Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Felix August Sødal Dietrichson

Retrofitting a Deep Sea Shipping Fleet

Keeping Up With Regulatory Emissions Targets

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstd
Co-supervisor: Martin Wattum
June 2023

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NTNU
Det skapende universitet

Master Thesis in Marine Systems Design

Stud. techn. Felix August Sødal Dietrichson

Retrofitting a Deep Sea Shipping Fleet

- Keeping Up With Regulatory Emissions Targets

Spring 2023

Background

The European Union (EU) and the International Maritime Organization (IMO) have set goals to achieve net-zero and low, respectively, greenhouse gas emissions by the year 2050, followed by strict regulations towards the shipping industry. The uncertainty with respect to which form and to which degree the regulations will take effect, presents a considerable risk for the shipping stakeholders, mainly being the shipowners. To set the global maritime shipping industry on the course of meeting the emissions goals of the Paris Agreement, net-zero and low-emissions shipping vessels must be viable and dominant options for ship owners within the coming decades. With an uncertain and complex future alternative fuel transition followed by unknown regulations, shipowners are required to take action toward decarbonizing their fleet beyond waiting for alternative fuel sources to be available.

Overall aim and focus

The aim of this thesis is to map alternatives for ship owners to decarbonize their fleet, increasing its efficiency, and develop an optimization model optimizing the fleet with respect to the alternatives, over an arbitrary time horizon, on the way toward a net-zero shipping industry.

Scope and main activities

1. Theory foundation and literature review of decarbonization options
2. Develop an optimization model optimizing a deep sea shipping fleet with respect to retrofit alternatives over a given time horizon
3. Data collection and processing of Klaveness' fleet for the case study
4. Develop optimization model in Python utilizing processed data for three case studies
5. Discuss and conclude the thesis work

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. From Torvald Klaveness AS, Senior Manager, Head of Project & Business Transformation Martin Wattum will be the co-supervisor and contact person, providing data for the case study.

The work shall follow the guidelines given by NTNU for the MSc Project work.

Stein Ove Erikstad
Professor/Responsible Advisor

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Abstract

This master's thesis revolves around an urgent global imperative: reducing greenhouse gas emissions within the international shipping industry. Even though deep sea shipping is the carrier of approximately 90% of the overall global transported goods, the shipping industry is a significant contributor to worldwide emissions, accounting for about 4% of the total greenhouse gas emissions. This considerable environmental footprint has placed the industry under the microscope, leading to an increasing call for emissions regulations and the introduction of emissions taxes. The International Maritime Organization (IMO) and the European Union (EU) have been pivotal in pushing forward these changes, putting forth stringent emission constraints and ambitious plans to decrease the shipping industry's emissions significantly, putting immense pressure on fleet owners and their operations.

A natural approach to tackling this challenge is to analyze alternative energy sources for shipping vessels. This thesis evaluates and presents four different fuel alternatives; ammonia, hydrogen, methanol, and liquid natural gas. However, these alternatives meet significant challenges for today's shipping vessels due to technical immaturity and underdeveloped infrastructure. The alternatives are presented for later research, as well as for emphasizing the need for alternative solutions beyond alternative fuel.

Addressing the regulatory demands requires a transformative approach, leveraging advanced modeling and decision-making techniques for identifying the most effective energy-efficient alternatives for a fleet of vessels. To this end, this thesis answers the research question: *How can an optimization model considering several energy-efficiency alternatives towards a deep sea shipping fleet, respecting a total annual emissions reduction by a set value over a given time horizon, contribute to solving a shipping fleet's challenges towards decarbonization?* The thesis introduces a binary linear optimization model for analyzing retrofit options compatible with vessels within a fleet over a given time horizon. The model utilizes data for the fleet of Torvald Klaveness and is designed to make strategic decisions regarding the timing and type of retrofit for each fleet vessel within a specific period. It is flexible and able to consider several retrofit alternatives with different values for multiple parameters, as well as an undefined number of vessels through a range of ages within the same fleet, over an arbitrary time horizon.

The model analyzing Klaveness' fleet is carried out for three distinct case studies, each focusing on a specific annual fleet emissions reduction target: 3%, 4%, and 5%. This staged approach allows for a nuanced understanding of the challenges and benefits associated with each emissions reduction level, providing a clear picture of the actions necessary to meet these targets. Nevertheless, with an annual emissions reduction target equal to 6%, the model is unable to find a feasible solution and returns the fleet and time horizon unaltered by retrofit options. In other words, more energy-efficient retrofit options or other emissions-reducing measures would be required for the vessels if the fleet is to obtain a higher annual reduction rate than for the three cases presented.

The analysis reveals that implementing an optimization model can be a powerful tool in achieving emissions reduction goals set by the IMO. By incorporating energy-efficient retrofits based on the model's suggestions, Klaveness' fleet can realize significant emissions reductions. However, the research also underscores that retrofitting alone may not be enough to achieve net-zero emissions within 2050, a goal advocated by the EU as well as Klaveness themselves. Achieving this lofty objective may necessitate the incorporation of additional measures, such as the integration of carbon-neutral or zero-carbon fuels or the deployment of fully electric propulsion systems. While these options pose their own challenges, from an operational, technical, and economic perspective, they underscore the multi-faceted approach required to fully decarbonize the shipping industry.

In conclusion, this thesis serves as a preliminary guide for a shipping company, demonstrating the power of guiding energy-efficiency retrofit decisions through an optimization model. It also emphasizes the need for a broader approach that includes advanced propulsion technologies and cleaner fuels to meet the net-zero emissions targets. Through this work, it is hoped that the industry will find itself better equipped to navigate the challenges ahead, reducing its environmental impact and driving towards a sustainable future.

Sammendrag

Denne masteroppgaven belyser en presserende global utfordring, nemlig behovet for å kutte klimagassutslipp i internasjonal skipsfart. Selv om rundt 90% av den internasjonale godstrafikken skjer via dyphavsskipsfart, er det en betydelig kilde til globale utslipp, med rundt 4% av verdens totale klimagassutslipp. Dette understreker skipsindustriens viktige rolle i overgangen til grønnere alternativer, som har resultert i økte krav om utslippsreguleringer og innføring av klimagasskatter. Den Internasjonale Maritime Organisasjonen (IMO) og Den Europeiske Union (EU) har vært betydelige pådrivere for disse endringene, og fremmet strenge tiltak og ambisiøse planer for å redusere utslipp innen skipsfart. Dette har imidlertid lagt et enormt press på skipseiere og deres drift.

En naturlig tilnærming for å håndtere denne utfordringen vil derfor være å vurdere alternative energikilder for shippingskip. Følgelig analyserer og vurderer denne oppgaven fire forskjellige drivstoffalternativer: ammoniakk, hydrogen, metanol og flytende naturgass. Disse alternativene møter imidlertid vesentlige hindringer som følge av teknisk umodenhet og underutviklet infrastruktur. Alternativene er presentert for videre forskning og for å fremheve behovet for alternative løsninger utover kun alternative drivstoff.

For å oppfylle de regulatoriske utslippsreguleringene er det behov for en transformativ tilnærming, som benytter seg av avanserte modellerings- og beslutningsteknikker. Dette vil kunne identifisere de mest energieffektiviserende alternativene for en skipsflåte. I lys av dette har oppgaven som formål å besvare følgende forskningsspørsmål: *Hvordan kan en optimeringsmodell som tar i betraktning flere energieffektive alternativer for en dypvannsflåte, og tar hensyn til total årlig utslippsreduksjon med en bestemt verdi over en gitt tidsperiode, bidra til å løse de utfordringer en skipsflåte står overfor med tanke på dekarbonisering?* Oppgaven introduserer en binær lineær optimeringsmodell for å analysere ulike retrofitalternativer, kompatible med skip i en flåte over en fastsatt tidsperiode. Modellen bruker data fra Torvald Klaveness' skipsflåte og er utformet for å veilede strategiske beslutninger om når hvilket alternativ skal installeres for hvert skip i en flåte over en bestemt tidsperiode. Modellen er fleksibel og kan vurdere flere retrofitalternativer med forskjellige verdier for flere parametere, så vel som et ubestemt antall skip av flere aldre innenfor samme flåte, over en variabel tidsperiode.

Modellen som analyserer Klaveness' flåte blir testet for tre forskjellige scenarioer, hver med fokus på et spesifikt årlig utslippsreduksjonsmål for flåten: 3%, 4% og 5%. Denne stegvise tilnærmingen gir en mer detaljert forståelse av de utfordringene og fordelene som er knyttet til hvert nivå av utslippsreduksjon, og gir et tydelig bilde av de tiltakene som kreves for å oppnå disse målene. Modellen makter imidlertid ikke å identifisere en optimal løsning med et årlig utslippsreduksjonsmål på 6%, og returnerer flåten og tidsperioden uendret. Det vil med andre ord bli nødvendig med flere energieffektive alternativer eller andre utslippsreduserende tiltak for å oppnå et høyere (årlig) utslippsnivå enn de tre test-scenarioene.

Analysen viser at implementeringen av en optimeringsmodell kan være et effektivt verktøy for å oppnå utslippsreduksjonsmålene satt av IMO. Ved å innlemme energieffektive retrofitalternativer basert på modellens anbefalinger, kan Klaveness' flåte oppnå betydelige utslippsreduksjoner, noe som fører industrien mot en mer bærekraftig fremtid. Likevel viser analysen at oppgraderinger alene trolig ikke er nok til å oppnå nullutslipp innen 2050, et mål satt av både EU og Klaveness selv. For å oppnå dette ambisiøse målet, kan det være nødvendig å innføre ytterligere tiltak, som integrering av karbonnøytrale eller null-karbon drivstoff, eller implementering av hel-elektriske fremdriftssystemer. Selv om disse alternativene har sine egne utfordringer, både fra et operativt, teknologisk og økonomisk perspektiv, understreker de den mangefasetterte tilnærmingen som kreves for å fullstendig dekarbonisere skipsindustrien.

Til slutt funger denne oppgaven som en innledende veiledning for rederier, og viser styrken ved energieffektive oppgraderinger og veiledning gjennom beslutninger tatt ved hjelp av en optimeringsmodell. Den fremhever også nødvendigheten av en mer omfattende tilnærming som inkluderer avanserte fremdriftsteknologier og renere drivstoff for å nå nullutslippsmålene. Gjennom dette arbeidet er håpet at industrien vil bli bedre forberedt på å navigere i fremtidige utfordringer, redusere sitt klimaavtrykk og innrette driften mot en mer bærekraftig fremtid.

Preface

This thesis is the work of a Master of Science degree at the Norwegian University of Science and Technology (NTNU) at the Department of Marine Technology. The work was written during the spring semester of 2023 and is the final work of the five-year integrated master's degree program with specialization in Marine System Design with a workload corresponding to 30 ECTS credits. The thesis was written in collaboration with the shipping company Torvald Klaveness where I interned during the summer of 2022 and proposed a collaboration, which was accepted. It was agreed that Klaveness would provide the necessary data to perform the case study for their shipping fleet, and in return, I would inform them about my findings and results.

The main motivation for doing this work was to obtain knowledge about alternatives for emissions reduction of shipping vessels, without focusing solely on alternative energy sources, as well as contributing to Klaveness' future decarbonization plan for its fleet. Additionally, gaining insight into the shipping industry from a ship owner's perspective, played a vital role.

The preliminary sections of this paper provide a detailed overview of the thesis' scope, which finds its roots in the project report written during the fall of 2022 by me. Although initially designed as a preparatory study for this thesis and offering a portion of the literature review, the project thesis led to a shift in the overall direction of this research. The decisions related to the final scope of this thesis were made in collaboration with the supervisor.

This master's thesis was written entirely by Felix August Sødal Dietrichson and has allowed me to expand my own knowledge in a self-chosen direction within the maritime industry. The work has been a challenging yet enjoyable part of my education at NTNU.

Felix August Sødal Dietrichson

Trondheim, June 10th 2023

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Acknowledgement

I would like to thank my supervisor, Professor Stein Ove Erikstad (NTNU), for guidance throughout the writing of this thesis, sharing knowledge, and providing quality references. Thank you for insightful guiding hours, as well as pleasant talks about non-school-related topics. I would also like to thank my co-supervisor, Martin Wattum at Torvald Klaveness, for valuable insight into the shipping industry from a ship owner's perspective, your time for answering questions, sharing of data, contribution to the case study, as well as my intern period during the summer of 2022.

Finally, I would like to thank Per Henrik and Jacob for an uplifting and motivating working environment, sharing coffee breaks, billiard matches, and both hard and fun times, making the writing process of this thesis far easier.

Thank you,

Felix August Sødal Dietrichson

Abbreviations

AUN	Floating Fertilizer
BLC	Boundary Layer Control
BLP	Binary Linear Programming
BTL	Biomass-to-liquids
CAPEX	Capital Expenses
CCs	Combination Carriers
CCS	Carbon Capture & Storage
CH_3OH	Methanol
CH_4	Methane
CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
CONOPS	The Concept of Operations
CPP	Clean Petroleum Products
CSS	Caustic Soda Solutions
DCS	Fuel Oil Data Collection System
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EMSA	European Maritime Safety Agency
EEXI	Energy Efficiency Existing Ship Index
EGR	Exhaust Gas Recirculating
ENVEX	Environmental Expenses
ETS	European Union's Trading Scheme
EU	European Nations
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
GA	General Arrangement
GHG	Greenhouse Gas
GJ	Giga-Joule
GloMEEP	Global Maritime Energy Efficiency Partnerships Project
GSP	Green Shipping Program
GT	Gross Tonnage
H_2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydro-treated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
KCC	Klaveness Combination Carriers
kUSD	Thousand United States Dollar
LBG	Liquid Biogas
LNG	Liquid Natural Gas
LOA	Length Overall
LPG	Liquefied Petroleum Gas
MGO	Marine Gas Oil
MDO	Marine Diesel Oil
MUSD	Million United States Dollar
MT	Metric Tons
NH_3	Ammonia
NM	Nautical Miles
NMCE	The Norwegian Ministry of Climate and Environment
NO_x	Nitrogen Oxides
NPV	Net Present Value
OPEX	Operational Expenses
PM	Particulate Matter
RAMS	Reliability, Availability, Maintainability, and Safety
ROI	Return on Investment
SEEMP	Ship Energy Efficiency Management Plan
SVO	Straight Vegetable Oil
SCR	Selective Catalytic Reactor
SFC	Specific Fuel Consumption
SFOC	Specific Fuel Oil Consumption
SoC	Statement of Compliance
TRL	Technology Readiness Level
UN	United Nations
VOYEX	Voyage Expenses

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1 Introduction

The following chapter will present the background and motivation for this thesis, as well as its objective together with the scope and limitations, followed by its outline.

1.1 Background and motivation

The shipping industry has become increasingly significant in the global transportation of cargo, and it is evident that maritime transportation is a more environmentally and economically viable option when compared to road and air transport (European Parliament [1]). However, the maritime shipping industry is responsible for approximately 4% of the world's total emissions, with a 4.9% increase from 2019 to 2021, with deep-sea shipping accounting for about 80% of the overall shipping emissions (European Parliament [1], Lloyds list [2]). Despite this, roughly 90% of the world's traded goods are transported by deep-sea cargo vessels (Solvang [3]). However, the emissions from both international maritime transport and domestic navigation, are predicted by the EU to have a constant increase as depicted in Figure 1.1. Consequently, the maritime transportation sector is required to reduce its total greenhouse gas emissions without reducing its capacity, as the international goods market cannot afford such a decline.

