port fees and fairway dues for the diesel and LNG alternatives. More specifically, the port fees and fairway dues are doubled for both the diesel and the LNG alternative in this combined future scenario. Lastly, the fuel prices for all three alternatives are increased with an annual rate of 3.41% for the electric vessel, 5% annually for the diesel vessel and 3.5% annually for the LNG vessel.

5. Results

In this chapter, the results from the cost model are presented. In section 5.1., the total life cycle costs are presented and broken down into capital costs in section 5.1.1., and into operational costs in section 5.1.2. In section 5.2., the results from the sensitivity analysis are presented and further broken down into the respective cost drivers.

5.1. Total life cycle costs

The total LCC included in the analysis of the electric, diesel and LNG vessels are illustrated in figure 4. The most expensive vessel will be the electric vessel, followed by the LNG and lastly the diesel vessel.



	Electric	Diesel	LNG
🟧 Operational costs	27 547 067	27 077 580	24 193 067
🟦 Construction costs	4 921 960	1 411 113	3 668 893

Figure 4. Total life cycle costs over 30 years at current prices.

The electric vessel is the alternative with the highest cost in total at $32 469 027, followed by the diesel vessel at a total of $28 488 693 and last the LNG vessel at $27 861 960. The difference in the total life cycle costs between the diesel and the LNG alternatives is $626 733, with the diesel being more expensive due to higher costs for maintenance, spare parts, port fees and dues. However, when compared to the electric propulsion the difference becomes larger, as the electric vessel's total life cycle cost is $3 980 334 and $4 607 067 more expensive than the diesel and LNG, respectively. This difference is mainly driven by the high costs associated with the replacement of batteries during the electric vessel's lifetime.

In figures 5, 6 and 7 the accumulated life cycle costs are represented for the three different propulsion alternatives. Year 0 represents the construction of the vessels, and thus only the capital expenses as calculated in this thesis are included. From year 1 to year 30 the accumulated operational costs with a 2% inflation rate applied are included. Not included in these figures, are the scrapping costs for each vessel. This is because the costs of scrapping for the three propulsion systems have not been thoroughly investigated in this thesis and is therefore omitted.

In figure 5, representing the electric vessel, there are two peaks at year 11 and year 21, which are not present in figures 6 and 7 for the diesel and LNG. These peaks are due to the battery changes based on current prices and current maritime industry standard of a lifetime for batteries of 10 years.

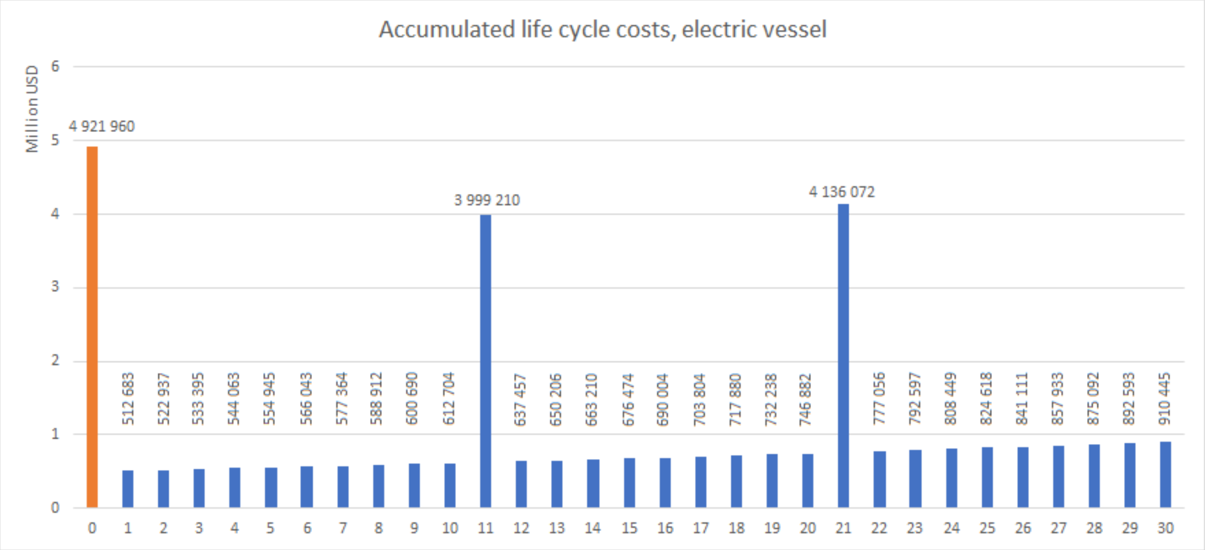


Figure 5. Accumulated life cycle costs for the electric propulsion system vessel over 30 years.

The capital costs for year 0 between the three alternatives differ due to different construction costs described in section 4.1., consisting of the capital expenses for the batteries for the electric vessel and more expensive fuel tanks for the LNG vessel. The accumulated operational costs over 30 a year lifetime are different between the propulsion alternatives as well. This is mainly due to the different propulsion systems having different costs for maintenance and spare parts, where the diesel vessel has the highest cost. The fuel prices also have an impact on the difference in operational costs, the vessels all run on different fuels and these all have different costs resulting in a higher cost for the diesel and LNG propulsion vessels compared to the electric vessel. Also included in the operational costs, are the port fees and fairway dues which are different for the three propulsion system alternatives. The electric vessel has a lower cost for fees and dues due to a zero-emission propulsion system.

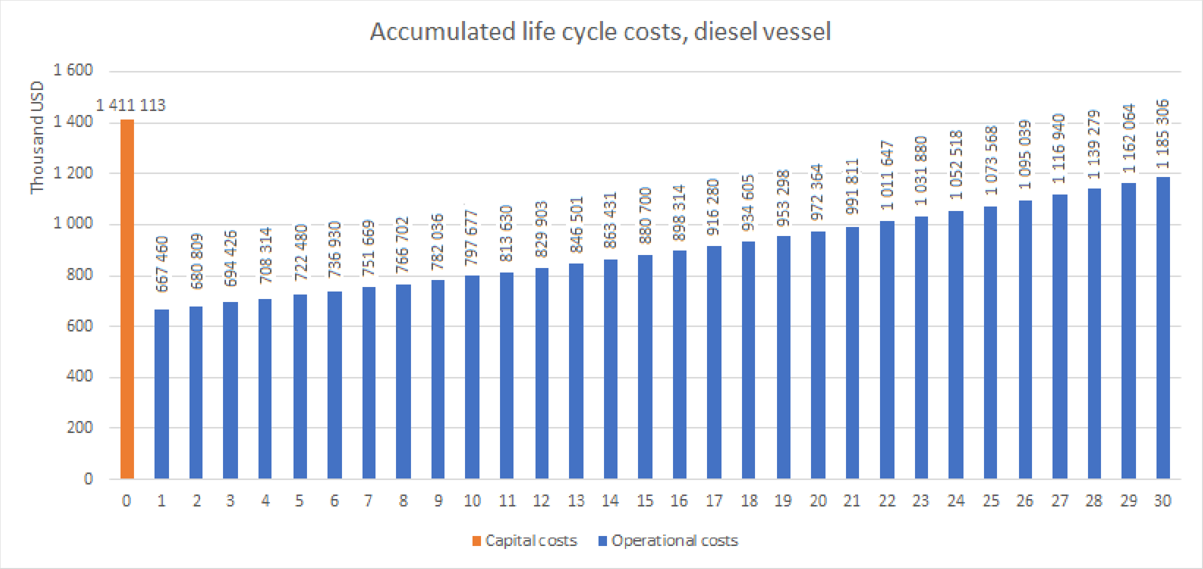


Figure 6. Accumulated life cycle costs for the diesel propulsion system vessel over 30 years.

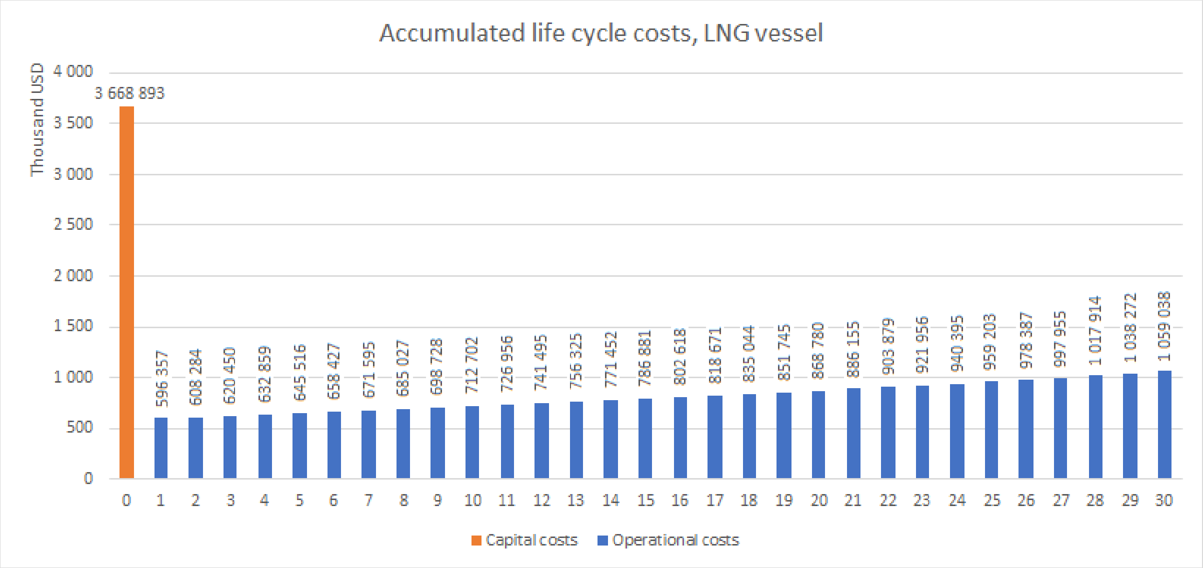


Figure 7. Accumulated life cycle costs for the LNG propulsion system vessel over 30 years.

By comparing the accumulated annual operational expenses, it clearly shows that the electric vessel is cheaper in operational costs compared to the other two propulsion system alternatives. The main factor resulting in the electric vessel being more expensive in total operational costs, is the new batteries which have to be installed twice during the vessel's lifetime after 10 years each.

5.1.1. Construction costs

Figure 8 illustrates the construction costs for the three propulsion system alternatives, as presented in section 4.1. The capital costs of the electric propulsion system is a total of $4 921 960, consisting of the battery cost at $4 820 360 (out of which approximately ⅓ is the cost of ship common systems at $1 446 108, leaving $3 374 252 for the cost of batteries alone) and the cost of the electric engine at $101 600. The total cost of the diesel propulsion alternative is calculated to $1 411 113; this includes the diesel engine at $1 128 890 and ship common systems at $282 223. The LNG propulsion system is in this thesis calculated at €2 million more in capital costs than the diesel propulsion system, with a total cost of $3 668 893. Included in the cost for the LNG propulsion system, is the cost for the engine at $1 806 224, the LNG fuel tanks at $1 580 446 and ship common systems at $282 233.

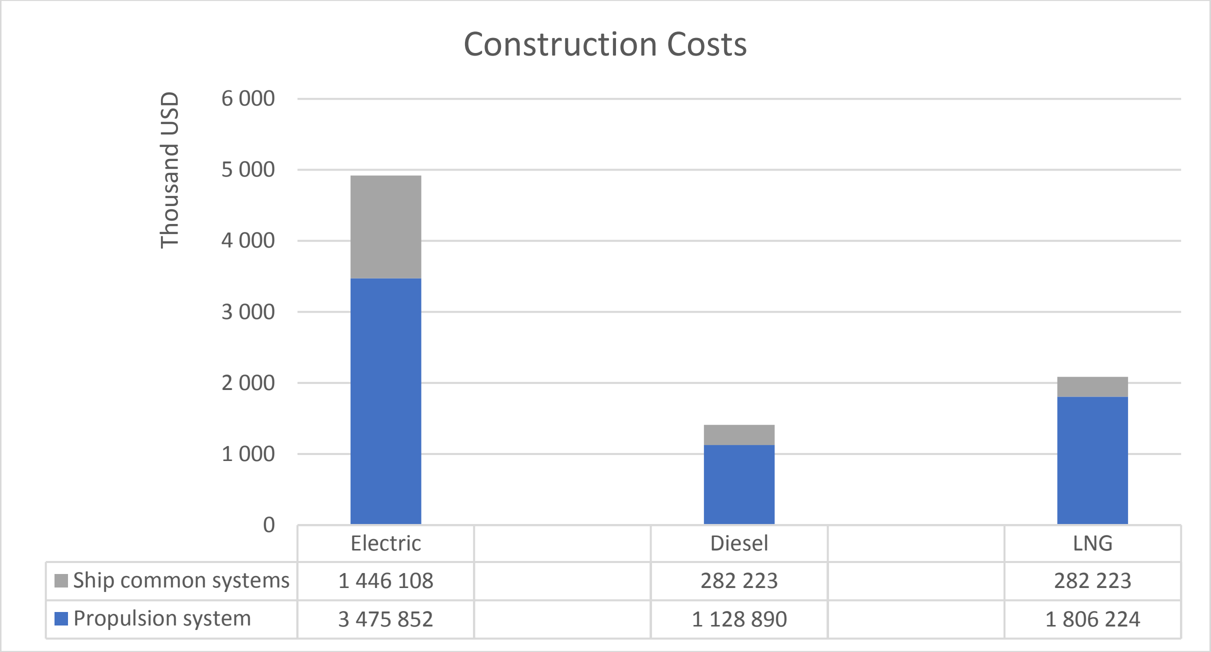
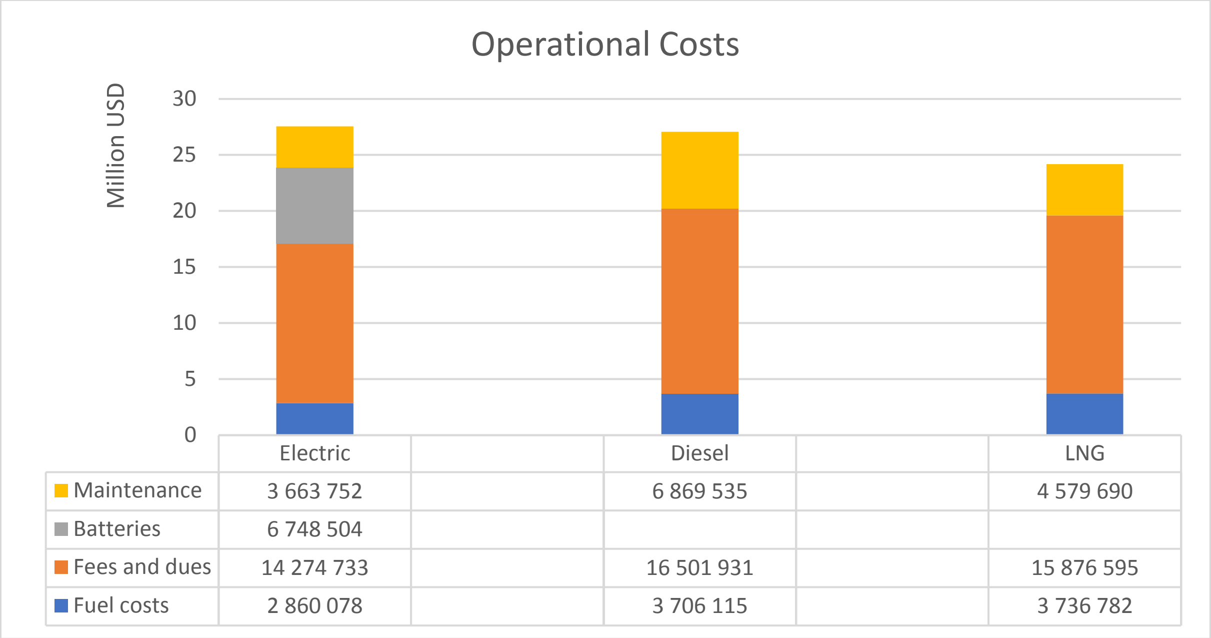


Figure 8. Construction costs for vessel propulsion system alternatives.