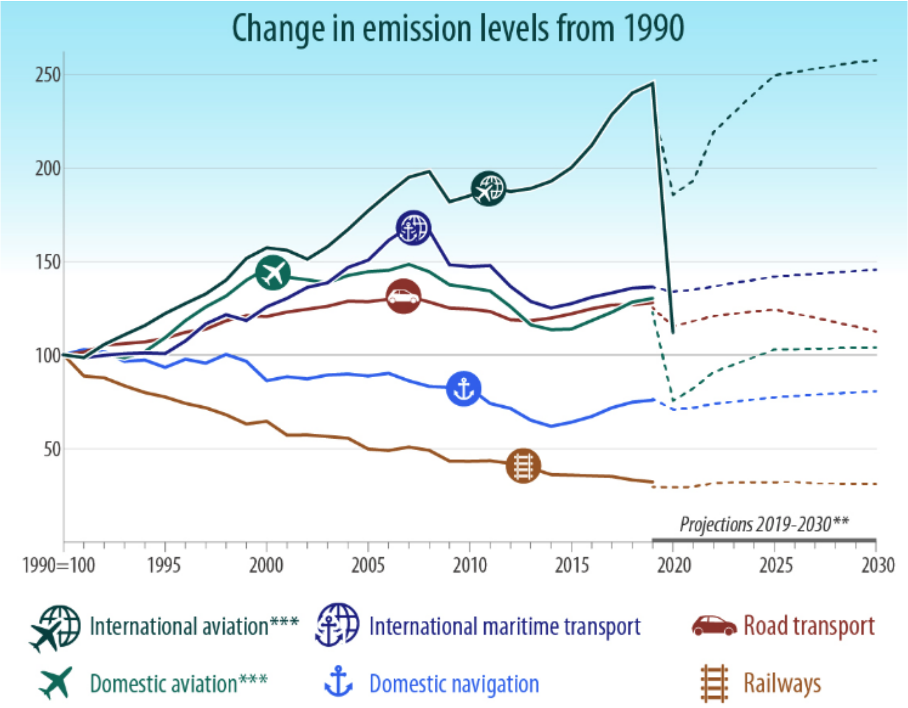


Figure 1.1: Transport emissions (European Parliament [1])

Given the maritime transport sector's critical role in the global economy and the significant amount of greenhouse gas (GHG) emissions it generates, it is imperative that the industry undergoes significant transformation to reduce its emissions while maintaining its freight rate. In 2015, at the United Nations (UN) Climate Change Conference in Paris, world leaders established a climate agreement, known as *The Paris Agreement* (Paris Agreement [4]). This agreement set long-term goals for a sustainable future, with a particular emphasis on significantly reducing global greenhouse GHG. This mandate requires almost every industrial sector, including shipping, to significantly reduce its emissions and become more sustainable. In order to foster collaboration among different industries toward the common goal of sustainability, it is essential to establish a clear definition of this concept. The UN defined sustainability in 1987 as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations [5]).

Sustainability is based on three pillars, commonly referred to as the three P's: People (society), Profit (economics), and Planet (environment). These three pillars are interdependent, collectively defining sustainability, with the planet/environment serving as the foundation for the other two.

In order to ensure a sustainable future for the shipping industry, it is crucial for market drivers to allocate resources strategically. This involves transforming operations to become more energy efficient while maintaining their functionality. Market drivers typically encompass stakeholders who own or manage assets such as vessels or fleets, and they play a key role in driving sustainability efforts. To make informed decisions about technology development and infrastructure priorities, it is important to conduct studies that assess the decision criteria preferences held by these stakeholders. Such studies will provide valuable insights into the areas that require further technological advancements and infrastructure improvements. Sustainable solutions should be economically viable, socially responsible, technically feasible, and environmentally friendly. Ultimately, the stakeholders of these assets hold the final authority in determining which investments are relevant and when they should be made.

Currently, several challenges follow with alternative fuels for the shipping industry, such as immature technology, underdeveloped infrastructure, and lack of financing for the development of the two. Consequently, ship owners are currently primarily focusing on increasing their vessel's cargo transport capability per energy unit, hereby referred to as the vessel's "efficiency". They strive towards reducing the vessel's fuel consumption, thereby transporting more goods per unit of GHG emitted. Measures to increase ship efficiency may include solutions such as optimizing the vessel's design decreasing its resistance and increasing its cargo capacity, monitoring ship performance with respect to the hull's coating to reduce friction towards the water, or installing available solutions to increase the vessel's efficiency, such as air-lubrication systems or rotor sails, further discussed in Section 5.4. Bio-fouling, or the growth of organisms on the ship's hull, is a significant problem for ship owners as it significantly increases the vessel's friction, and reduces its performance and efficiency, thereby increasing the vessel's specific fuel consumption (SFC).

It is indisputably a rapid need for a technological evolution within the shipping industry. Its fuel consumption and hence its GHG emissions are required to be reduced, as well as it must be able to keep up its annual transport rate, or even have it increased. In other words, the shipping industry necessitates a higher level of efficiency. This thesis will attempt to evaluate different energy-efficiency measures for shipping vessels in light of a fleet and provide recommendations for the vessel fleet owner with respect to energy-efficiency alternatives, through advanced decision-making with the help of optimization theory.

1.2 Research question and objective

The research question this thesis aims to solve is: *How can an optimization model considering several energy-efficiency alternatives towards a deep sea shipping fleet, respecting a total annual emissions reduction by a set value over a given time horizon, contribute to solving a shipping fleet's challenges towards decarbonization? The model should be flexible and able to consider several energy-efficiency alternatives with different values for several parameters, as well as an undefined number of vessels with different ages, over an arbitrary time horizon.*

In navigating the complex decision-making process related to identifying and implementing appropriate energy-efficiency measures for a specific vessel or entire fleet, a multitude of factors come into play. For fleet owners, the main objective usually revolves around financial expansion and profitability. Therefore, committing to high-cost enhancements for their vessels necessitates a strong belief in the economic viability and potential return on these investments. This thesis aims to merge a shipowner's practical insights with a comprehensive literature review and principles of optimization theory, in order to formulate an optimization model that can project the timeline for a shipping fleet. This model will dictate when and which vessels within the fleet should incorporate the designated energy-efficiency features.

The successful integration of these features should trigger a consistent reduction in emissions over time, ensuring the total emissions from the fleet continually decrease until the end of the projected timeline. Data necessary for this research is gathered through quantitative internet-based research and is subjected to qualitative filtering. In order to demonstrate the model's efficacy, a case study using data provided by the shipping company Torvald Klaveness for their fleet operated by Klaveness Combination Carriers (KCC) is carried out. Nonetheless, the model is versatile enough to accommodate a broad range of criteria and diverse data sets with varied parameters, thereby making it applicable for multiple fleet owners in addition to Klaveness.

1.3 Scope and limitations

The scope of this thesis focuses on the design and application of an advanced optimization model, tailored for guiding strategic decisions in retrofitting a fleet of vessels to achieve specified emissions reduction targets over a timeframe. The study conducts real-world data from the fleet of Torvald Klaveness and analyzes several energy-efficiency retrofit options with diverse parameters. The thesis limits itself to a certain range of energy-efficiency features suitable for implementation within a fleet of uniform vessel designs. Each energy-efficiency feature's characteristics, including installation and operational costs and potential for fuel reduction, are derived from the author's comprehensive research evaluating the economic, environmental, technical, and social aspects of each feature. Furthermore, each vessel's specifications are restricted to key attributes necessary for the successful integration of each energy-efficiency feature, though a multitude of variables could significantly influence the actual decision-making process. To ensure the successful completion of the thesis within the allotted time frame, such limitations were deemed essential.

Furthermore, an evaluation of alternative fuels for shipping vessels is a natural approach when discussing emissions-reducing measures for the industry. This thesis outlines and discusses four popular alternative fuels; ammonia, hydrogen, methanol, and liquefied natural gas (LNG). However, the four alternatives are only presented, swiftly discussed, and compared, and the thesis limits itself to focus solely on retrofit alternatives as emissions-reducing measures. This is due to the noteworthy challenges today that follow alternative fuels, such as technological immaturity and underdeveloped infrastructure. The assessment is included for the purpose of further research, discussed in Section 10.1, and for highlighting the need for alternative solutions besides alternative fuel.

1.4 Thesis organization

The organization of the thesis and its structure is presented in Figure 1.2. Section 2 and Section 3 outlines the basis theory and background backing the need for this thesis. Section 4 and Section 5 presents possible solutions for the decarbonization of shipping vessels, while Section 6 explains key parameters for a shipowner to respect when evaluating different decarbonization solutions. Section 7 presents a possible solution model respecting the shipowner's criteria whilst evaluating the different alternatives. Section 8 and Section 9 carries out, analyses and discuss three case studies for the fleet of Klaveness with respect to the possible decarbonization alternatives also respecting the shipowner's criteria. Section 1 and Section 10 are the introduction and conclusion sections, respectively.

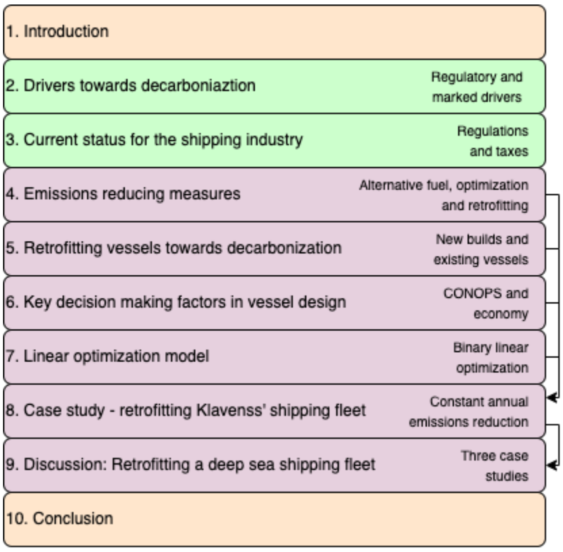


Figure 1.2: Structure of the thesis

The following list includes a more comprehensive explanation of each section's content:

- Section 2 presents the regulatory and the marked drivers essential for the decarbonization of the marine industry, in particular the shipping industry. Further, it presents energy-efficiency measure methods for shipping vessels, that are to be utilized later in the thesis.
- Section 3 discusses the shipping industry's status today with respect to present and upcoming regulations for regulatory drivers. Emissions regulations in terms of set goals and taxes are presented, followed by the world's merchant fleet's current challenges.
- Section 4 discusses possible alternatives for reducing a vessel's fuel consumption and emissions, evaluating alternative fuels, optimizing operations, and retrofit possibilities.
- Section 5 discuss retrofitting of vessels, different alternatives, and their possible costs and effect on the respective vessel. The retrofit options presented will be utilized during the case study for Klaveness' fleet.
- Section 6 takes on the concept of operations (CONOPS) for a vessel and its economy as two essential decision-making factors for a shipowner during the design process of a vessel, whether a new build or during retrofitting. The two factors will play vital roles throughout decisions made in regard to the case study.
- Section 7 presents a binary linearly linear optimization model proposing a solution for a fleet consisting of several vessels that are to be retrofitted with different alternatives, mapping the fleet's time horizon and deciding when each vessel should be retrofitted with which option. The model will be used for analyzing Klaveness' fleet of combination carriers.
- Section 8 consists of three case studies for Klaveness' combination carrier fleet, utilizing the optimization model developed for: 3%, 4%, and 5% annual emissions reduction for the fleet. The results are presented and analyzed.
- Section 9 discuss the results from the three case studies, comparing them to each other and evaluating the results. The results are put in light of the background theory presented in the early sections, as well as their economic, operational, and economic implications.
- Section 10 concludes the thesis work and presents further recommended work.

In the appendix Section I, a poster summarizing this thesis created in conjunction with an exhibition at NTNU, Marine Technology, is presented. The poster's intention is to introduce the problem of the thesis and present how the problem is approached and solved, whilst presenting and discussing the results.

2 Drivers towards decarbonization

There is an undeniable need for a shift in the maritime industry towards sustainability. To make this shift a reality, key drivers and decision-makers must be put in place. Two main drivers that set specific requirements for the industry to follow and provide both the technology and economy necessary for these requirements to be fulfilled are known as the *Regulatory Drivers* and the *Market Drivers*.

2.1 Regulatory drivers for decarbonization of the shipping industry

The regulatory drivers for the decarbonization of the shipping industry are typically official organizations raised by governments to set and enforce regulations for private businesses. The drivers can often be segmented into international, regional, and national.

2.1.1 International Maritime Organization

It says "IMO – the International Maritime Organization – is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO's work supports the UN sustainable development goals" on the official website of IMO (International Maritime Organization [6]). IMO is an international regulatory driver and has adopted mandatory measures to reduce greenhouse gas emissions from the international shipping sector as part of its pollution prevention treaty, under the MARPOL convention outlined in 1973 (IMO Marpol [7]). The treaty has been updated regularly and consists of six annexes, including regulations aimed at preventing and minimizing pollution from vessels - both accidental pollution and from routine operations. In accordance with its initial GHG strategy, IMO has set specific targets for reducing the carbon intensity and total annual GHG emissions of international shipping. By 2030, CO_2 emissions per unit of transported goods should be reduced by at least 40% compared to 2008 levels, with a further effort towards a 70% within 2050. Additionally, total annual GHG emissions from international shipping should be reduced by at least 50% by 2050, compared to 2008 levels. The detailed timeline of IMO's initiatives for climate change and GHG reduction from 2011 to 2050 is presented in the appendix, as shown in Figure A1. As the official international shipping regulator, IMO has a significant amount of power and responsibility in driving GHG reduction efforts in the maritime sector. Recent IMO initiatives have focused on reducing emissions and establishing stricter Energy Efficiency Design Indexes (EEDI) for new vessels, considering the vessel's carbon dioxide emissions per unit of transport work, and may be calculated using Equation 1, variables described in Table 1 (MAN [8]). The lower a vessel's EEDI, the more efficient it is. A similar index assessing existing vessels is the Energy Efficiency Existing Ship Index (EEXI), setting limits on the amount of CO_2 existing vessels can emit per unit of transport work. The calculation is the same as for the EEDI. IMO's efforts are crucial in achieving a more sustainable future for the shipping industry.

$$EEDI = \frac{CO_2 \text{ Emissions}}{\text{Benefit Cargo}} = \frac{\sum P \times Cf \times SFOC}{Capacity \times Speed} \tag{1}$$

Variable	Description
P	The vessel's main and auxiliary engine power
Cf	Conversion factor between fuel consumption and CO_2 emission
$SFOC$	Specific fuel oil consumption

Table 1: EEDI variables

2.1.2 European Union

"The European Climate Law writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% within 2030, compared to 1990", it says on the home page of the European Commission (European Commission [9]). The EU functions as a regional regulatory driver and this law aims to ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part. The strategy consists of five main objectives (European Commission [9]):

1. Set the long-term direction of travel for meeting the 2050 climate neutrality objective through all policies, in a socially fair and cost-efficient manner
2. Set a more ambitious EU 2030 target, to set Europe on a responsible path to becoming climate-neutral by 2050
3. Create a system for monitoring progress and taking further action if needed
4. Provide predictability for investors and other economic actors
5. Ensure that the transition to climate neutrality is irreversible

This strategy is aligned to meet the 2°C temperature reduction goal of the United Nations, which is integrated into the Paris Agreement. The European Climate Law sets a legally binding emissions-reducing target for all EU Institutions and Member States, including Norway, which are bound to take the required measures at the EU and national levels to meet the goal. The progress of the law will be reviewed every five years. Additionally, the law also includes a process for setting a 2040 climate target. The goals set by the EU are slightly stricter than the goals set by the International Maritime Organization, as the EU aims for net zero by 2050, and IMO aims for 50% GHG emissions reduction from ships compared to 2008 by 2050.