The single biggest cost for the electric vessel is the cost for the batteries alone, this cost is higher than the total construction costs for each of the other two alternatives, which makes the electric propulsion system the most expensive. The rest of the costs for the electric system are associated with the engine and ship common systems. On the other hand, the alternative with the lowest cost is the diesel propulsion system, due to a less complicated system in comparison. The difference between the diesel and the LNG propulsion is mainly because of the more expensive fuel tanks installed on the LNG vessel, which makes the LNG propulsion system about $2 million more expensive than the diesel system.

5.1.2. Operational costs

Figure 9 illustrates the total operational costs at current prices of the concept vessel, as presented in section 4.2., compared to diesel and LNG propulsion over 30 years of operation with an inflation rate of 2%. Included in the operational costs for all three propulsion alternatives are the cost of fuel, port fees & fairway dues and maintenance & spare parts. The biggest cost driver for all three vessels are the port fees and dues incurred over the 30-year lifetime. Also, there is an added cost for the electric vessel for two battery changes during its lifetime, at the amount of $6 748 504, which does not exist for the other two alternatives.



	Electric		Diesel		LNG
🟨 Maintenance	3 663 752		6 869 535		4 579 690
⬜ Batteries	6 748 504				
🟧 Fees and dues	14 274 733		16 501 931		15 876 595
🟦 Fuel costs	2 860 078		3 706 115		3 736 782

Figure 9. Total Operational costs for vessel propulsion system alternatives, including cost of fuel, maintenance & spare parts and port fees & fairway dues.

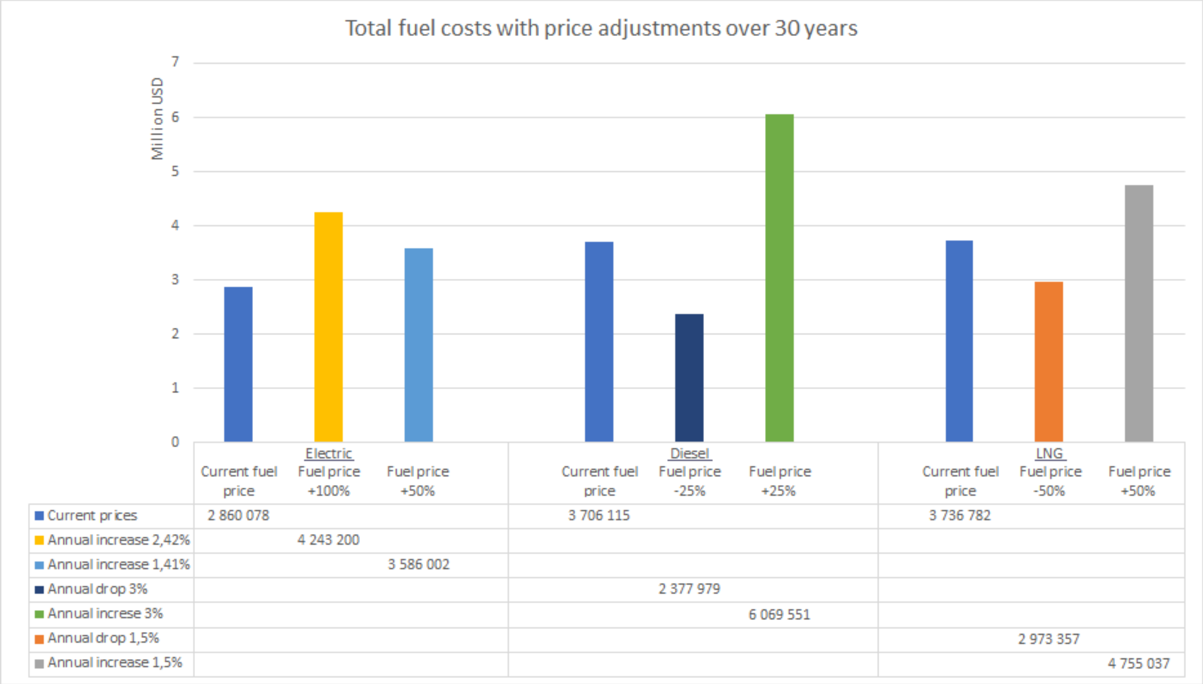
5.2. Sensitivity analysis results

In this section, the results of the sensitivity analysis projections are presented. The cost elements chosen for the sensitivity analysis are the fuel costs, battery costs for the electric propulsion system and the implementation of a future carbon tax. These three elements were chosen due to the large impact they have on the overall costs for the three vessels over 30 years of operation.

In section 5.2.1., the fuel prices calculated over 30 years are presented with estimated price fluctuations for all three propulsion alternatives. In section 5.2.2., the operational costs for the electric vessel are presented with adjustments for 2 or 1 battery change during the vessel's lifetime. Finally, in section 5.2.3, the results of future carbon tax calculations applied on the diesel propulsion vessel are presented and compared to the other two propulsion systems.

5.2.1. Fuel cost

The sensitivity analysis in section 4.4.1. evaluates the price fluctuations for the three propulsion alternatives. Figure 10 presents the change in total fuel cost for the three alternatives when changes in fuel prices occur. Based on the projections, the changes in fuel prices are set at a gradual increase of 1.41% and 2.42% annually over the 30 years of operation for the electric vessel. The respective changes for the diesel and LNG fuel correspond to an increase and a decrease of 3% for the diesel propulsion vessel, and a 1.5% increase and decrease for the LNG vessel. An inflation rate of 2% is also applied on the fuel prices for all three alternatives.



	Electric			Diesel			LNG		
	Current fuel price	Fuel price +100%	Fuel price +50%	Current fuel price	Fuel price -25%	Fuel price +25%	Current fuel price	Fuel price -50%	Fuel price +50%
■ Current prices	2 860 078			3 706 115			3 736 782		
■ Annual increase 2,42%		4 243 200							
■ Annual increase 1,41%			3 586 002						
■ Annual drop 3%					2 377 979				
■ Annual increse 3%						6 069 551			
■ Annual drop 1,5%								2 973 357	
■ Annual increase 1,5%									4 755 037

Figure 10. Fuel price adjustments over 30 years.

At current prices, the total fuel cost for the vessels are $2 860 078 for the electric vessel, $3 706 115 for the diesel propulsion vessel and $3 736 782 for the LNG vessel. With the different price scenarios presented in the sensitivity analysis in section 4.4.1., fuel price for the electric vessel increases to a total cost of $4 243 200 in scenario 1, and to $3 586 002 in scenario 2 as illustrated in figure 10. The respective changes on the fuel price for the diesel propulsion vessel results in a total of $2 377 979 in scenario 1, and a total of $6 069 551 in scenario 2. The fuel cost for the LNG vessel amounts to a total of $2 973 357 in scenario 1, and a total of $4 755 037 in scenario 2.

The economic scenario is vulnerable to the difference between the costs at the highest and the lowest fuel prices. Due to the higher costs of the diesel, the difference between the highest and lowest cost is higher for the diesel propulsion alternative, with a difference of $3 691 572 from the highest to lowest price, while for the LNG that difference is $1 781 679, while for the electric vessel there is only a difference of $657 198. Meaning that the diesel propulsion vessel is more sensitive to fuel price fluctuations compared to the two other alternatives, which have a lower difference between the highest and lowest cost.

Even though the difference between the highest and lowest price on the fuel is highest for the diesel propulsion vessel, when comparing the fuel costs illustrated in figure 10 in total operational costs, as illustrated in figure 11, compared to current prices, the difference for the electric vessel in scenario 1 is $1 383 122 and in scenario 2 at $725 924. The difference in operational costs compared to current prices for the diesel propulsion vessel is $1 328 136 in scenario 1 and $2 363 436 in scenario 2. For the LNG vessel, compared to current prices, in scenario 1 the difference in total operational costs is at $763 425, and in scenario 2 at $1 018 254.