2.1.3 National drivers

The regulations imposed by different countries can vary significantly. National governments set restrictions on vessels sailing under their flag, necessitating vessel owners operating in international waters to comply with national emission restrictions in addition to international requirements. In recent times, taxation and regulations for greenhouse gases such as CO_2, NO_x, and SO_x have become increasingly significant for national drivers. In 2019, the Norwegian parliament introduced strict requirements pertaining to NO_x and SO_x emissions in the Norwegian world heritage fjords (Sjøfartsdirektoratet [10]). Moreover, the parliament mandated that all tourist vessels operating in the world heritage fjords must be low or zero-emission vessels by no later than the year 2026. Such initiatives are crucial for accelerating the adoption of greener solutions within the maritime industry. They drive the development of more advanced technologies and solutions and pave the way for other countries and companies that share the same objective and vision.

2.2 Market drivers for decarbonization of the shipping industry

The drive towards decarbonizing the shipping industry is primarily driven by market factors that are not exclusively instigated by governmental entities, but nevertheless contribute to the reduction of GHG emissions within the sector. Such drivers seldom instigate efforts to diminish their carbon footprint unless mandated by regulations or incentivized by economic benefits. These two factors are frequently interrelated, whereby an increase in emission taxes or the availability of cheaper alternative fuels can incentivize companies to take on decarbonization projects.

2.2.1 Joint industry initiatives

The decarbonization of the shipping industry's energy consumption is contingent upon industry-wide initiatives that are being spearheaded by both public and private entities. These collaborative endeavors are accelerating the energy transition process. For instance, the Green Shipping Programme ([11]), the daughter company of the class company Det Norske Veritas (DNV) ([12]), is a noteworthy industry-led initiative supporting shipowners in their quest to adopt eco-friendlier practices. This program facilitates the implementation of innovative retrofits, such as air-lubrication systems and coating optimization, in existing vessels, as well as providing guidance in the design of sustainable vessels. Other joint industry initiatives include the Green Maritime Forum ([13]) and the Global Industry Alliance ([14]).

2.2.2 Financial

The most significant obstacle to the acceleration of the green shift in decarbonizing the world's shipping fleet is the lack of sufficient financing. Retrofitting a vessel to operate on for instance hydrogen instead of marine gas oil or designing, developing, and constructing a vessel fueled on methanol incurs substantial costs for the stakeholders, investors, and owners, of the respective vessel. Therefore, financing market drivers play an indispensable role in hastening the green transition. The Poseidon Principles, signed in December 2021, constitute a crucial player in green financing, with an increasing number of prominent ship owners and lenders endorsing the principles (Poseidon [15]). The Poseidon Principles offer a framework for evaluating and disclosing the climate alignment of ship finance portfolios. By setting a benchmark for responsible banking in the maritime sector and providing actionable guidance on how to attain this, the Poseidon Principles strive to contribute to the GHG reduction ambitions of the International Maritime Organization and enable financial institutions to align with the IMO's strategies.

Given that banks play an essential role in financing new projects, they have the power to decide which projects to support financially. By endorsing the Poseidon Principles, banks commit to measuring the carbon intensity of their loans and publicly reporting the results. Consequently, the financing provided by these banks is compelled to prioritize carbon reduction projects.

2.2.3 Cargo owners

There is a growing emphasis among cargo owners on the decarbonization of the world's shipping fleet as well. The Sea Cargo Charter is an exemplary initiative seeking to align chartering practices with the environmental goals outlined by the IMO (Sea Cargo Charter [16]). Some cargo owners are opting to charter vessels with lower carbon footprints, and their chartering departments operate under increasingly stringent carbon dioxide budgets. Several charterers have endorsed the Sea Cargo Charter agreement to respect the established framework and report their emissions performance. Such initiatives compel charterers to choose less carbon-intensive vessels, thereby facilitating the transition to a greener shipping industry.

2.2.4 Infrastructure

The green shift in the marine industry faces a significant hurdle in the form of inadequate infrastructure to support various alternative fuels and electric solutions, such as port charging and fuel storing facilities. Establishing a functional infrastructure for non-fossil fuel-powered vessels, comparable to the current infrastructure for vessels using conventional fuel, entails a substantial cost and a challenging design process. The integration of the new infrastructure with the existing one is a complex task, further adding to the difficulty and cost of the project.

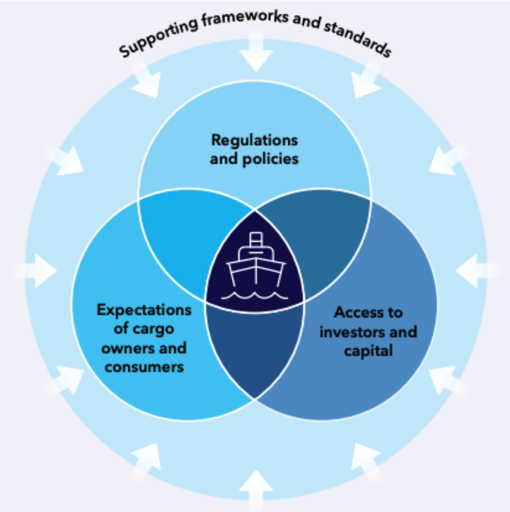
2.2.5 Risks

Carbon risk is a concept of several aspects, encompassing the financial, charter, and regulatory risks associated with uncertainties related to carbon prices for ship owners, as highlighted by the EDHEC-Risk Institute ([17]). Financial risk pertains to the potential loss of and negative return on investment, while charter risk refers to the risk of cargo owners not prioritizing emissions and costs in their contracts. Regulatory risks are associated with new regulations affecting the market value of an asset or requiring costly investments, resulting in financial risks. These risks have the potential to disrupt financing from institutions toward the development of solutions for the green shift.

It is worth noting that vessels currently under design and construction will likely take around five years from project initiation to launch, and will have a lifespan of approximately 25 to 30 years (TPK4164 NTNU lecture [18]). As such, these vessels will be subject to the stringent regulations of the IMO that will come into effect and be continuously re-evaluated during their operational lifetime. The regulations in effect in 2040, for instance, are very challenging to accommodate in vessels designed and ordered today due to the technological constraint, and therefore, these vessels will need to comply with new regulatory requirements, which may involve significant retrofitting or installation of several carbon-reducing solutions, such as propulsion system renovation or hybrid system installation. Such interventions entail significant costs, including investments and revenue losses from downtime. The associated uncertainties with these regulatory changes represent a significant risk for the stakeholders of the vessel.

2.3 DNV's 2050 maritime forecast

According to DNV's 2050 maritime forecast, which was released in 2022, significant and transformative measures are anticipated to be implemented in the coming years (DNV 2050 forecast [19]). The report emphasizes that in 2023, additional regulatory measures will be implemented to address the decarbonization of shipping. This includes a revision of the IMO GHG Strategy, which will tighten the GHG emissions reduction goals for international shipping. The report also identifies three essential drivers for the decarbonization of the shipping industry, supported by frameworks and standards that establish sustainability evaluation criteria and targets, GHG emission calculation methods, and reporting requirements. These drivers include (1) regulations and policies, (2) the expectations of cargo owners and consumers, and (3) access to capital and investors. The report illustrates this concept as a "triangle", represented by a Venn diagram in Figure 2.1a.



(a) Three key fundamentals for driving the shipping decarbonization (DNV 2050 forecast [19])

The regulatory framework aimed at reducing GHG emissions from international shipping, as established by the IMO and the EU, is still in the process of being established. Figure 2.2 provides a visual representation of the planned framework, including the measures that will be taken to address the issue, such as the EEDI and the EEXI, as well as the Carbon Intensity Indicator (CII) (DNV [20]). Furthermore, the EU has introduced two additional measures, namely the EU Emissions Trading System and the FuelEU Maritime, which focus on the global trading market and the fuel standards for marine sector fuel consumption, respectively (DNV 2050 forecast [19]). Both of these measures target the entire supply chain, from the oil field to the combustion process onboard the vessels, with a focus on the well-to-wake approach (Bureau Veritas [21]).

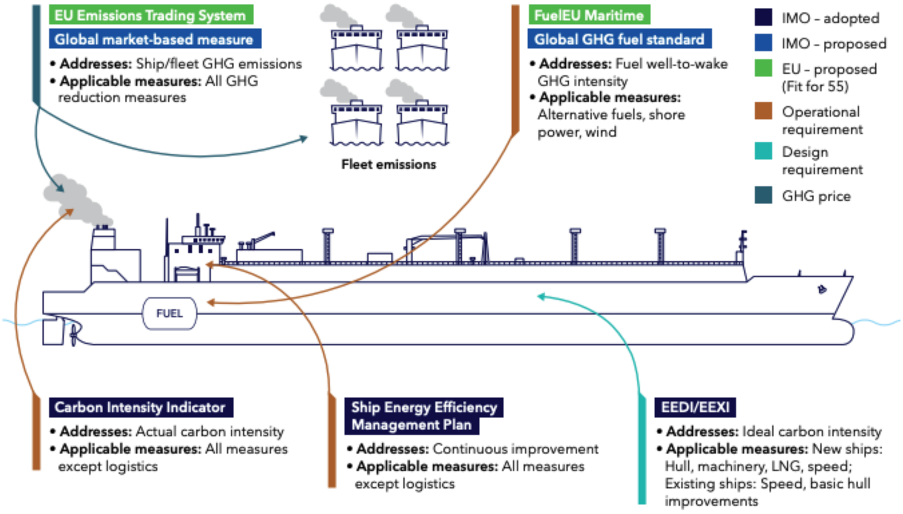


Figure 2.2: IMO and EU regulatory framework (DNV 2050 forecast [19])

2.4 IMO's Carbon Intensity Indicator

Carbon intensity is a critical metric used to assess the efficiency with which an economy utilizes its carbon resources to produce output (IMO [22]). It measures the quantity of CO_2 emissions per unit of economic activity. Policymakers, investors, and companies have become increasingly interested in tracking and managing their carbon footprint by utilizing carbon intensity as a key indicator. The carbon intensity indicator is a measure of how efficiently a cargo transporting vessel transports goods or passengers. As of January 1^{st} 2023, the IMO CII scheme has entered into force, making it mandatory for vessels carrying goods or passengers to report their CII for their 2023 data in 2024. The CII unit will be calculated annually based on the amount of CO_2 emissions per cargo-carrying capacity and nautical miles sailed.

Vessels are assessed using a rating system that spans from A, representing the highest level of performance, to E, indicating inferior performance. At present, the rating system can only assign ratings up until the year 2026, with further restriction levels to be established that are progressively more rigorous towards the year 2030. A review of the rating system is scheduled for the year 2025, with the aim of analyzing the collected data and imposing additional limitations as necessary. Vessels that have been rated D for three consecutive years or that have received an E rating are obligated to establish a corrective action plan. This plan should include measures such as an installation or modification of operations. The reporting timeline for CII is depicted below in Figure 2.3.

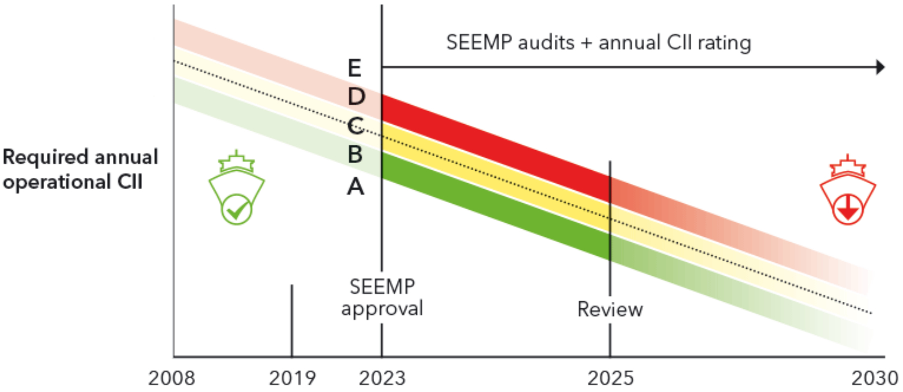


Figure 2.3: Carbon Intensity Index (DNV [20])

The CII must be calculated and reported to the Fuel Oil Data Collection System (DCS) verifier, along with the aggregated DCS data for the previous year, including any correction factors and voyage adjustments, no later than three months after the end of a calendar year (DCS [23]). If a vessel is required to develop a plan of corrective actions, the Ship Operational Carbon Intensity Plan (SEEMP Part III) must be updated with a corrective action plan and verified before the Statement of Compliance (SoC) can be issued, with the same deadline for issuance: May 31^{st} the following year. The enhanced SEEMP aims to ensure continuous improvement and should include an analysis of why the required CII was not achieved, along with a revised plan (DNV [20]).

2.4.1 Carbon Intensity Index vs. Energy Efficiency Existing Ship Index

The EEXI and the CII are both regulatory measures introduced by the IMO to address GHG emissions from ships. The EEXI focuses on assessing the energy efficiency of existing ships, considering factors such as the vessel's design, engine power, and fuel consumption. It sets a minimum efficiency requirement that vessels must meet to reduce their emissions. On the other hand, the CII aims to measure the carbon intensity of ships during their operations. It takes into account the vessel's actual fuel consumption and the distance traveled. The CII provides a standardized metric to evaluate and compare the energy efficiency of different vessels.

While the EEXI sets a baseline for ship efficiency, the CII provides a dynamic and performance-based assessment of emissions during operations. Together, these indices complement each other by promoting energy efficiency improvements in existing ships and monitoring and reducing carbon intensity during ship operations. The CII is commonly considered a valuable indicator for evaluating the effectiveness of improvements made to a vessel during performance-based assessments. It provides a standardized metric for measuring the impact of these improvements on reducing carbon intensity during ship operations. By assessing the actual fuel consumption and distance traveled, the CII offers a dynamic and comprehensive evaluation of a vessel's energy efficiency, making it a preferred choice for measuring the value of implemented enhancements, or retrofits, between the two. The CII will therefore be the favored option for this thesis as an energy measurement of vessels.

2.4.2 Calculation of CII

To determine the CII rating of a vessel, several calculations have to be performed. Firstly, the attained CII for the vessel can be derived as in Equation 2 with variables presented in Table 2, as exemplified by Stormgeo ([24]). The calculation includes correction factors and voyage adjustments for various vessel types and circumstances but can be severely simplified for a standard bulk or combination carrier. The annual emissions can be calculated by multiplying annual fuel consumption (MT) with the CO_2 emissions factor for the respective fuel type, and the transport work can be defined as the annual distance sailed in nautical miles (NM), as reported under IMO Data Collection System, times the vessel's deadweight (DWT) or gross tonnage (GT), depending on the type of vessel. Furthermore, a correction factor and voyage adjustments may be applied to the basic CII calculations to account for special designs and operational circumstances and determine the vessel's rating.

$$\begin{aligned}
&CII_{attained}\\
&= \frac{\text{Annual Fuel Consumption} \times CO_2 \text{ factor}}{\text{Annual Distance Sailed} \times \text{Capacity}} \times \text{Correction factor}\\
&= \frac{\sum_{j=1}^{N} C_{Fj}[FC_j - (FC_{voyage,j} + TF_j + (0.75 - 0.03y_i) \times FC_{electrical,j} + FC_{boiler,j} + FC_{others,j}))]}{f_i \times f_m \times f_c \times f_{iVSE} \times C \times (D_t - D_x)}\\
&= \frac{\sum_{j=1}^{N} FC_j \times C_{Fj}}{C \times D_t} C_{corr}
\end{aligned} \tag{2}$$

Variable	Description
j	The fuel oil type
C_{Fj}	The fuel oil mass to CO_2 mass conversion factor for fuel oil type
FC_j	The total mass of consumed fuel oil of type j in the calendar year, as reported under IMO DCS
$FC_{voyage,j}$	The mass of fuel of type j consumed in voyage periods during the calendar year
TF_j	The quantity of fuel j removed for STS or shuttle tanker operation
$FC_{electrical,j}$	The total mass of consumed fuel oil of type j consumed for the production of electrical power
$FC_{boiler,j}$	The total mass of consumed fuel oil of type j consumed by the boiler
$FC_{others,j}$	The total mass of consumed fuel oil of type j consumed by other fuel-consuming related devices
f_j	The capacity corrector factor for ice-classed vessels
f_m	The factor for ice-classed vessels having IA Super and IA
f_c	The cubic capacity correction factor for chemical tankers
f_{iVSE}	The correction factor for ship-specific voluntary structural enhancement
C	The ship's capacity DWT or GT depending on vessel type
D_t	The total distance traveled (in NM), as reported under IMO DCS
D_x	The total distance traveled (in NM) for voyage periods deductible from CII calculation
C_{corr}	The correction factor for converting from MT fuel consumed to grams

Table 2: CII variables

A CII reference value is required for the respective vessel and will be based on the reported carbon intensity performance of the respective vessel type from 2019, presented in Equation 3. a and c are parameters for the respective vessel type estimated through regressions fits, presented in appendix Section E. The vessel's capacity will be in DWT if the vessel transports anything but typically vehicles or passengers, and will if so be in GT.

$$CII_{reference} = a \times capacity^{-c} \tag{3}$$

Further, the required CII for the vessel will be calculated as shown in Equation 4, based on the CII reference and the required annual reduction factor Z set by IMO. The annual reduction factors are based on 2019 values ranging from 2023 to 2026 and are listed in Table 3. Z values for 2027 and later is to be further strengthened and developed taking into account the review of the short-term measure by IMO.

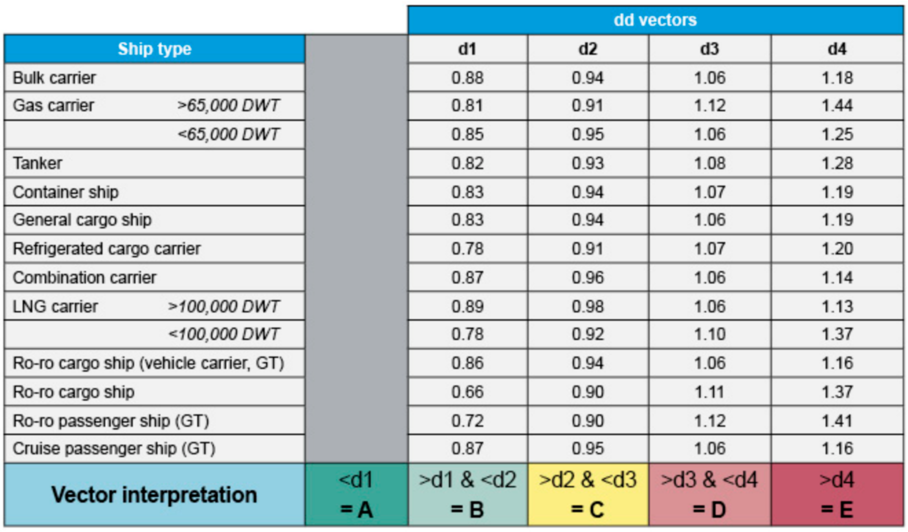
	2023	2024	2025	2026	2027 →
Z	5%	7%	9%	11%	To be determined

Table 3: Annual reduction factor

$$CII_{required} = CII_{reference} \times \frac{100 - Z}{100} \tag{4}$$

Finally, the CII results for the respective vessel may be calculated as shown in Equation 5, by diving the vessel's attained CII by its required. The value attained represents the vessel's CII score, ranging from A to E, using the table shown in Figure 2.4. For instance, a combination carrier attaining a CII_{result} equal to 0.91, will be rated $> d1$ & $< d2$ with the CII score B.

$$CII_{result} = \frac{CII_{attained}}{CII_{required}} \tag{5}$$



			dd vectors			
Ship type			d1	d2	d3	d4
Bulk carrier			0.88	0.94	1.06	1.18
Gas carrier	>65,000 DWT		0.81	0.91	1.12	1.44
	<65,000 DWT		0.85	0.95	1.06	1.25
Tanker			0.82	0.93	1.08	1.28
Container ship			0.83	0.94	1.07	1.19
General cargo ship			0.83	0.94	1.06	1.19
Refrigerated cargo carrier			0.78	0.91	1.07	1.20
Combination carrier			0.87	0.96	1.06	1.14
LNG carrier	>100,000 DWT		0.89	0.98	1.06	1.13
	<100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier, GT)			0.86	0.94	1.06	1.16
Ro-ro cargo ship			0.66	0.90	1.11	1.37
Ro-ro passenger ship (GT)			0.72	0.90	1.12	1.41
Cruise passenger ship (GT)			0.87	0.95	1.06	1.16
Vector interpretation		<d1 = A	>d1 & <d2 = B	>d2 & <d3 = C	>d3 & <d4 = D	>d4 = E

Figure 2.4: CII table score (IMO [25])

2.4.3 CII calculation example

A bulk carrier assesses the specification listed in Figure 2.5a and will be used to calculate the CII for the years 2023 to 2026, respecting the Z-values listed in Table 3. Further, the calculations for the CII score are presented in Table 4, and are based on the assumption that the vessel does not implement any form of emissions reduction measures, and stays homogeneous throughout the respective time horizon.

Bulk carrier	Value
FC_j	$5,504$
C_{Fj}	3.17
Dt	$60,045$
C	$62,000$
C_{corr}	$E6$
a	$4,745$
c	0.622

(a) Bulk carrier example data

$CII_{attained}$	$CII_{reference}$	$CII_{required}$			CII_{result}
$\frac{5{,}504 \times 3.17}{62{,}000 \times 60{,}045} \times E6$ $= \mathbf{4.69}$	$4,745 \times 62,000^{-0.622}$ $= \mathbf{4.96}$	2023	$4.96 \times \frac{100-5}{100}$	$= \mathbf{4.71}$	**1.00**
		2024	$4.96 \times \frac{100-7}{100}$	$= \mathbf{4.61}$	**1.02**
		2025	$4.96 \times \frac{100-9}{100}$	$= \mathbf{4.51}$	**1.04**
		2026	$4.96 \times \frac{100-11}{100}$	$= \mathbf{4.41}$	**1.06**

Table 4: CII bulk carrier example results

From 2023 until 2025, the bulk carrier is graded to score C, keeping in the interval $> d2$ & $< d3$. However, in 2026, the vessel reaches the limit of $d3$ and will be scored to a grade of D. If the ship owner does not introduce any emissions-reducing measures within the consecutive three years from 2026, they will have to come up with a corrective action plan and should include measures for reducing the vessel's emissions to an acceptable level.

2.5 Emissions policy and maritime decarbonization technology

Figure 2.6 presents the links between the relationship of the legislation and maritime decarbonization technology. The figure is split into three main parts; (1) a shipowner part where the interest is in the fuel cost of the ship, (2) a policymaker part where the interest is in the emissions part of the vessel, and (3) a solutions part where the interest in how vessels can reduce both their emissions and fuel consumption. The common interest for the ship owners and the policymakers is solutions for reducing fuel consumption and hence emissions. Evaluating the regulatory and the marked drivers, their joint interest would hence be in investing in fuel and emissions-reducing measures to ensure stability and economic growth within the shipping market. This joint interest encourages regulatory drivers to fund and invest in market initiatives with a focus on lowering emissions, such as DNV and the Green Maritime Forum. The potential for collaboration, development, technological, and economic growth lies within the solutions area (3), which is precisely the area of focus for this master's thesis.

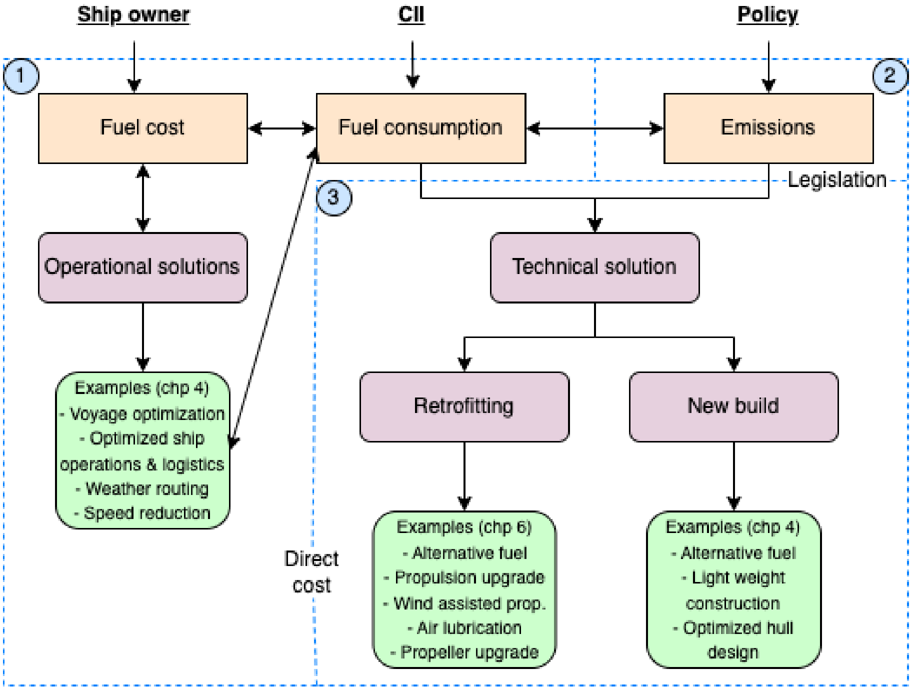


Figure 2.6: Emissions policy and maritime technology linked

3 Current status for the shipping industry

As emphasized in Section 1.1, the imperative for transitioning towards a more environmentally sustainable marine industry cannot be overstated. However, realizing this vision will necessitate joint efforts by both regulatory bodies and market forces, as well as significant investments in measures aimed at reducing GHG emissions and the development of stringent regulations in this regard.

3.1 World's shipping fleet

For the marine freight industry being as vital as it is for the world economy, there are some alternatives for existing vessels to reduce their annual emissions without compromising their annual cargo freight significantly. Such alternatives often are referred to as retrofits, discussed in detail in Section 5, such as scrubber systems, air lubrication systems, or Flettner rotors. As of February 2023, it was predicted that over 4000 shipping vessels will be equipped with exhaust gas cleaning systems, or scrubbers, by the end of the year, according to Statista ([26]). New Scientist reports that as of October 2022, 78 large vessels have air lubrication systems, with at least 155 more planned for installation in the coming years (New Scientist [27]). The air lubrication system has the potential to reduce friction between the vessel and water, thereby reducing fuel consumption and emissions. Flettner rotors, resembling vertical cylinders, function as sails that use rotational energy to harness wind energy. Although no statistical data are available regarding the number of vessels with Flettner rotors, it is estimated that approximately 7% of the world's merchant fleet, comprising $58,000$ vessels, including $17,800$ cargo vessels, have installed at least one of the three retrofit options mentioned above (Statista [26]). This is a remarkably low number, highlighting the need for motivation of shipowners to invest in energy-efficient solutions for their fleet.

To achieve a greener industry, international shipping companies must collaborate and adhere to the same regulations, which typically set limits on GHG emissions, fuel types, and taxes on some greenhouse gases such as CO_2 and NO_x. Such regulations are essential for maintaining the competitiveness and sustainability, both environmentally and economically, of the industry.

3.2 Rules and regulations

The maritime industry is currently at a crossroads, as shipowners and fuel suppliers are hesitant to commit to zero-carbon fuel due to a lack of a comprehensive global infrastructure. On one end, shipowners are reluctant to invest in vessels that rely on zero-carbon fuel as the infrastructure for such fuel is not yet in place, and there is no certainty as to whether the fuel will be available globally in the future. On the other hand, infrastructure developers, ports, and fuel suppliers do not perceive any existing or growing market for a particular type of fuel and are therefore wary of investing in infrastructure without a clear return on investment (ROI). The various types of relevant fuel alternatives for shipping vessels each have their own unique set of specifications, advantages, and disadvantages, making it challenging for both parties to determine which type of fuel to commit to. This lack of knowledge and development of zero- or low-emission energy sources, coupled with the limited demand from shipowners for zero- or low-emission fuel, presents significant obstacles for investments in low-carbon fuel technology and infrastructure.

In particular, alternative fuels, such as ammonia and hydrogen (discussed in Section 4.1), are less economically viable for shipping vessels, with lower energy density and higher production costs than conventional fuel, as well as a host of stricter safety requirements and regulations. Moreover, the infrastructure for either of these fuels is still in its infancy, making it difficult for fleets to transition away from traditional marine gas or diesel oil. However, in order for the shipping industry to play its part in achieving the United Nations net-zero emissions goal by 2050, it is crucial to establish mature and stringent international regulations and economic incentives to facilitate the transition to low-carbon fuel options.

3.2.1 International Maritime Organization

IMO's comprehensive long-term plan aims to reduce GHG emissions by at least 50% relative to the 2008 levels by 2050 and achieve a reduction of the average carbon dioxide intensity by at least 40% by 2030 and 70% by 2050, as discussed in Section 2.1. Figure 3.1 illustrates the GHG emissions reduction for an LNG carrier design in accordance with these targets. The magnitude of the emissions gap, as represented by the difference between the business-as-usual scenario (blue line) and the targets (green line), increases linearly with an elevation in the year 2030, necessitating accelerated decarbonization and a concerted effort to reduce shipping emissions.

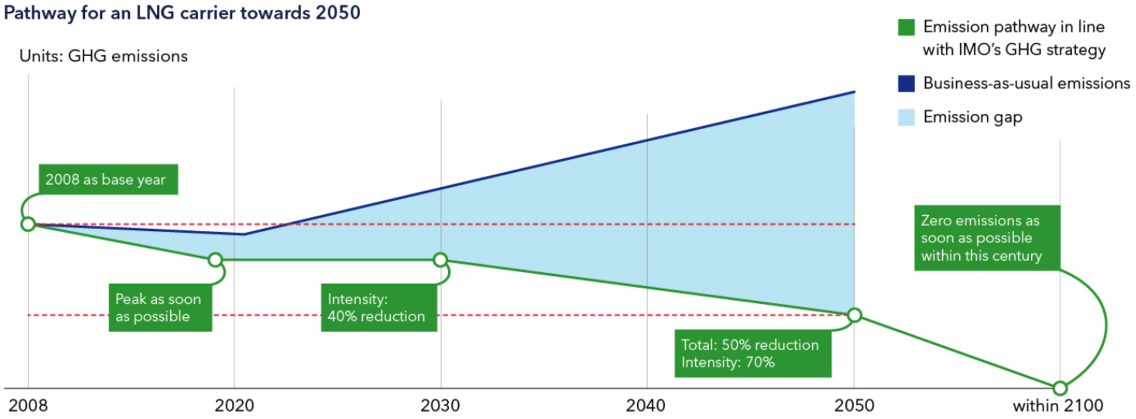


Figure 3.1: IMO's GHG reduction ambitions for an LNG shipping vessel for 2050 (IMO [28])

3.2.2 European Union

In 2023, the European Union is scheduled to undertake a comprehensive analysis of emissions data from the shipping industry (Gerretsen [29]). From January 2023, shipping was included in the European Union's trading scheme (ETS), and all vessels that transport goods in and out of the EU, regardless of the flag they are sailing under, are taxed by their emissions at the EU's tax rates (DNV [30]). The tax rates require shipping vessels to purchase carbon dioxide allowances to cover all emissions during a voyage in Europe's waters and half of the emissions generated by international voyages that start or finish in a European port.