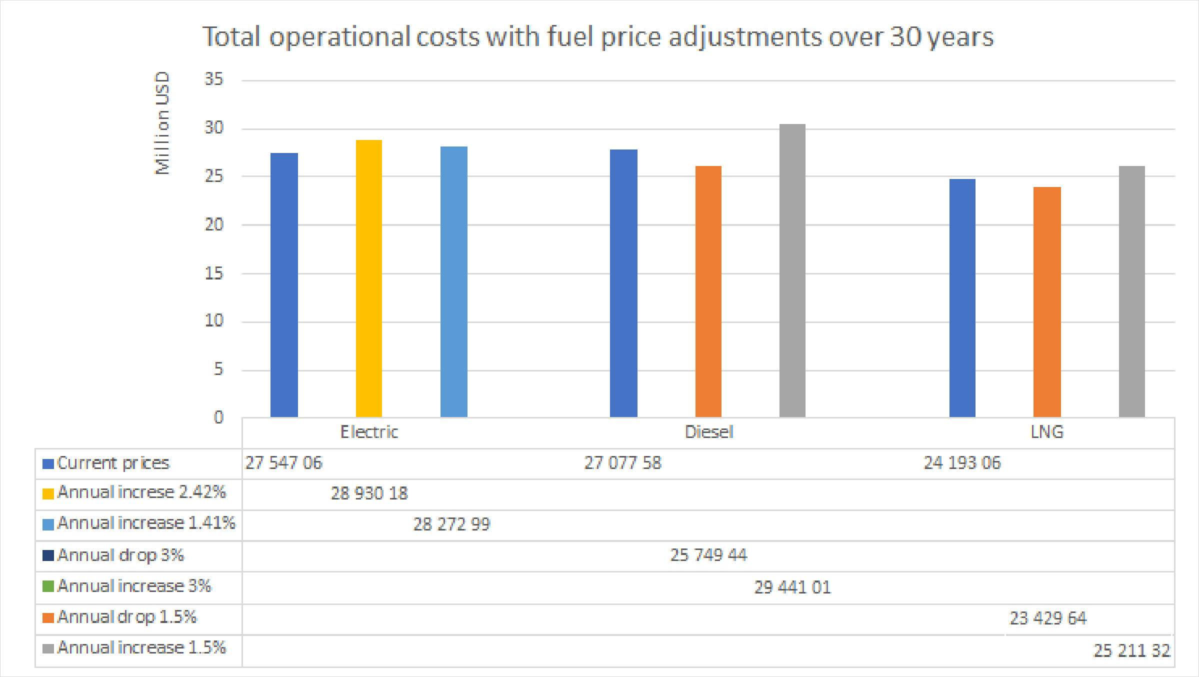


Figure 11. Total operational costs included fuel price adjustments over 30 years.[10]

5.2.2. Operational costs for electric vessel

In section 4.4.2. of the sensitivity analysis, the cost of batteries is evaluated and analysed in regard to a possible extended lifetime from 10 to 15 years, as well as the possible decrease in price/kWh by 50%. Figure 12 illustrates the annual operational costs for the electric vessel at current battery prices and with two battery changes during the vessel's lifetime, a total of $27 547 067. If the battery price drops by 50%, the operational costs for year 11 would drop from $3 999 210 to $1 999 605, and for year 21 the costs would drop from $4 136 072 to $2 068 036, with a total operational cost over 30 years at $23 479 426.

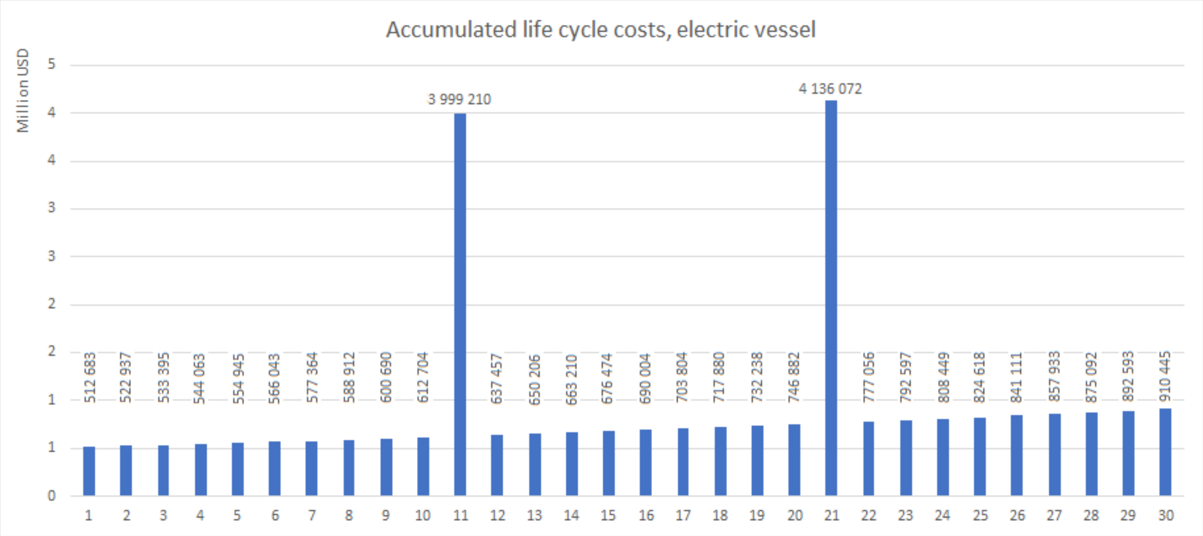


Figure 12. Timeline of annual operational costs for the electric vessel with 2 battery changes at current battery price.

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[10] In the operational costs for the electric vessel the cost of 2 battery changes of $6 748 504 is also included.

Figure 13 illustrates the total annual operational costs for the electric vessel at current battery prices and with one battery change over 30 years, to the total operational cost at year 16 of $4 064 256, giving a total of $24 172 815 for the vessel's total lifetime. If the battery price drops by 50%, the cost of year 16 would be $2 032 128, and the total cost over 30 years would drop to $22 140 687.