The European Council has enacted the European climate law, known as ”Fit for 55”, which establishes legally binding objectives for the EU and its member states (European Council [31]). The goals aim to reduce GHG emissions by 55% by 2030 compared to 1990 levels and to achieve climate neutrality by 2050. Their official website states: ”To reach these goals, EU member states need to take concrete measures to reduce emissions and decarbonize the economy. New rules and updates of EU legislation are needed to make the green transition a reality.” The Fit for 55 goals contain a range of legislative proposals and amendments to current EU legislation that will assist the EU in reducing GHG emissions and achieving climate neutrality. The goals adhere to the main parts (2) and (3) in Figure 2.6, and will play a major role in the development of technical solutions with green incentives. Figure 3.2 provides a visualization of the amendments contained in the Fit for 55 package.

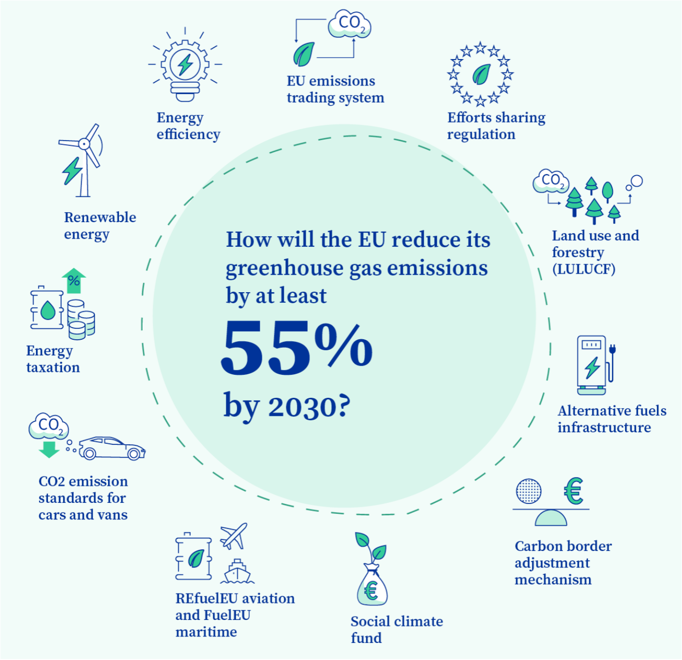


Figure 3.2: Fit for 55 amendments (European Council [31])

The transportation sector accounts for a significant portion of Europe's greenhouse gas emissions, with aviation and maritime transport responsible for 14.4% and 15.5% of the transportation emissions, respectively. To address this, the European Council has proposed a set of regulations to promote the use of renewable and low-carbon fuels in maritime transport, referred to as FuelEU maritime (European Council [31]). The scope of this initiative includes vessels of 5,000 GT or above and aims to encourage the uptake of sustainable fuels to reduce the sector's environmental impact. One such regulation is the carbon index indicator, discussed in Section 2.4, which is designed to incentivize emissions-reducing solutions.

3.2.3 Emissions taxes

The taxation of GHG emissions is also a topic of discussion by both the IMO and the EU. The EU has announced plans to tax nearly 70% of emissions from voyages to the European Economic Area (Adamopoulos [32]). The proposed tax rates vary by fuel type and include a tax of about 100 euros per tonne of carbon emissions on international shipping emissions and domestic bunkers. This taxation imposes stricter emissions regulations on shipowners, boosting incentives for green innovation, and looking for emissions-reducing solutions (EU [33]).

In June 2021, the Danish shipping company Maersk, proposed a carbon tax on ship fuel to encourage the transition to cleaner alternatives, proposing a tax rate of 150 USD per tonne of carbon dioxide emitted (Maersk [34]). The CEO at Maersk, Soren Skou, labeled the tax proposal ”a levy to bridge the gap between the fossil fuels consumed by vessels today and greener alternatives that are currently more expensive”.

The taxation of other GHG emissions is also being considered, with discussions on whether and how much these emissions should be taxed. For instance, the Norwegian government taxes propulsion machinery with an installed engine power greater than 750kW, with rates of approximately 2.3 euros per kilo of nitrogen oxide (NO_x) emitted, to support the development and funding of NOx-reducing technologies and solutions (Skatteetaten [35]).

3.3 Challenges for the world’s fleet

Given the current state of the global shipping industry, and in light of forthcoming regulations mandating substantial reductions in greenhouse gas emissions, it has become evident that urgent and comprehensive actions are required. Despite the implementation of emission-reducing measures, a relatively small percentage of the world’s shipping fleet has adopted such measures, while regulatory restrictions and emissions taxes are expected to become increasingly stringent. The majority of the world’s merchant fleet is owned and operated by countries with robust economies, which should serve as exemplars for other emerging nations that may face economic constraints in complying with forthcoming regulations, as such measures will incur significant costs. The joint effort between regulatory bodies and market drivers will assume a growingly vital role in influencing shareholders and investors to prioritize forthcoming decarbonization endeavors, presenting itself as one of the most significant obstacles faced by the maritime industry. To tackle this challenge and effectively convince shareholders and investors, it is imperative to establish economically and environmentally viable solutions. With the challenges ahead, market drivers must be motivated for investing in and developing emissions-reducing measures.

4 Emissions reducing measures

The shipping industry and the global merchant fleet are presented with the prospect of reducing their total greenhouse gas emissions, towards a more sustainable energy future. This can be achieved through exploring alternatives such as alternative fuels, energy-efficient retrofits of hull structure, or propulsion systems, as well as optimizing ship operations, logistics, and supply chain management.

4.1 Alternative fuel pathways

Engineers, shipowners, stakeholders, and infrastructure developers worldwide are exploring a range of alternative fuels for powering the global shipping fleet, each with its own advantages and limitations, making them more or less suitable for different types of ships and sailing routes. The suitability of a particular fuel for a given vessel depends on several factors, such as its energy efficiency and emissions profile, technical maturity (including engine readiness and infrastructure development), and safety considerations. Furthermore, the environmental impact of each fuel is influenced by its energy pathway. Therefore, a range of factors must be considered when selecting an alternative fuel for a vessel, including both its technical and environmental characteristics.

4.1.1 Energy pathways

Although alternative fuels may have lower GHG emissions during combustion, emissions are still produced throughout the fuel supply chain, including during production, transportation, storage, and consumption. Various methods can be used to address emissions at each step of the supply chain, such as different production techniques, transportation methods, and combustion processes. As a result of these variations, fuels that need to be distilled or created as they are an energy vector rather than pure energy, are often categorized into three types: *green*, *blue*, and *gray* (Chem4Us [36]), depicted in Figure 4.1. Green fuels generally have the lowest emissions, followed by blue and gray fuels, respectively.

A fuel is classified as *green* if it is produced using renewable energy and does not emit CO_2 into the atmosphere during production or consumption. *Blue* fuel is produced through the consumption of natural gas or fossil fuel, which releases a significant amount of CO_2. To mitigate this, the CO_2 produced during the production process is captured using carbon capture storage (CCS) and either used as raw material or stored geologically in for instance empty oil wells. Finally, *grey* fuel is similar to blue fuel, except that the CO_2 is not captured and stored. Among the fuel types that can be produced in different ways today, *grey* fuel is the most commonly used (Tous droits réservés [36]).

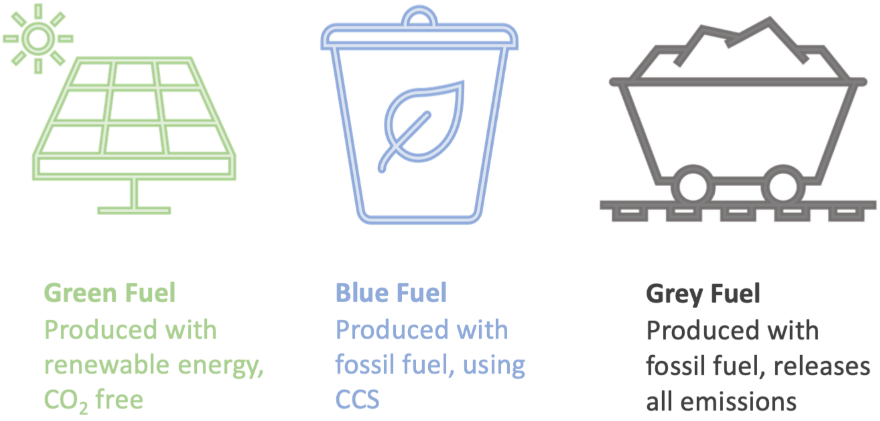


Figure 4.1: Green, blue and grey fuel pathways (Tous droits réservés [36])

4.1.2 Fuel categories

It is common to sort fuels into different fuel categories based on their origin (DNV [37]). Different energy sources may be refined into the same fuel, which presents significant variations in life cycle costs and emissions. The different fuel categories are listed below.

- *Fossil fuels* - origins from the decomposition of millions of years old carbon-based organisms
- *Blue fuels* - origins from reformed natural gas or fossil fuel with carbon capture storage
- *Biofuels* - origins from sustainable biomass sources
- *Electrofuels (e-fuels)* - origins from from renewable energy, nitrogen and non-fossil carbon

Resulting, fuels can be categorized based on both their production method, revealing their *energy pathway*, and their origin, revealing their *fuel category*.

Fossil fuels are derived from natural geological processes and are extracted from the earth through drilling and mining operations, utilized through combustion, and dominate the maritime energy landscape. However, the use of these resources has significant environmental consequences as the high carbon content of fossil fuels results in large amounts of carbon dioxide emissions, making it the largest contributor to GHG emissions worldwide.

Blue fuels refer to carbon-free fuels produced either directly from fossil fuels or indirectly through carbon capture and storage technology. The pioneering CCS project, Longship CCS, developed in Norway, is among the first to capture and store CO_2 emissions from the European continent, demonstrating remarkable progress in infrastructure and technology development (Longship CCS [38]). The cost of implementing the technology is currently considered economically unsustainable, and the lack of reception facilities and transportation opportunities for the CO_2 is a major barrier. Possible solutions may include underground storage using dedicated CO_2 carriers or repurposing CO_2 for other purposes.

Biofuels are derived from primary biomass or biomass residues, and various feedstocks can be utilized to produce liquid or gaseous fuels through the conversion of these biomass materials. The biofuels are consumed as fuel, releasing CO_2 and other greenhouse gases. Biodiesel and liquid biogas (LBG) are currently the most promising biofuels for shipping vessels. The most common biodiesel types include fatty acid methyl ester (FAME), biomass-to-liquids (BTL), and hydrotreated vegetable oil (HVO), which are considered viable alternatives to MDO and MGO (DNV [39]). Compared to fossil fuels, biofuels do not contain sulfur and therefore emit no SO_x while also reducing CO_2 emissions. The main challenges facing the use of biofuels as marine fuels are their high cost to shipowners and the current low production levels. Scaling up production would require a significant increase in feedstock absorption, which may not be sustainable.

E-fuels, also known as synthetic fuels, are carbon-neutral fuels produced through electrolysis. The electricity used in the process comes from renewable sources like wind or solar power, with carbon dioxide captured from the atmosphere or waste streams used in their synthesis. The production of e-fuels is reliant on the availability of sustainable electricity. Different synthesis methods yield diverse e-fuels such as hydrogen, ammonia, and methanol. They can be utilized in traditional internal combustion engines with minimal modifications, thus often referred to as "drop-in fuels". E-fuels can store excess energy during periods of high energy production, aiding in grid stability. Their widespread adoption is currently hindered by high production and distribution costs, conversion losses, and low overall efficiency compared to conventional fuels. As renewable electricity becomes cheaper and more available, the affordability and prevalence of e-fuels are expected to increase, contributing to the advancement of hydrogen and ammonia as marine fuels.

DNV's *Maritime Forecast* 2050 provides a comparative analysis of the carbon-neutral energy supply chain for the future, as depicted in Figure 4.2.

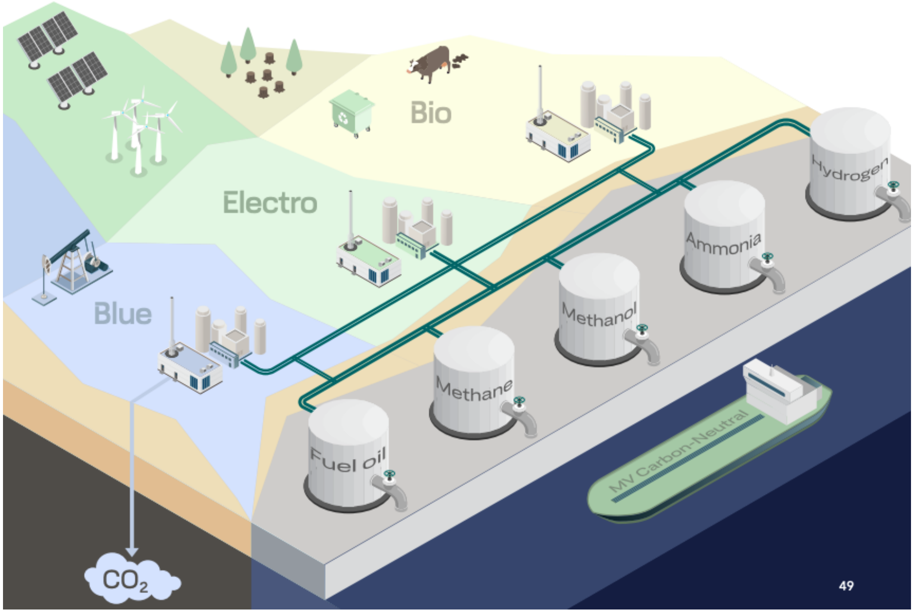


Figure 4.2: DNV's predicted future carbon neutral energy pathway (DNV [37])

4.2 Conferred fuel alternatives

The marine industry has witnessed growing interest in alternative fuels for shipping vessels, with numerous stakeholders involved in discussions and deliberations, including scientists, shipowners, port operators, fuel infrastructure developers, and stakeholders. The diverse range of relevant alternative fuels carries specific technical specifications and may each be better suited for specific types of vessels. Among these alternative fuels, four are frequently discussed as the primary candidates: ammonia, hydrogen, methanol, and liquid natural gas (LNG). This section aims to provide an analysis of these alternative fuels with a focus on their technical data, maturity, and safety aspects.

4.2.1 Marine gas oil

In order to evaluate the technical specifications of hydrogen, ammonia, methanol, and LNG as potential alternative fuels for shipping vessels, marine gas oil will be used as a reference point. In the context of marine shipping vessels, diesel oil is the predominant fuel used worldwide. However, the safety aspects of MGO as fuel for deep-sea shipping vessels serve as a benchmark for comparison with alternative fuels. MGO exhibits high flammability and can ignite easily in the presence of an open flame. Ingestion of MGO can be life-threatening, while skin contact poses no harm to humans. Moreover, the environmental impact of spillage or leakage is considered substantial. The consumption of MGO releases significant quantities of greenhouse gases, highlighting the pressing need for alternative fuels to reduce the environmental impact of shipping.

Technical data
MGO is a widely-used energy source due to its exceptional energy efficiency with an energy density of $41.1\frac{MJ}{l}$ (Global Combustion [40]). MGO-fueled engines are technically mature and well-developed. Wärtsilä's diesel and gas engines are among the best marine diesel engines commercially available, exhibiting an efficiency ranging between $42\% - 52\%$, depending on the engine type ([41]). This underscores the need for alternative fuel-based engines to be rigorously engineered to compete with the efficiency of diesel engines.

4.2.2 Ammonia

Ammonia (NH_3) is a versatile and widely used chemical with various applications, including its use as an alternative fuel. Ammonia production involves readily available raw materials, namely nitrogen, and hydrogen, which makes it an attractive option. However, it presents several challenges and limitations, such as requiring low-temperature storage ($-33°$C), which demands a significant amount of energy. While ammonia can be burned in internal combustion engines (ICE) or fuel cells, the latter is more efficient. However, converting existing shipping engines to run on ammonia requires significant modifications, especially if transitioning to a fuel cell engine.

In September 2022, Wärtsila launched their first 4-stroke engine that can run on ammonia, able to be fueled on diesel, LNG, or carbon-neutral bio-fuel (Fuels and lubes [42]). The engine obtains the ability of an effortless transition towards ammonia, when it is commercially available as a fuel, and marks the beginning "of a new era of future-proof medium speed, small-bore engines ([42])". Despite the advancements, it may still be several years before ammonia becomes commercially available as a marine fuel for shipowners. This is due to the necessary further development of infrastructure and the need for greater technical maturity in ammonia-fueled engines.

The second major challenge posed by ammonia as a fuel is its toxic properties. Ammonia is a transparent, odorless gas that is highly poisonous to humans if inhaled or if it comes into contact with the skin in liquid form. This renders it challenging to detect, necessitating the use of ammonia detectors at all times to ensure safety. Due to the high risk associated with ammonia, strict maintenance, monitoring, and safety measures will be necessary to prevent incidents. While ammonia consumption produces the harmful gas NO_x, these can be filtered out to some extent before being released into the atmosphere. Nonetheless, ammonia emits zero CO_2 and SO_x.

Technical data
The energy density of ammonia is significantly lower than that of MGO, with a value of $15.6\frac{MJ}{L}$ (Valera-Medina [43]). This means that vessels using ammonia as fuel must carry approximately three times more fuel to travel the same distance as those using MGO. Furthermore, ammonia acquires an advantage with respect to emissions taxes on CO_2, NO_x, and SO_x (discussed in Section 3.2), which are already in place in some regions and are likely to become more common.

4.2.3 Hydrogen

Hydrogen (H_2) is an energy carrier that can be produced through various methods including the electrolysis of water, or by reforming natural gas (Energy Efficiency & Renewable Energy [44]). Hydrogen can be utilized as a fuel in combustion engines or fuel cell engines, with fuel cells capable of achieving efficiency levels exceeding $50-60\%$.

The potential of hydrogen as a marine fuel has been investigated by the Green Shipping Program (GSP) of DNV in Norway, which concluded that cargo vessels fueled by hydrogen could potentially be competitive with the same level of economic support as the autonomous, GHG-friendly cargo vessel, Yara Birkeland (Green Shipping Program [45]). However, without the required economic support, hydrogen-powered vessels are currently not competitive with those using conventional fuel. Another major obstacle for hydrogen as a fuel is the fact that it is highly explosive and requires strict security measures, maintenance, and monitoring. The event of ignition during fueling in port or onboard during deep-sea operation could lead to catastrophic consequences for both humans and the vessel. One of the key advantages of hydrogen as a fuel is its zero emission of CO_2, NO_x, or SO_x during consumption.

Technical data
Liquid hydrogen has an energy density of $8\frac{MJ}{l}$ (Axane GCP [46]), posing significant challenges to using hydrogen as a fuel. Firstly, a hydrogen-fueled vessel would require five to six times the volume of storage tanks than MGO to achieve the same sailing distance. Secondly, to maintain liquid hydrogen, storage tanks must be perfectly insulated and maintained at $-252.87°$C and 1 bar. The large volume of liquid hydrogen storage with the temperature required for practical use necessitates significant amounts of energy, further increasing the vessel's total energy consumption.

4.2.4 Methanol

Methanol (CH_3OH) is a colorless, organic liquid and is a widely used commodity, available in over 100 ports worldwide and can be produced from a variety of feedstock resources, including renewable energy sources (Methanol Institute [47]). Methanol's simple chemical composition, consisting of one carbon atom, four hydrogen atoms, and one oxygen atom, results in a remarkably high carbon-to-hydrogen ratio, making it a promising candidate as a low-emission fuel for marine vessels.

The predominant industrial production process for methanol results in clean, pure methanol that is water-soluble and biodegradable. Methanol's ability to dissolve in water makes it less harmful to aquatic organisms, and it has lower NO_x and SO_x emissions than conventional hydrocarbon fuels. Methanol also has the potential to be carbon-neutral, as it can be produced from renewable sources or even from captured carbon dioxide. The conversion process of a conventional 2-stroke marine engine into being methanol-compatible is relatively straightforward, making methanol one of the most prominent "drop-in fuels" available today (DNV 2050 forecast [19]). While a four-stroke, lean-burn Otto-cycle engine has shown promise in test runs with methanol, commercial availability is still pending (Wartsila [48]). Despite its potential as a low-emission fuel, methanol is toxic to humans in small quantities, and strict safety measures are necessary throughout the vessel operation and supply chain.

Technical data
Methanol has a boiling point of 64.7°C, which enables it to remain in liquid form at room temperature, without necessitating a heating or cooling system for storage onboard a vessel (Chemical Book [49]). It obtains an energy density that is roughly half that of HFO (Bureau Veritas [50]). Due to its lower carbon and higher hydrogen content compared to other liquid fuels, and its heating value of $15.8\frac{MJ}{l}$, the storage volume required for methanol is approximately three times that of MGO per energy unit, according to DNV (DNV [51]).

4.2.5 Liquid natural gas

Liquefied natural gas is an alternative fuel with the main component methane (CH_4), and it contains varying amounts of other hydrocarbon components (DNV [52]). As shown in Figure Figure 4.3, the world LNG-fueled fleet is predicted to grow significantly in the next five years, with orders already being placed beyond that time frame.

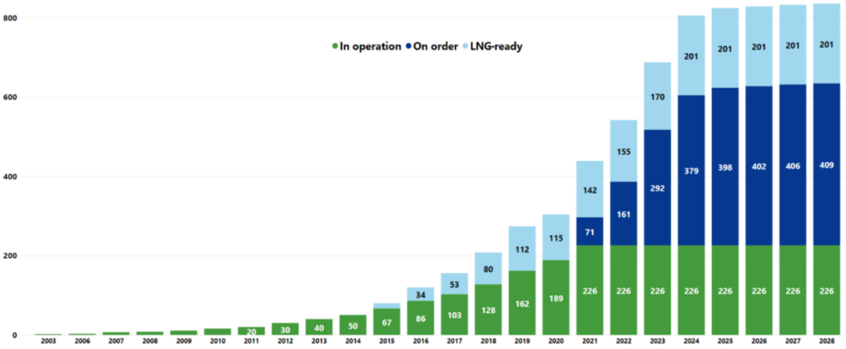


Figure 4.3: LNG-fueled fleet forecast (DNV [52])

LNG is already a technically mature marine fuel and can be used in all 2-stroke and low-pressure 4-stroke piston engines. However, additional equipment and facilities are required to make it compatible with existing conventional propulsion systems. These include commercially available fuel tanks that have restricted geometrical requirements and require more space compared to MGO tanks, as well as insulated cryogenic tanks due to the required storage temperature at 1 bar absolute pressure (DNV [51]). The fuel is commercially available in most major shipping hubs, but further investments are required to make it more widely available and to reduce its cost (DNV [52]). The risk of using LNG as fuel for marine vessels is relatively low, as a leak will not result in an explosion, nor seriously harm humans, but would affect the ecosystem. When it comes to emissions, LNG has the potential to reduce NO_x emissions by $20-80\%$ compared to MGO and CO_2 and CH_4 emissions by $20-25\%$ (Riviera Newsletter [53]).

Technical data
The energy density of LNG is about $22\frac{MJ}{l}$ at its $-162°C$ storage temperature. As a result, nearly three times the storage space compared to MGO is required, owing to the additional cooling and safety systems, as well as the storage tank geometry requirements.

4.2.6 Alternative fuel assessment

Two major barriers remain to the adoption of ammonia, hydrogen, methanol, or LNG as marine fuels. These include the lack of investments in the development of propulsion technologies and the respective fuel infrastructures. Moreover, the complete well-to-wake emissions from these fuels, which encompass both the entire supply chain and combustion processes, must be considered in the overall fuel evaluation. The emissions and associated costs of each fuel are greatly dependent on their pathways (green, blue, or grey) and categories (fossil, blue, bio, or electro). These factors will influence the future popularity of each fuel type noteworthy. A significant challenge lies in determining the most viable well-to-wake option, one with the lowest total costs and emissions. SALT, a Norwegian ship design company ([54]), conducted a prospective assessment of alternative marine fuels from 2025 to 2050, predicting the potential popularity of various fuels, as illustrated in Figure 4.4. The analysis indicated a steady rise in popularity for ammonia and hydrogen, with an even steeper increase rate commencing from 2035, leading to a near-linear projection trend until 2050. The popularity of biofuels, methanol, liquid petroleum gas (LPG), and liquid natural gas (LNG) increases gradually until 2035, after which the growth rate stabilizes and remains nearly constant until 2050. Conversely, the use of oil-based fuels suffers a significant decline, decreasing almost linearly from 2025 to 2050. The findings suggest that hydrogen-based fuels have promising potential as alternative fuels in the future, without significant adoption until approximately 2035. However, as it is a near-impossible task to predict a market demand quarter of a decade forward in time, due to unforeseen market fluctuations and other real-world events that will affect the respective predicted data, this prediction should be taken with a pinch of SALT. Nevertheless, the urgency of reducing the shipping industry's overall emissions, in line with the forthcoming emissions regulations discussed in Section 3.2, demands a more expeditious transition than alternative fuel options can provide as of today. Hence, alternative solutions must be explored to meet the industry's decarbonization goals.

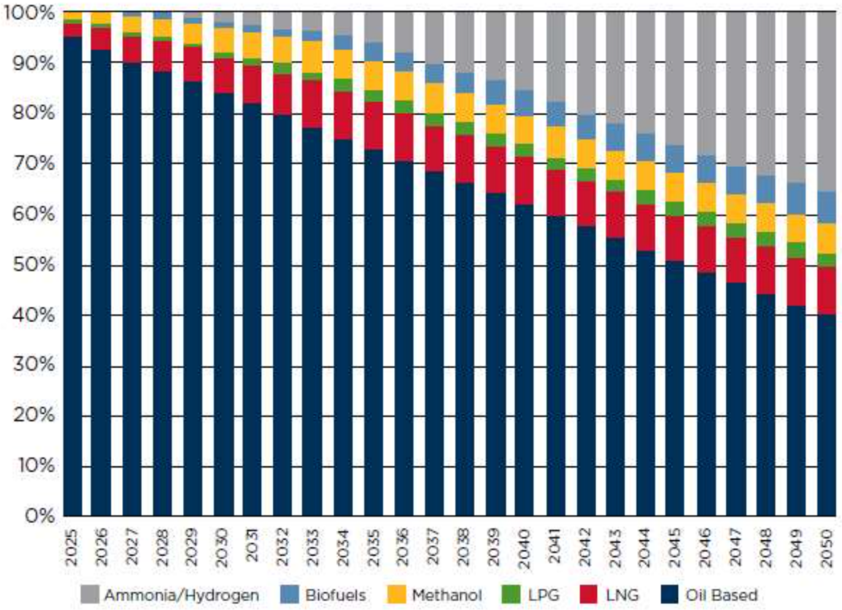


Figure 4.4: Alternative fuel assessment (SALT [54])

4.3 Logistics and supply chain

The optimization of logistics and supply chain in the shipping industry has been a key objective since the commercialization of this sector, with the primary aim of maximizing profits. It is noteworthy that cargo vessels are known to often cover long distances without any cargo or even empty containers, leading to zero profits and incurring operational costs such as fuel, wages, and taxes. Recently, the focus has shifted towards digitalization to optimize the logistics and supply chain of individual vessels and fleets, which has become an attractive approach for shipowners. While the costs of developing, maintaining, and implementing such operations are high, it is still more cost-effective than frequently sailing empty vessels. Optimizing cargo space and reducing the number of empty containers has the potential to increase a vessel's revenue without incurring additional operating costs, ultimately leading to increased profits, increasing its efficiency.

4.4 Optimizing ship operations

The optimization of a vessel's operations, such as speed, hull design, routing, and onboard technologies, presents an opportunity to streamline its use of fuel, crew, and other costly parameters. During the vessel's design phase, the planned sailing routes, cargo type, including density, loading and unloading methods, and form, whether liquid or solid, should be optimized relative to each other, along with probable adjustments in operations and other factors that may affect the vessel's cargo capacity.

Moreover, the ship's operating speed and sailing route should be continuously monitored and improved as the vessel's performance depends on its fuel consumption per unit of cargo freighted. Hence, its performance fluctuates significantly due to factors such as weather conditions and the respective cargo market. By navigating its fleet with respect to weather conditions and taking advantage of the wind and sea state, reducing the vessel's total resistance, and monitoring the cargo market, the ship operator can increase the vessel's performance noticeably. In addition, the vessels in the fleet should communicate to ensure that their routes are interdependent, and the operator may send them on specific missions, minimizing the fleet's total fuel consumption, and maximizing its total profit. Together with the implementation of automation and digitalization of the vessels' control systems, shipowners have the potential to operate their fleet even more profitably by increasing revenue, lowering operating costs, and reducing wear and tear on the vessels due to higher efficiency as their routes are optimized with respect to each other.

4.5 Improving port-based measures

In addition to the potential for shipowners to improve their fleet through digitalization and physical upgrades, ports also have significant potential for improvement. One approach is to encourage low-emission vessels to visit by offering them incentives, such as discounts on port fees for ships with lower emissions, or by implementing low-emissions policies that require trading vessels to be more environmentally friendly. This could be essential for the survival of companies that rely on central and important ports. Furthermore, ports can install shore power for hybrid and electric vessels, improve their infrastructure by installing electric cranes and cargo handling equipment, alternative fuel storage facilities, and utilize renewable energy for energy-consuming equipment that currently relies on conventional energy.

The port management and logistics can also be optimized to minimize the time vessels spend waiting outside the port for loading and unloading cargo and streamline cargo handling to facilitate swifter handling and minimize transportation of goods within the port. Such improvements in port management and logistics can reduce operational costs for shipping companies and enhance the efficiency of the overall supply chain.

4.6 Retrofit

Retrofitting refers to the process of upgrading or modifying an existing system or equipment to improve its efficiency, functionality, or environmental impact. Retrofitting has gained increasing attention in various industries, including the shipping industry, where older vessels can be modified with new technologies and equipment to improve their performance, reduce emissions, and comply with regulatory requirements. Retrofitting has the potential to extend the lifespan of existing vessels, reduce the its carbon footprint, and enhance the overall sustainability of the shipping industry.

4.6.1 Propulsion system

In order to enhance sustainability within the shipping industry, retrofitting cargo vessels has been proposed as a viable solution. One approach involves retrofitting the vessel's propulsion system to accommodate alternative fuels (Section 4.1), such as LNG or ammonia, which can lead to significant reductions in emissions compared to traditional fossil fuels. However, the conversion of an existing propulsion system to be compatible with fuels like ammonia requires significant modifications, including the replacement or upgrade of the engine, fuel tanks, and piping system. Depending on the existing internal fuel infrastructure onboard and the proposed alternative fuel, such conversions may have a challenge being cost-effective in the long term. Additionally, the retrofitting process may be constrained by the vessel's existing architecture, which may not allow for the installation of larger fuel tanks in their original location, thus requiring additional space on the deck or in the cargo holds.

Retrofitting attributes of the vessel, such as the propulsion system or the propeller, can also improve the vessel's performance, for example, by increasing fuel efficiency or installing emissions control systems. Additionally, add-ons to the propeller can be introduced, such as a propeller duct. Another approach is installing a hybrid system often implemented with the help of a shaft generator, or wind-assisted propulsion such as rotor sails, providing additional propulsion power to the vessel.

These, and more, retrofit options are further discussed in Section 5.4 with respect to the case study for Torvald Klaveness in Section 8. Retrofitting cargo vessels with these technologies not only contributes to the reduction of greenhouse gas emissions but can also lead to significant cost savings for shipowners in the long run.