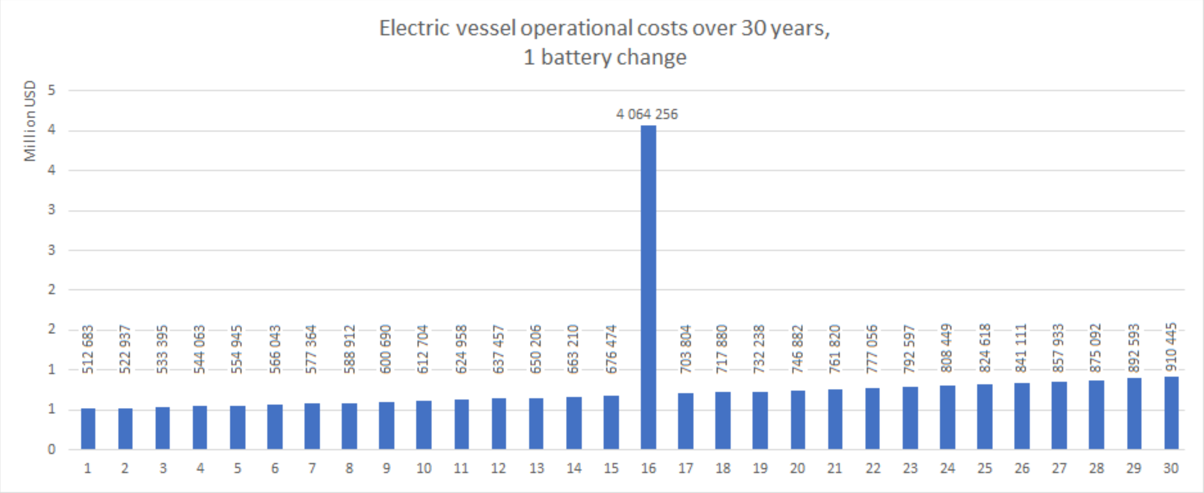
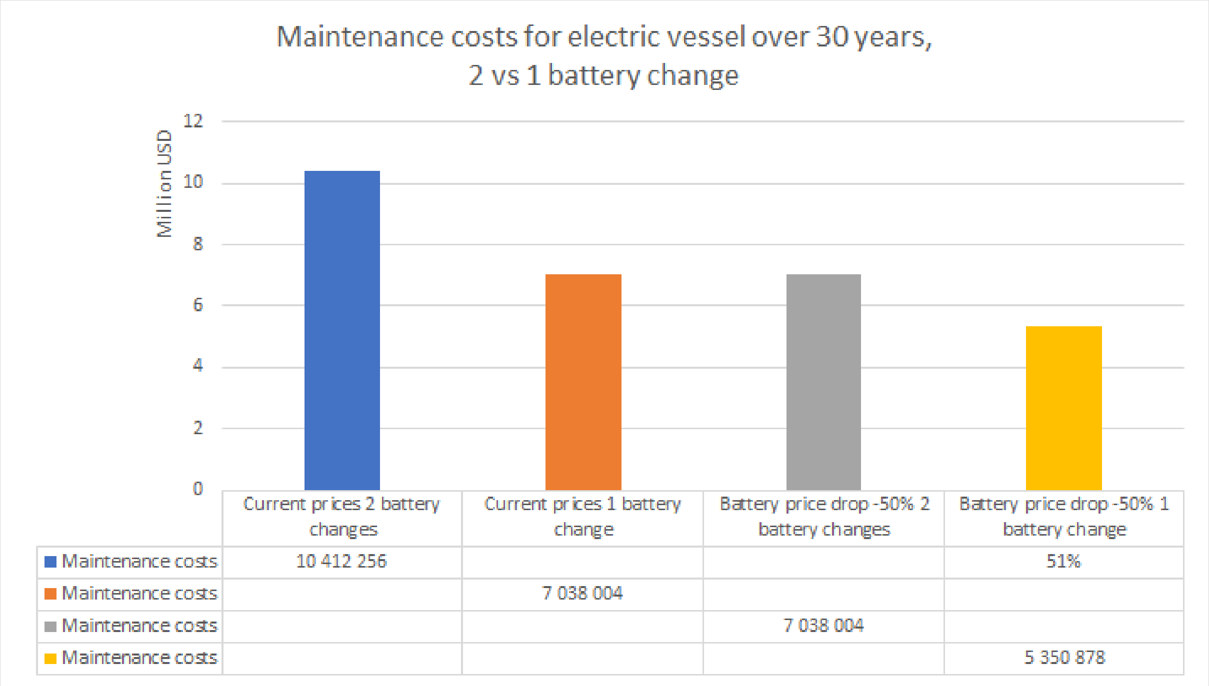


Figure 13. Timeline of annual operational costs for the electric vessel with 1 battery change at current battery price.

Illustrated in figure 14 are the differences in battery cost dependent on 2 or one battery change over the vessel's lifetime, together with a comparison if the battery prices would drop by 50%. The total maintenance costs are 32% lower if the battery life is prolonged to 15 years and only one battery change is needed, as well as if the battery price drops by 50% for 2 battery changes, compared to 2 battery changes at current prices. If the battery life already was prolonged to 15 years, and the prices dropped to half, the total maintenance costs would drop by 24%. If both the prices drop and the battery life is prolonged, the total maintenance costs for the electric vessel drops by 49% compared to 2 battery changes at current prices.

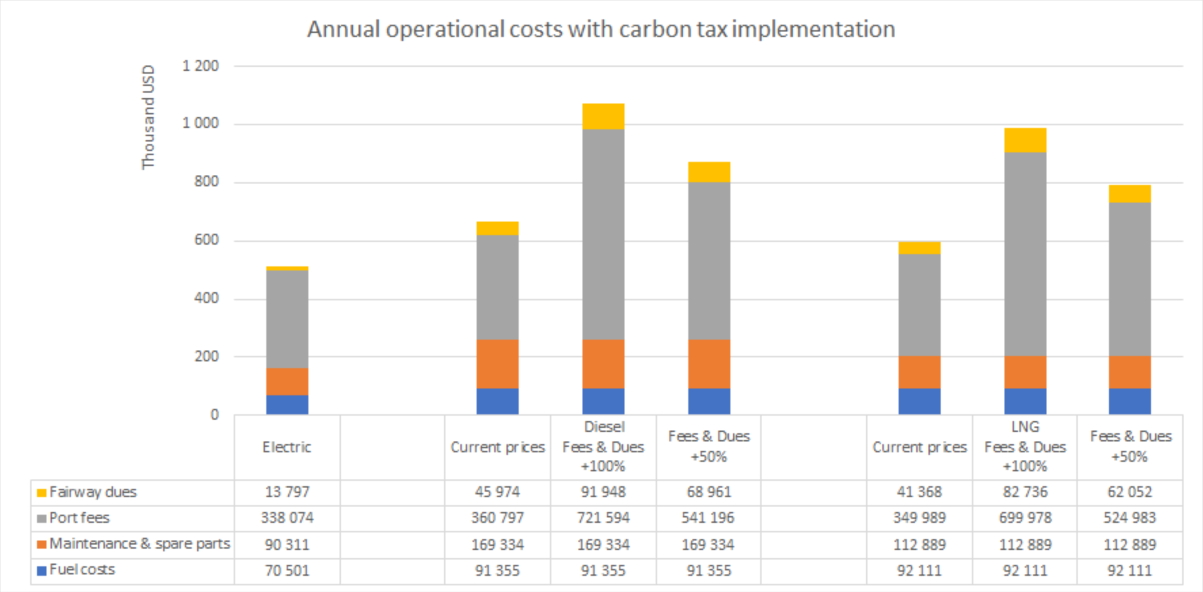


	Current prices 2 battery changes	Current prices 1 battery change	Battery price drop -50% 2 battery changes	Battery price drop -50% 1 battery change
🟦 Maintenance costs	10 412 256			51%
🟧 Maintenance costs		7 038 004		
⬜ Maintenance costs			7 038 004	
🟨 Maintenance costs				5 350 878

Figure 14. Total maintenance cost for the electrified concept vessel over 30 years, including battery price drop and 2 vs 1 battery change.

5.2.3. Carbon tax implementation

In figure 15 the annual operational costs over for the three vessel alternatives are presented with an applied carbon tax for the diesel propulsion vessel with double the cost for fees and dues in scenario 1, and a 50% increase of fees and dues in scenario 2. The total annual costs for the electric vessel is at $512 683.[11] For the diesel propulsion vessel at current prices the annual operational costs amount to $667 460, and for the LNG vessel the annual operational costs are at $596 357. With a carbon tax implemented on the port fees and fairway dues, resulting in a 100% increase in these costs, the annual operational costs for the diesel propulsion vessel would go up to $1 074 232. If the costs were only increased by 50%, the annual operational costs for the diesel propulsion vessel would amount to $870 846. The same increase in port fees & dues for the LNG vessel would result in total operational costs of $987 714 with a 100% increase, and $792 036 with a 50% increase.



	Electric			Diesel				LNG	
			Current prices	Fees & Dues +100%	Fees & Dues +50%		Current prices	Fees & Dues +100%	Fees & Dues +50%
🟨 Fairway dues	13 797		45 974	91 948	68 961		41 368	82 736	62 052
▨ Port fees	338 074		360 797	721 594	541 196		349 989	699 978	524 983
🟧 Maintenance & spare parts	90 311		169 334	169 334	169 334		112 889	112 889	112 889
🟦 Fuel costs	70 501		91 355	91 355	91 355		92 111	92 111	92 111

Figure 15. Future operational cost predictions with implemented carbon tax on the port fees & fairway dues for the diesel vessel.