4.6.2 Emissions control devices

The emissions control systems onboard a cargo vessel may be continuously improved, which involves for instance the installation of exhaust gas cleaning systems, also known as scrubbers, to reduce the emissions of sulfur oxides and particulate matter (PM). Scrubbers work by spraying alkaline water into the exhaust gas stream, reacting with and removing harmful pollutants before they are released into the atmosphere. Another approach is retrofitting vessels with selective catalytic reduction (SCR) systems, which can reduce nitrogen oxide emissions by converting it into nitrogen and water through a chemical reaction. These technologies have the potential of helping to comply with increasingly strict emissions regulations as well as reduce the shipowner's operating cost when emission taxes are considered.

4.6.3 Vessel design

Retrofitting cargo vessels with advanced technologies can lead to significant improvements in their energy efficiency and environmental impact. One such technology is air lubrication, which involves injecting air bubbles beneath the hull to reduce drag and friction, and hence increase fuel efficiency. Another area of focus is hull hydrodynamics, where design improvements can reduce wave resistance and improve speed. Additionally, using lightweight materials in ship construction can decrease weight and hence fuel consumption. These design upgrades can improve their performance as well as reduce their carbon footprint and contribute to a more sustainable shipping industry and reduce the shipowner's operational cost.

4.6.4 Retrofit Effects

To evaluate the impact of implementing retrofit options on emission reductions, it is essential to quantify the reductions as a percentage relative to the vessel's emissions before any retrofitting. The total emission reduction achieved when a new option is installed becomes dependent on the options already in place. This dependency can be expressed using a recursive relation.

Let μ_i represent the percentage reduction in emissions achieved by implementing retrofit option i. Consider a sequence of n retrofit options to be implemented, indexed as $i = 1, 2, \ldots, n$. The total emission reduction after using option i, denoted as θ_i, can be calculated using the recursive relation shown in Equation 6.

$$\theta = \begin{cases} \theta_0 = 0 \\ \theta_i = \theta_{i-1}\left(1 - \frac{\mu_i}{100}\right) + \mu_i \end{cases}, \qquad i = 1, 2, \ldots, n \tag{6}$$

In this relation, θ_0 represents the initial emission reduction, which is zero before any retrofit options are implemented. Subsequently, θ_i represents the total emission reduction achieved after implementing retrofit option i. The equation incorporates the cumulative effect of previously implemented options (θ_{i-1}) and the percentage reduction achieved by the current option (μ_i). This recursive relation allows for the calculation of the overall emission reduction as each retrofit option is successively implemented.

5 Retrofitting vessels towards decarbonization

The current generation of vessels, produced in the last decade, predominantly rely on marine diesel oil for propulsion and possess a typical lifespan of $25 - 30$ years. To address the pressing issue shipowners stand before, required to decrease their fleet's total emissions during the next decades as outlined in Section 1, measures to mitigate their emissions and ensure continued profitability of their fleets must be undertaken. One possible strategy is the retrofitting of vessels, an expensive endeavor that involves the acquisition of new equipment and significant labor. The success of retrofitting depends on reducing the vessel's annual operating expenses enough to justify the associated initial and operational costs of the retrofit option. It is critical for shipowners to ensure that the retrofit pays for itself within a shorter payback period than the remaining lifespan of the vessel. By adopting this approach, shipowners can achieve greater sustainability, enhance profitability, and keep pace with the ever-tightening regulatory landscape. Moreover, owners of vessels that have had their annual emissions reduced can be expected to benefit from the rise in emission taxes as they will have a competitive advantage over those with higher emission levels.

Retrofitting vessels refers to the process of modifying, upgrading, or updating the respective vessel to improve their performance or adapt them to new uses. This can include a wide range of changes, such as installing a new or upgrading the excising engines and propulsion systems, upgrading the vessel's electrical systems, adding new safety features, installing additional systems reducing fuel consumption, or even completely refitting the vessel to serve a different purpose. Retrofitting can be a cost-effective way for a shipowner to improve the efficiency and performance of their vessel, or make the ship compliant with new sets of rules and regulations or updated concepts of operations for the vessel (discussed in Section 6.1), for instance related to emission and safety, without having to invest in a brand new vessel.

Common types of retrofitting are converting a ship to a barge or a tanker to a bulk carrier, implementing a scrubber or a small modification in the electrical system onboard the vessel, and everything in between. In other words, the term *retrofitting* is very broad and refers to any modification performed on a vessel. Typically, shipyards either specialize in the building process of vessels, or the retrofitting. This is common to develop expertise within the respective field to be able to offer the best possible service to the ship owner as possible. This naturally depends on the size of the shipyard, so larger shipyards can of course commonly perform both. The shipyard *Green Yard* in Norway, offers new-builds, repair, retrofits, and recycling of vessels (Green Yard [55]). The market of a shipyard can be divided into the new-building of a vessel, and the aftermarket work for the vessel, including the retrofitting process. A vessel's life cycle model is presented in Figure 5.1, with ship upgrading, retrofit, and conversion being included in the aftermarket of a shipyard. Additional to the process of the actual retrofit, a whole lot of planning and project management is involved in the process to make it as efficient as possible, as a vessel not transporting cargo, is revenue lost, and the retrofit process is an expensive task. Hence, the motivation for streamlining the retrofit process is obvious, including the specification process, yard assessment, project risk management, construction monitoring, and project management support, being paramount (DNV [56]). Typically, a consulting firm is hired to assist in the design and planning process of the retrofit to make sure the transition is carried out as profitably as possible. DNV and Kongsberg Maritime are two Norwegian companies offering consulting services with respect to retrofitting (DNV [56], Kongsberg [57]).

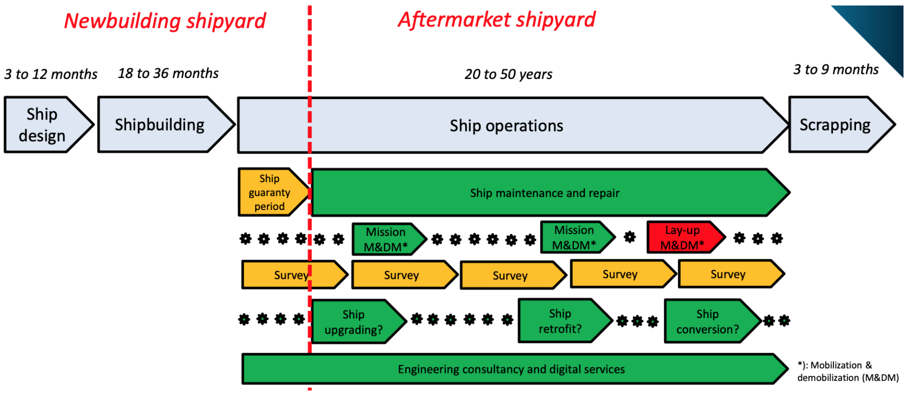


Figure 5.1: Vessel life cycle including newbuilding and aftermarket (NTNU TPK4164 lecture [18])

5.1 Retrofitting process

The process of retrofitting a shipping vessel typically involves several steps, including planning and design, procurement of materials and necessary equipment, and installation and testing of the retrofit implemented (NTNU TPK4164 lecture [18]). Firstly, the shipowner and stakeholders will need to identify the specific changes or upgrades they want to do to the ship, often involving engineers and other experts within the field as consultants helping to determine the feasibility and cost of the retrofitting project. With the plan outlined, the required materials and equipment will have to be procured, such as engine propulsion systems, electrical components, and other specialized equipment. What the shipowner and the shipyard are responsible to procure respectively, will depend on the internal agreement between the two and is commonly outlined in their contract. Next, the retrofitting work can begin and will take place at the shipyard where the vessel has been brought, with specialists, mechanics, technicians, and engineers who will be responsible for the installation and modifications necessary, often supervised by the shipowner. When the retrofit work is finished, the ship will have to undergo testing to ensure that it is operating properly and meeting all relevant safety and performance requirements. This may include sea trails, where the vessel is taken out to sea and its systems are tested in real-world conditions. When the tests are completed and the results are approved, the retrofit work is finished and the shipowner has the vessel returned. The overall retrofitting process of a shipping vessel can be time-consuming and expensive, but may also provide significant benefits in terms of improved performance, efficiency, and compliance with new sets of regulations and rules.

5.2 Existing vessels

The retrofitting of vessels operating today built within the past decade which has a lifespan left correlating with a retrofit installation being worthwhile, will typically be performed the way described above in Section 5.1. Starting with the identification of what is to be retrofitted, before materials and equipment necessary for the retrofit are procured. Further, the retrofit work is performed, and so the vessel is tested with respect to the retrofit installation and its purpose before the vessel is delivered back to the shipowner. This process is well-known and can be quite time consuming and expensive, including several professions and laborers.

The retrofit process of a vessel is complex and involves several stages, including an upstream and a downstream production process. During the upstream stage, raw materials are extracted and acquired to match the specific designs of the vessel being retrofitted. In the downstream stage, disassembly, parts production, installation, and other processes are carried out to complete the retrofit. These are only a few components of the overall retrofit process, which demonstrates the comprehensive nature of retrofitting a vessel. Planning and mapping out the materials and components needed for the retrofit is crucial to ensure a successful outcome and a minimization of downtime for the vessel. The retrofit industry relies on this detailed planning and execution to deliver high-quality retrofitted vessels. From a shipowner's perspective, it is desirable to install retrofit options on the respective vessel in its planned dry-dockings, which is every five years for a standard cargo vessel, and sometimes more often, depending on the shipowner and their strategy. This means that installation of retrofit options should be carefully timed, and calculated for when an economic assessment of the upgrade is being carried out.

5.3 New-builds

Planning for a vessel's retrofit after a few years of operation, during the vessel's design period, is a complex task that demands exceptional planning skills, organization, and design. By integrating retrofit planning early in a vessel's operational life, substantial efficiency gains may be achieved. Forward-thinking retrofit measures can significantly cut down the time needed for implementing the retrofit in the future. Furthermore, a forward-looking approach to vessel design, considering the integration of abatement technologies from the start, may ease and enhance the effectiveness of future installations of such equipment. The shipowner will need to identify the specific changes or upgrades they plan to make to or for the vessel in the future. This identification process may involve research and evaluating new technologies or systems that are likely to become available within the lifetime of the vessel. An estimation of the pace the respective technology seems to develop and the potential infrastructure needed for the technology to be operable, must too be outlined. Next, the vessel's design will need to be adapted to accommodate the planned retrofitting work, which may involve incorporating features such as additional structural support, implementing access points, or integrating electrical connections and systems that will make it easier, or possible even, to install new equipment at a later time. Lastly, potential additional room will have to be made onboard if the future technology likely will demand extra volume, such as storing for alternative fuel.

It is also crucial to consider the potential impact of the planned retrofitting on the vessel's performance and safety, which may include simulations or other forms of analyses to assess how the changes will affect the vessel's for instance stability, propulsion, safety or other critical systems. When the vessel design process is finished, the ship owner will have to carefully and safely document the retrofitting plan and include it with the construction contract to make sure the vessel is built in a way allowing for the planned retrofitting work to be carried out smoothly when the time comes. Planning for retrofitting a vessel during the design period requires careful consideration of the specific changes that will be made, the impact on the vessel's design and performance, and the need for thorough documentation to ensure a successful retrofitting process.

5.4 Emissions reducing retrofit options

Emissions-reducing abatements typically all involve high initial costs, but they may be worthwhile in the long run due to potential reductions in operational costs. Therefore, precise calculations are essential to determine whether an investment in a particular abatement will be profitable. However, this is a complex task, as the reduced operational and voyage costs are dependent on several factors, including future oil prices, emissions taxes, the reliability of the technology, and the correlation between its calculated maintenance interval and lifetime with its expected performance.

While the investment cost of the abatement can be estimated relatively precisely based on equipment cost, labor, and yard cost, accurately predicting the reduced operational and voyage costs is challenging. The shipowner must consider several variables, such as the technology's robustness as well as fuel prices and emissions taxes, making the calculations intricate.

Klaveness has implemented or planned to implement and considered the installation of various retrofit options discussed in Section 4.6. For the case studies in Section 8, cost and emissions reduction estimations for the retrofit options presented will be discussed in the following subsections. Estimating the installation cost of these abatements is a complex calculation process that includes equipment, labor, off-hire, and yard costs. However, accurate cost estimates can be obtained by leveraging the shipowner's connections in the market, contacting relevant yards, and the company producing the respective abatement. To decide the weight of the different attributes of the options, this thesis will conduct internet research to look up costs and fuel reduction potential, summarized in Table 12. In addition, economic discussions with the supervisor and co-supervisor at Klaveness will be taken into account. After discussion with a co-supervisor, installation costs of fairly large retrofit options, accumulate to about 600 thousand USD (kUSD), in addition to equipment costs.

5.4.1 Shaft generator

The shaft generator utilizes a higher percentage of the potential of the main engine and makes sure it operates at a lower specific fuel oil consumption (SFOC). The shaft generator utilizes the high efficiency of a 2-stroke diesel engine, as well as excessive energy produced by the main engine due to for instance heavy weather, and produces electrical power for the ship's electrical grid, using the rotational energy of the main engine. The shaft generator functions by converting the mechanical energy from the main engine's rotation into electrical energy. The generated electricity is then transmitted through the ship's electrical grid to power the various onboard systems and equipment. The generator cooperates with the rest of the ship's systems by ensuring a steady and reliable supply of electrical power. This is particularly favorable for large cargo vessels that require a significant amount of electricity to operate. Shaft generators are also efficient and cost-effective, as they reduce the need for separate generators and reduce fuel consumption. Additionally, they are easy to maintain and can be integrated into the ship's existing infrastructure, as presented in Figure 5.2.

The specifications for a shaft generator are summarized in Table 5. Based on the information gathered from industry sources, the cost of a shaft generator for a cargo vessel is estimated to be approximately 400 USD per kW, as reported by the Global Maritime Energy Efficiency Partnerships (GloMEEP) ([58]). The Switch ([59]) suggests that a bulk ship typically requires a shaft generator with a capacity of $1-2$ MW. Considering that KCC's vessels are approximately 230 meters in length, slightly longer than the industry average for bulk carriers which is approximately 200 meters, a shaft generator with an estimated output of 1.8 MW is deemed suitable for their vessels. The total cost of equipment and installation for the shaft generator is estimated to be approximately 1.32 million USD (MUSD). The annual operating cost of the shaft generator is estimated to be 3% of its total cost. GloMEEP indicates that the implementation of a shaft generator could lead to a fuel reduction potential of $2-5\%$, and for KCC's combination carriers, a fuel reduction potential of 4% is assumed.

Cost	Size	Equipment cost	Total cost	Operational cost (% × total cost)	Fuel reduction
400	1.8	720	1.32	3	4
$\frac{USD}{kW}$	MW	kUSD	MUSD	%	%

Table 5: Shaft generator specifications

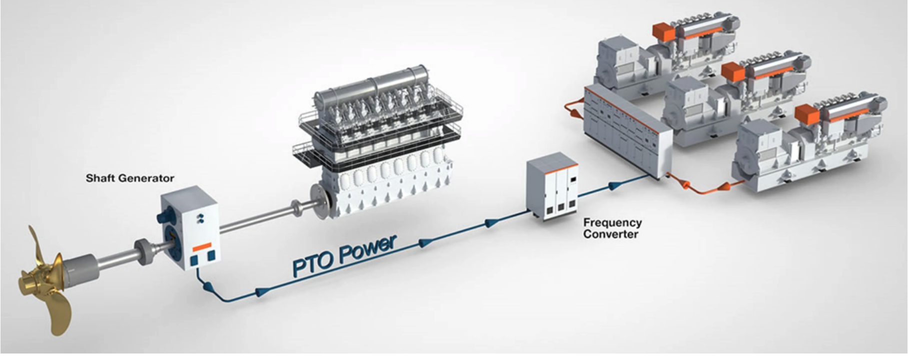


Figure 5.2: Shaft generator (Wärtsila [60])

5.4.2 Air-lubrication

Air lubrication is a technique used on cargo vessels to reduce friction between the ship's hull and the surrounding water. This is achieved by releasing a layer of air bubbles under the vessel along the hull's surface through a specially designed system installed on the hull, as presented in Figure 5.3. The purpose of air lubrication is to reduce drag and friction and improve the vessel's hydrodynamic performance, which in turn improves the vessel's fuel efficiency and reduces emissions. By reducing the amount of energy required to propel the ship through the water, air lubrication can result in significant cost savings for shipowners and operators.