Figure 16 illustrates the total LCC for all three propulsion alternatives, with the electric vessel including 2 battery changes, and a carbon tax resulting in double the cost of port fees and fairway dues for the diesel propulsion vessel. If that carbon tax is expanded to include the emission of greenhouse gases as well, the operational costs for the LNG vessel would increase further, making it even more expensive than the electric vessel.[12] Total operational costs over 30 years for the diesel propulsion vessel with a 100% increase in port fees and fairway dues amounts to $44 990 623, with a 50% increase in port fees and fairway dues the total operational costs are $36 739 658. Were the same rates applied on the LNG vessel as on the diesel propulsion vessel, the total

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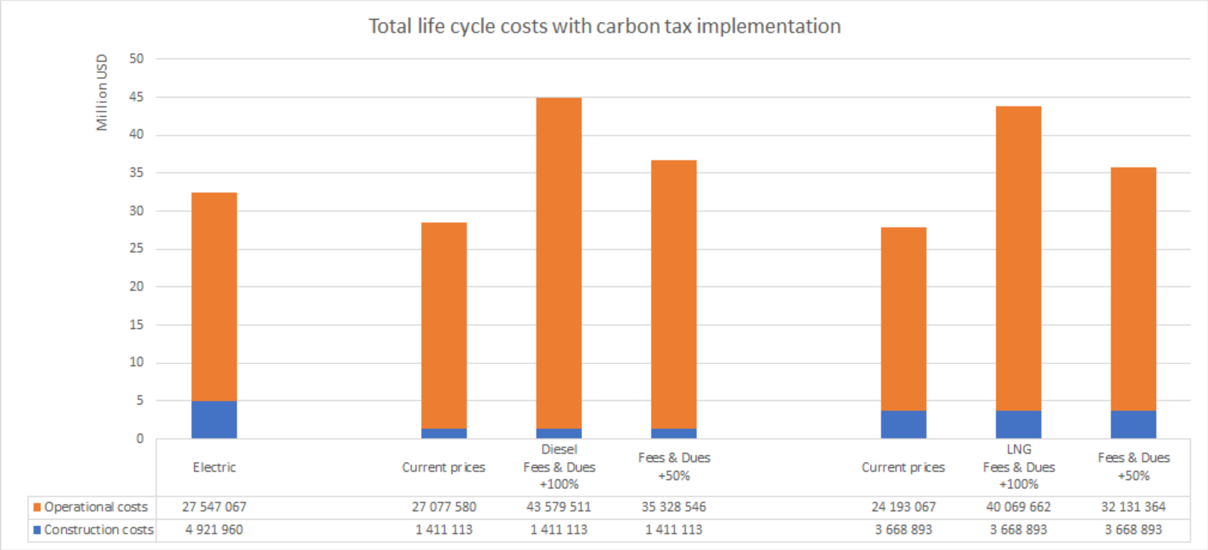
[11] In figure 15 the electric vessel is illustrated without the cost of battery changes, since these costs are only incurred twice during the operational lifetime of the vessel, and do not represent all annual operational costs.

[12] In figure 16 illustrating the total life cycle costs for the propulsion alternatives, the operational costs for the electric vessel includes the cost for two battery changes, to correctly represent the maintenance costs incurred over 30 years.

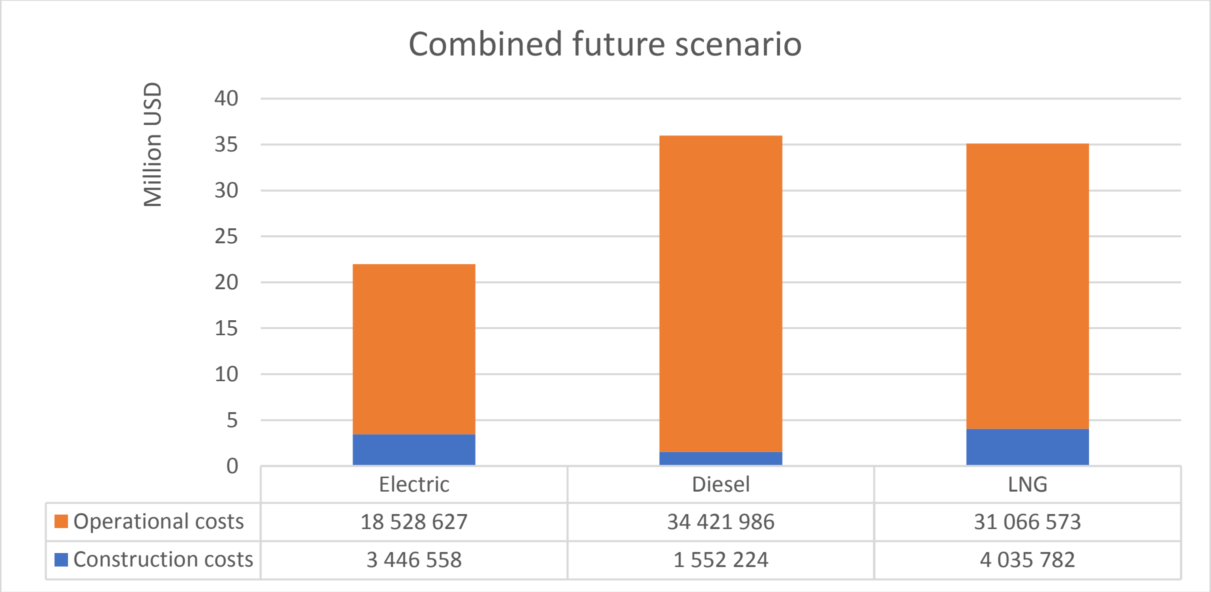
LCC for the LNG vessel would amount to $43 738 554 with a 10% increase in port fees & fairway dues, and to $35 800 257 with a 50% increase in port fees & fairway dues.



	Electric	Current prices	Diesel Fees & Dues +100%	Fees & Dues +50%	Current prices	LNG Fees & Dues +100%	Fees & Dues +50%
■ Operational costs	27 547 067	27 077 580	43 579 511	35 328 546	24 193 067	40 069 662	32 131 364
■ Construction costs	4 921 960	1 411 113	1 411 113	1 411 113	3 668 893	3 668 893	3 668 893

Figure 16. Total LCC comparison with carbon tax implementation.

If the future projections presented in the sensitivity analysis were to come true: the price for the batteries is lower by 50%, the batteries have an extended lifetime to 15 years, the carbon tax is implemented on the diesel and LNG propulsion system, the fuel prices increase for all three propulsion alternatives, with a 25% for the electric, 64% for the diesel and 27% for the LNG, and the construction costs for all three alternatives is increased with 10%. The results of these future projections would be as presented in figure 17. In that case, the electric propulsion system is the option with the lowest cost, both in capital, compared to the LNG alternative, and operational costs compared to both the diesel and LNG propulsion alternative.



	Electric	Diesel	LNG
■ Operational costs	18 528 627	34 421 986	31 066 573
■ Construction costs	3 446 558	1 552 224	4 035 782

Figure 17. Combination scenario of future projections.

6. Discussion

6.1. Previous research

Since the trend to applying electric propulsion systems on marine vessels is relatively new, there are not many published studies related to a comparative LCCA in this area especially when it comes to pure electric propulsion. Previous analyses of life cycle costs on inland waterway vessels have been lacking in defining the difference in cost between different propulsion systems. By performing this analysis, we have pin-pointed the cost elements which are different between three propulsion systems; electric, diesel and LNG. Those costs are categorized in capital and operational costs. In the capital costs category, the cost elements that differ among the alternatives are the machinery main components (engines), the fuel systems (fuel tanks) and the ship common systems (main switchboard, fire alarm, ventilation, cooling and electrical cable installations). In the operational cost's category, the cost elements included in the analysis are the fuel costs, the port fees and fairway dues and the maintenance and spare parts costs.

The results in this study show that the electric propulsion is about 3.5 times more expensive in construction costs than the traditional diesel propulsion alternative and 1.5 times more expensive than the LNG propulsion. Along this line, the MANES's study (MAN Energy Solutions, 2019) on the perspective of battery on board vessels have resulted in the construction costs of the electric vessel to be 3 times more expensive than a traditional diesel propulsion vessel. This difference derives from the fact that in the MAN study, their capital costs are applied to the total construction costs for the vessel. In this thesis, only the cost elements that are different between the three propulsion alternatives are evaluated.

On a comparative LCCA of a hybrid and diesel propulsion short-route ferry, Wang et al. (2018) have concluded that the hybrid alternative is 3.5 times more expensive than the diesel propulsion system in construction costs while the total operating cost for the diesel propulsion is 1.5 times more expensive than the hybrid option. Regarding operational phase, they also conclude that minimum cost is achieved with the maximum use of the batteries and when instead of charging the batteries onboard, the batteries are charged on shore during night-time when the electricity price is lower.

6.2. Technological limitations

The electric concept vessel is dependent on recharging its batteries in both ports within 4 hours, which is a quite narrow window. One possible solution to the time-restriction is to have containers on the quay with already charged batteries which can simply be exchanged for the empty batteries onboard, plugged in and the vessel is ready to go. This would, however, mean that the ship operator will need to have three sets of batteries, one set onboard, one set in the port of Trollhättan and one set in the port of Gothenburg. This would dramatically increase both the capital and operational costs for the ship operator and is not economically defendable.

Another option is to develop the charging infrastructure along the route, more specifically at the locks. During the study visit onboard a ferry operating in Gothenburg, the vessel's operational profile and charging cycle was described. This ferry "tops up" the charge every 4th hour by running on a diesel engine that recharges the batteries and moves the vessel forward. When the concept vessel is on route between the port of Gothenburg and the port of Trollhättan, there are two locks it has to pass through, where it stands still for 2 hours. During this time the vessel would be able to connect to a shore connection and top up its charge, reducing the necessary time to recharge in both ports, and possibly reduce the necessary size of the batteries installed onboard, lowering capital and operational costs for new batteries.

6.3. Environmental aspect

Depending on the area of operation for vessels, the optimal fuel will vary greatly, as the alternative should fulfil all three aspects of economic viability, environmental acceptability and technical / operational restrictions. For an inland waterway vessel travelling on Göta Älv, the optimal fuel could very well be LNG due to its specific properties. Such as: no sulphur content, lower CO^2 emissions (by 20-30 %), decreases about 80-85 % of NO_x and barely produces any PM (Burel et al., 2013). There is, however, an issue with using LNG: the methane-slip. This is a big problem, because methane is a much more potent GHG with a higher global warming potential (GWP) than CO^2. So even though CO^2, SO_x, NO_x and particulates are lower when using LNG as a fuel, the methane-slip would counteract the positive impact by LNG if the problem is not solved.

For a vessel to switch over to LNG, there are some further convincing arguments apart from the fuel-contents. Along with the global sulphur cap, the sulphur limit for EU waters and the building of an LNG terminal in the port of Gothenburg, the motivation for using LNG as a fuel is strengthened. One big downside for using LNG though, is the much more expensive fuel tanks that have to be installed. Not only are they more expensive, the bigger size will diminish the available cargo capacity onboard, and thus lower the revenue for the shipowner.

Moreover, a possible future scenario would include the implementation of carbon tax on vessels. When that extra cost for pollution is applied, in this thesis the tax is applied on the port fees and fairway dues, the operational costs for the diesel propulsion vessel will increase and if the carbon tax expands to include greenhouse gases as well, the operational costs for the LNG propulsion alternative will also increase, making the electric propulsion a safe option to invest in.

6.4. Carbon tax implementation

With future, stricter regulations for emissions of CO^2 and greenhouse gases being implemented in the future, it is possible that the diesel and LNG propulsion systems are unable to meet future environmental demands. This might result in a higher cost in the future to convert existing vessels to more sustainable options, making them poorly suited options for transport on the Swedish inland waterways. Worst case scenario, it is not worth converting them to run on another fuel at all, and they will be taken out of operations while waiting for a new build to arrive to pick up operations.

6.5. Port fees and fairway dues

The only fees and dues which are assumed to be different between the three propulsion alternatives in this thesis are the compulsory port fees and fairway dues. The reason for them being different is because of the environmental discount that the different propulsion systems allow for. Another big cost not accounted for in this thesis, that represents a large portion of the voyage costs for the shipowner, is the pilotage fee. This fee is also compulsory, and applies to all vessels longer than 70 m, wider than 14 m, or deeper than 4.5 m,[13] and consists of a starting fee of $631, and an additional $196 for every initiated 30 minutes (Sjöfartsverket, 2018).

The regulations for the pilotage fee are, however, at the moment under review. Future regulations regarding compulsory pilotage onboard will be based on a risk assessment of the vessel, where factors such as the vessel’s length, the amount of fuel oil onboard and what type of manoeuvring equipment is installed on board will decide whether or not the vessel must have a pilot onboard or not, not the physical dimensions of the vessel alone (Röriksson, 2019). If the proposed regulations of basing the pilotage fee on the risk that a vessel poses are accepted and changed in the future, the pilotage fee might very well be different for the three propulsion systems analysed in this thesis.

6.6. Fuel cost

In this thesis, the electricity prices are only estimated to increase in the future. However, it might be the case that the electricity prices will decrease in the future, as opposed to our calculations of an annual increase of 2.42% and 1.41%. Furthermore, for the diesel propulsion alternative we calculate an annual decrease and increase of 3% in fuel prices, and a 1.5% annual increase and decrease in fuel prices for the LNG alternative, both of which might very well change more or less than that. Even though the price of electricity only increases in this thesis, the electric vessel is still a favourable option compared to the other two alternatives. Would the electricity prices decrease in the future, this would only make the electric vessel a more favourable option compared to the other two propulsion systems as it is already today the option with the lowest fuel cost.

At current prices the electric alternative is lower in fuel costs than the diesel and LNG. In scenario 1 of the sensitivity analysis performed on the fuel prices, the cost for MGO and LNG are estimated to decrease, whilst the electricity price is estimated to increase by almost 50% over 30 years. The fuel cost for the electric vessel is the highest out of the three alternatives in this scenario. In scenario 2, however, where all three alternatives increase in fuel price (with a more cautious increase for diesel and LNG compared to electric prices), the electric alternative is almost half the fuel cost of the diesel alternative, and more than $1 million lower than the LNG alternative.

The fuel cost for a vessel is dependent on several factors, such as the fuel price, the operational profile and the SFOC of the engine. In this thesis, only one ship building company and one engine propulsion manufacturer were interviewed for identifying the construction and operational costs and the cost for a diesel and LNG engine. Had more manufacturers and ship building companies been interviewed, there would be more data gathered on engine specifications and on construction and operational costs, and a more accurate analysis could have been made on the construction and operational costs for the three propulsion system alternatives.

The figures provided in interviews with stakeholders that were put into the cost model are estimates made by a ship building company and an engine propulsion manufacturer based on market prices and experience in the field. The numbers provided were general figures regarding the construction and operation of a vessel. Had more time and stakeholders been available for an

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[13] Since the dimensions of the three vessels is larger than the maximum dimensions required for the compulsory pilotage fee, all three vessels are subject to the pilotage fee. This cost is therefore assumed to be the same and not calculated in this thesis.

interview, the figures presented in this thesis could have been broken down further and thus highlighting the difference between the three propulsion systems further.

6.7. Scrapping costs

In this thesis, there has not been a thorough analysis performed on the scrapping costs for the different propulsion system alternatives. Therefore, the scrapping costs are not included in the life cycle costs of the vessels, since speculations in this area would contain too many uncertainties for the costs to be reliable.

6.8. Battery cost

Even though the current higher capital cost for the electric vessel, and lower battery price and longer battery lifetime on the horizon seems like a motivation for the shipping business to postpone the shift to electric propulsion, this is not entirely correct. In purely financial terms it is highly motivated to postpone the shift, but by postponing the shift the technological development takes longer than if it were to be implemented earlier. New technologies and their development are dependent on them being used and evaluated. Therefore, there is still a high incentive to make the shift now. The current low electricity price is also an incentive to make the shift now, not later. With increasing electricity price projections for the future, it makes more sense to invest in electrical propulsion now, for higher revenue early on.

The cost elements analysed in this thesis are only the ones identified as being different between the three alternative propulsion systems selected. Costs for similar cost elements have not been analysed, and there is therefore a bigger comparable difference in costs between the alternatives than if the total LCC for the vessels would have been investigated. Since the scope of this study was to highlight the differences between three alternative propulsion systems, therefore the method selected for interviews and data collection provided sufficient data for the purpose of this thesis.

7. Conclusion

In this thesis, we set out to answer three research questions. More specifically to identify the cost elements to include in a comparative analysis between three different propulsion systems for an inland waterway vessel, analyse how the life cycle costs are different on two cost levels: investment and operation, and what factors have the biggest impact on the life cycle costs for the three alternative propulsion systems.

Through a literature review and interviews with a ship building company, a maritime consultant company and an engine propulsion manufacturer, the cost elements relevant to include in a comparative life cycle cost analysis of capital and operational costs for the three propulsion systems were identified and analysed in a cost model. The capital costs include the elements of main machinery where the different engines are estimated as well as the batteries for the electric propulsion, the fuel tanks as part of the systems for main machinery and the ship common systems. On the operational cost category, the main cost elements are the fuel, the port fees and fairway dues and the maintenance and spare parts.

These cost elements were through additional interviews with several stakeholders analysed and the costs that are different among the alternatives were included in a cost model together with their respective amounts. Through analysing the cost elements identified for the comparison of the three propulsion systems in a sensitivity analysis, the cost elements having the biggest impact on the life cycle costs for the three propulsion alternatives were identified.

As the results from the life cycle cost analysis show, the electric concept vessel will be more expensive in both construction and operational costs with current prices and industry standards compared to a similar size vessel installed with a diesel or LNG propulsion system. The electric vessel is, however, more favourable in regard to local environmental impact because of its zero-emission propulsion system.

With strong indications that technological development will prolong the lifetime for the heavy-duty marine batteries in the future, the cost for replacing these batteries are cut in at least half (if calculated on same prices as today). Because the maintenance costs are largely reduced for the electric vessel, the total operational costs over its entire lifetime are also reduced. This reduction brings the electric vessel under the total operational costs of the diesel propulsion vessel, making it a strong competitor to traditional propulsion systems. If the battery prices drop as well, then the electric propulsion will be, by far, the option lowest in cost on the market when regarding operational costs.

The electric propulsion system is the most favourable option compared to the other two alternatives in regard to fuel cost, even though the price of electricity is only estimated to increase in the future scenarios of this thesis. If the fuel prices increase for all three alternatives, as presented in a combined future scenario, the electric alternative’s fuel cost is almost half that of the diesel alternative, and more than $1 million lower than the LNG alternative.

In addition, if the Swedish government adopts a carbon tax on fossil fuels used nationally, as it is suggested in this study, the diesel propulsion vessel will have more than double the operational expenses than the electric vessel, making the electrical vessel, again, a strong competitor on the market.

In the end, there are overall strong incentives to go electric sooner rather than later, as the future scenarios suggest. By investing in an electric propulsion system early on, the vessels are already in place when new regulations come into force. And with environmental discounts already applicable on all fees and dues today for vessels with lower emissions and a high environmental class, there is a strong motivation for choosing an electric propulsion system.

8. Future research

The cost elements analysed in this thesis are only the ones identified as being different between the three alternative propulsion systems selected. Costs for similar cost elements have not been analysed. Although the scope of the study was to highlight the differences in the alternative propulsion systems, a holistic view of total LCC for the three vessels where all cost elements are included would be a valuable aspect to investigate since the difference in marginal cost of the alternatives would be smaller in that case.

In addition, in this study the costs for scrapping a vessel have not been investigated, they are therefore not included in the analysis. Since there is a significant difference between the material components of the electric and the diesel and LNG propulsion the total LCC of this study could bring a notable difference in the results, this is therefore an interesting angle to investigate.

When time and resources are limited, the access to costs figures can be challenging, especially in a competitive commercial market, where companies are secretive regarding their costing strategy as that being part of their competitive advantage. Among the stakeholders interviewed in this thesis, there is only one shipbuilding company and one engine propulsion manufacturer, we therefore believe that further access to market prices as alternatives to evaluate and compare would make the findings more credible.

By performing the analysis on inland waterway vessels intended to operate on Swedish waterways, the research and its findings are limited. If the analysis was to be performed in a different location, such as the Netherlands or China which have a more developed IWW network, using the same propulsion systems and operational profile, the results would be different from the ones presented in this thesis as more data would be available for research.

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Appendix A

Cost items for ship construction

Complete cost breakdown of costs identified for the vessels.

1. Ship General

10. Specification, estimating, model test, drawing, ordering
11. Insurance, fees, general expenses, representation
12. General work and models
13. Provisional rigging during construction (staging etc.)
14. Work in connection with ways, launching and docking
15. Inspection, measurements, tests and trials
16. Guarantee and mending work
17. Services to ship during repair
18. Wages
180. Overhead costs
19. General consumption articles

2. Hull

20. Hull materials, general hull work
21. Afterbody
22. Engine area
23. Cargo area
24. Forebody
25. Deck houses and superstructures
26. Hull outfitting
27. Material protection, external
28. Material protection, internal

3. Equipment for cargo

30. Hatches and ports
31. Equipment for cargo in holds and on deck
310. Container cell guides
32. Special cargo handling gear
320. Container straps
321. Container locks
33. Auxiliary systems and equipment for cargo
34. Cargo and stores insulation

4. Ship equipment

40. Manoeuvring machinery and equipment
400. Bridge control
41. Navigation and searching equipment
42. Communication equipment
43. Anchoring, mooring and towing equipment
44. Repair/maintenance/cleaning equipment, outfitting in workshop/store
45. Lifting and transport equipment for machinery components

5. Equipment for crew and passengers

50. Lifesaving protection and medical equipment

51. Insulation, panels, bulkheads, doors, sidescuttles, skylights
52. Internal deck covering, ladders, steps, railings etc.
53. External deck covering, step and ladders, fore and aft gangway
54. Furniture, inventory and entertainment equipment
55. Galley and pantry equipment, arrangements for providing ironing and laundry
56. Transport equipment for crew, passengers and provision
57. Ventilation, air conditioning and heating system
58. Sanitary systems with discharges, drainage systems for accommodations

6. Machinery main components
60. Diesel engines for propulsion
61. Steam machinery for propulsion
62. LNG propulsion system
620. LNG pumps
621. LNG boil off-system
622. Glycol system
63. Battery propulsion system
630. Battery installation
64. Transmission and foils
65. Boilers, steam and gas generators
66. Motor aggregates for main electric power production
67. Other aggregates and generators for main and emergency electric power production
68. Workshop and storeroom
680. Spare gear, stores and tools
69. Machinery control room

7. Systems for main machinery components
70. Fuel systems
700. Fuel tanks
701. Engine room tanks
71. Lube oil systems
72. Cooling systems
73. Compressed air systems
74. Exhaust systems and air intakes
75. Steam, condensate and feed water systems
76. Distilled and make-up water systems
77. Auxiliary engines
770. Main generators
771. Steam generating plant
772. Heat exchangers
773. Pumps
774. Air compressors
775. Separators
776. Incinerators
777. Auxiliary distribution boards
78. Engine room ventilation system
79. Automation systems for machinery
790. Automatic control of machinery and systems

8. Ship common systems

80. Ballast and bilge systems, gutter pipes, outside accommodations
81. Fire and lifeboat alarm-, firefighting-, wash down systems
82. Air and sounding systems from tanks to deck
820. Emergency stop facilities
83. Special common hydraulic oil systems
84. Central heat transfer systems with chemical liquids
85. Electrical systems general part
86. Electrical power supply
87. Electrical distribution common systems
870. Main switchboard
871. Emergency switchboard
88. Electrical cable installation
89. Electrical consumers