Air lubrication is integrated with the vessel through a system of perforated pipes or plates installed on the hull. Compressed air is injected into the pipes, which then release a stream of air bubbles along the length of the hull. The system is controlled by a computerized control system, which adjusts the amount of air released based on the vessel's speed, sea conditions, and other factors.

The air lubrication specifications are summarized and presented in Table 6. In a Ship & Bunker interview with Silverstream's CEO Noah Silberschmidt in November 2021, it was reported that the air lubrication technology offered by Silverstream typically has an investment cost of approximately 0.95 MUSD (Ship & Bunker [61], Silverstream [62]). Using this information as a reference, the estimated investment cost of the air lubrication system for a combination carrier is estimated to be 1.55 MUSD, including an installation cost of 0.6 MUSD. Furthermore, the annual operational cost of the air lubrication system is estimated to be 3% of the total cost. Silverstream claims that its air lubrication system can reduce fuel consumption by an average of 6% during sailing reducing friction and improving the vessel's hydrodynamics.

Equipment cost	Total cost	Operational cost (% × total cost)	Fuel reduction
950 kUSD	1.55 MUSD	3 %	6 %

Table 6: Air lubrication specifications

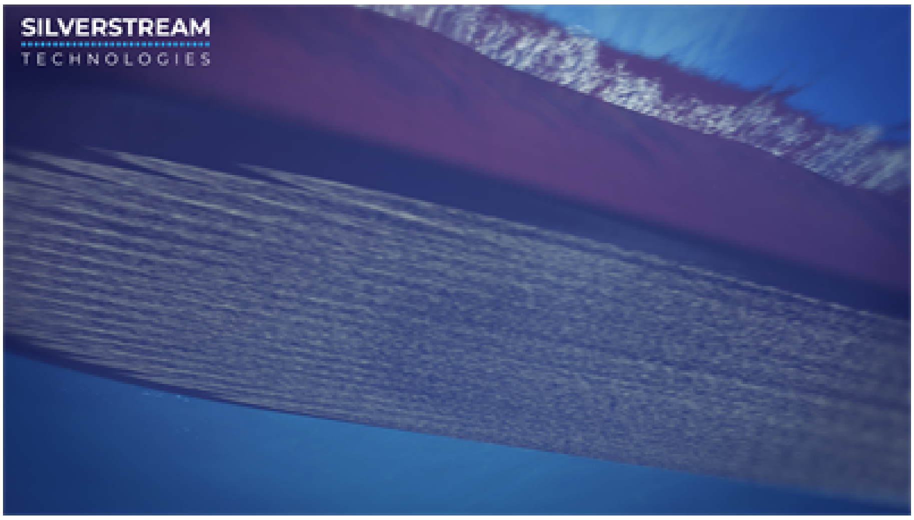


Figure 5.3: Air lubrication (Silverstream [62])

5.4.3 Propeller duct

Propeller ducts are a type of energy-saving device installed on the stern of cargo vessels, as presented on the left-hand side in Figure 5.4. The purpose of the duct is to improve the vessel's hydrodynamic efficiency by redirecting the flow of water around the propeller, and its functionality is based on the principle of *boundary layer control* (BLC)[1], as illustrated on the right-hand side in Figure 5.4. When water flows around the hull of a vessel, a layer of fluid forms along the surface of the hull. This layer, known as the boundary layer, is characterized by low velocity and high turbulence. By installing the duct, the flow of water around the propeller is redirected, creating a more efficient flow pattern that reduces the turbulence in the boundary layer. The result is an increase in propulsive efficiency, which can lead to significant fuel savings for the vessel. The duct is designed to be highly efficient at low speeds, making it particularly useful for cargo vessels that spend a significant amount of time operating at low speeds.

The specifications for a propeller duct are presented in Table 7. Based on information from the GloMEEP, it is estimated that propeller ducts for bulk carriers, tankers, multi-purpose vessels, and similar types of vessels can cost up to 0.6 MUSD (GloMEEP [64]). Taking into account installation costs, the total investment required for a propeller duct amounts to 1.2 MUSD. The annual operational costs associated with propeller ducts are relatively low, estimated to be around 2% of the total investment. It is important to note that the propeller duct is a static device and does not contain any movable parts, thus requiring low maintenance costs. Becker Marine Systems claims that the potential fuel savings achieved through the use of their Becker Mewis Duct can reach up to 8% (Becker Marine Systems[65]).

Equipment cost	Total cost	Operational cost (% × installation cost)	Fuel reduction
600 kUSD	1.2 MUSD	2 %	8 %

Table 7: Propeller duct specifications

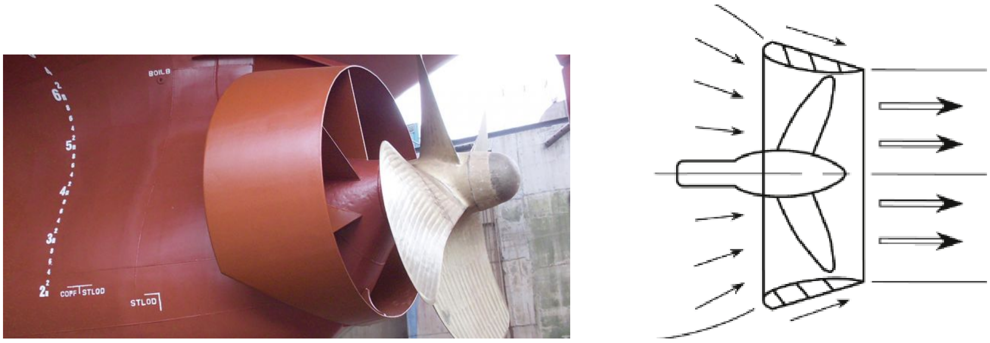


Figure 5.4: Propeller duct (Becker Marine Systems [65], Ship Journal [66])

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[1] ”BLC is a generic definition to classify all those methods that can be used to reduce the skin friction drag, by controlling the turbulent transition, the development of the turbulent flows, and the separation (laminar as well as turbulent), all phenomena occurring within the boundary layer.” (Definition from Aerodyn) [63]

5.4.4 Wind-assisted propulsion

Wind-assisted propulsion systems retrofitted onboard a cargo vessel has the potential to significantly reduce their carbon footprint and fuel consumption, with Flettner rotors, or rotor sails. Flettner rotors are spinning cylinders that use the *Magnus effect*[2] to generate propulsion, while sails capture wind energy to provide additional thrust in the vessel's sailing direction. With lower pressure created 90 degrees relative to the wind direction, lift is created as presented in Figure 5.5, normal to the lower pressure. These technologies can be integrated with existing propulsion systems to reduce fuel consumption and emissions. Wind-assisted propulsion can be particularly beneficial for long-haul shipping, where large cargo vessels consume vast amounts of fuel and the vessel is exposed to continuous high-speed wind. Rotor sails are becoming more and more attractive to shipowners, as their required area-to-provided energy-ratio, is far less than for conventional sails. The Norsepower Rotor Sail technology is around ten times more efficient than a conventional sail, due to its area-efficient energy production (Norsepower [68]).

Specified specifications for a rotor sail are presented in Table 8. According to estimates from the GloMEEP, the cost of Flettner rotors ranges from 0.4 to 0.95 MUSD, depending on the specific rotor model (GloMEEP ([69])). For a combination carrier in Klaveness' fleet, the cost of a Flettner rotor is presumed to be 0.7 MUSD, as these vessels are not among the smallest nor largest vessel types. When factoring in installation costs, the total investment required for one Flettner rotor installation is 1.3 MUSD. The operational costs associated with this technology are estimated to be 6% of the total investment, due to the complexity of the machinery and its many moving parts, which require regular maintenance and lubrication oil. Norsepower, the manufacturer of Flettner rotors, claims that these devices can save up to 15% of fuel during sailing, provided the vessel operates under optimal wind conditions, estimated to 11% for normal weather conditions (Norsepower [68]).

Equipment cost	Total cost	Operational cost (% × installation cost)	Fuel reduction
700 kUSD	1.3 MUSD	6 %	11 %

Table 8: Rotor sail specifications

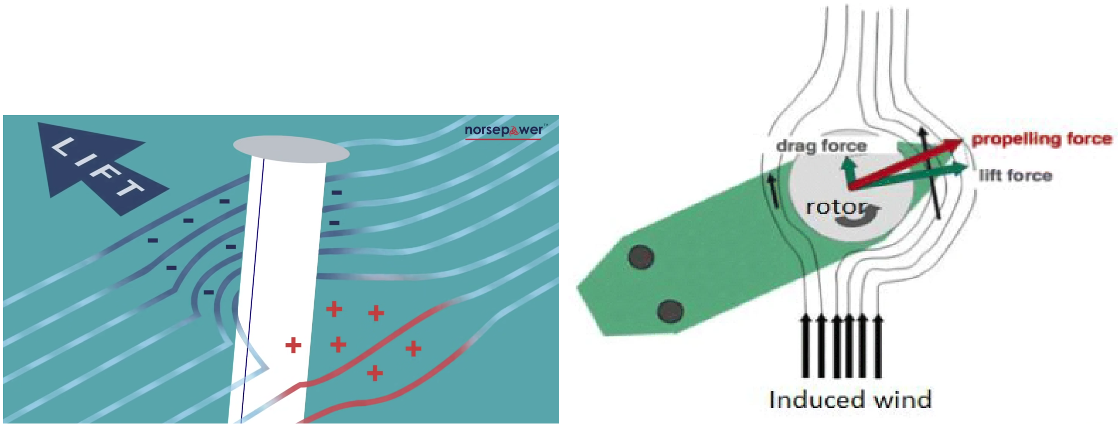

Figure 5.5: Flettner rotor (Norsepower [68], Springer Link [69])

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[2] ”Magnus effect, generation of a sidewise force on a spinning cylindrical or spherical solid immersed in a fluid (liquid or gas) when there is relative motion between the spinning body and the fluid.” (Definition from Britannica [67])

5.4.5 Scrubber

Scrubbers are devices that clean the exhaust gases from a ship's engines by removing pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter from the emissions released to the vessel's engines and fuel consumption (Yara [70]). The scrubber system works by spraying a chemical solution (such as seawater or alkaline chemicals) into the exhaust gas stream, which reacts with the pollutants to form harmless substances that can be safely discharged into the ocean. However, scrubbers require energy to operate, and hence increase the vessel's total fuel consumption.

In a research paper written in 2015 evaluating technology for mitigating sulfur emissions in marine container transport, it claims a 3% increase in fuel consumption considered for the scrubber system (Research Gate [71]). However, Yara claims their scrubber absorbs, or removes by mass, $> 80\%$ of SO_x emissions and particulate matter. The left-hand side in Figure 5.6 presents Yara's open loop scrubber concept, using seawater to absorb the SO_x and PM from the emissions. On the right-hand side, a more detailed sketch from Marine Insight of a wet scrubber using sea or fresh water with chemical additives to remove a significant amount of NO_x and SO_x from the exhaust.

A scrubber's specifications are presented in Table 9. Despite the fact that a scrubber system increases the overall fuel consumption of a vessel, it allows ship owners to procure less expensive fuel that has a higher sulfur content while still releasing exhaust emissions that comply with approved levels of SO_x. As a result, VOYEX savings are projected to reach approximately 4%, accounting for increased fuel consumption, lower fuel costs, and reduced emissions taxes. According to S&P Global [72], the cost of installing a scrubber is estimated to range between 1 and 5 MUSD, depending on the vessel's size and other factors. For a combination carrier, the estimated cost is approximately 2 MUSD due to its relatively small size compared with tankers and other large vessel types. Therefore, the total cost of scrubber installation for this type of vessel is projected to be 2.6 MUSD, with annual operational costs amounting to 2% of the total installation cost.

Equipment cost	Total cost	Operational cost (% × installation cost)	Fuel reduction
2.0 MUSD	2.6 MUSD	2 %	4 %

Table 9: Scrubber specifications

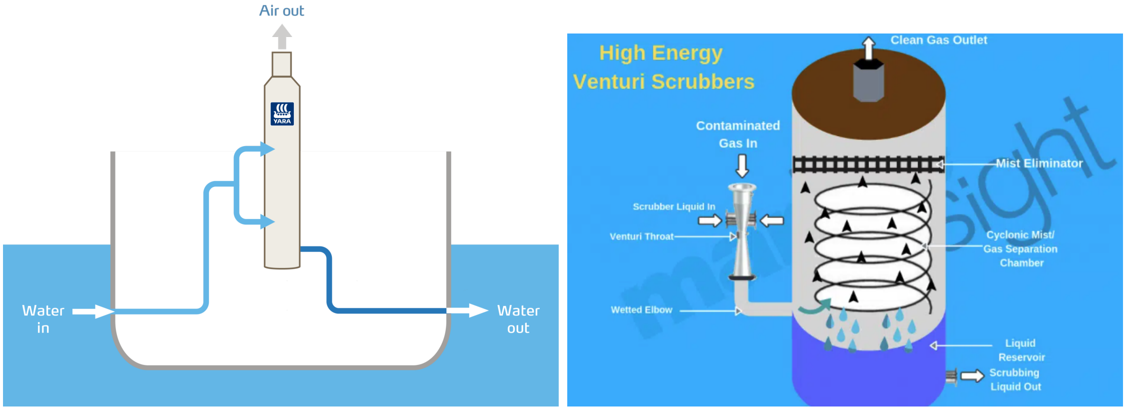

Figure 5.6: Scrubber (Yara [70], Marine Insight [73])

5.4.6 Electrical system upgrade

Electrical system upgrades as a retrofit option for vessels offer an innovative solution to lower operational costs, improve reliability, and reduce environmental impacts. Upgrading the electrical systems enhances the energy efficiency of the vessel and reduces energy wastage. It involves the replacement or modification of existing components such as switchboards, generators, wiring, and transformers to improve power distribution and consumption across the vessel. It also allows for the implementation of new technology, such as weather routing systems. ABB Marine & Ports, a pioneering force in sustainable maritime technologies, provides electrical upgrade solutions that can enhance vessel reliability and efficiency, reducing operational costs and environmental footprint (ABB [74]). Their retrofitting solutions include advanced generators, drive technology, and Azipod propulsion, each of which can be tailored to the specific requirements of the vessel.

In Figure 5.7, an example of a standard electrical system is depicted. The image illustrates the integration of new components into the existing system, exemplifying how the retrofitting process can be carried out without significant disruption to the vessel's operations. The electrical upgrade specifications are presented in Table 10.

The cost of an electrical upgrade for a vessel largely depends on the complexity of the upgrade, the size of the ship, and the current state of the vessel's electrical systems. According to data from GloMEEP, the investment required for an electrical upgrade ranges from 0.3 to 1.0 MUSD (GloMEEP [75]). For a combination carrier in Klaveness' fleet, an electrical upgrade is estimated to cost around 0.5 MUSD. Factoring in installation costs estimated to be half that of installing a large retrofit option such as a Flettner rotor or a propeller duct due to the less physical and material outfitting, the total installation cost is estimated to be 0.8 MUSD. In terms of running costs, it's anticipated that electrical upgrades would entail around 2% of the initial investment annually for maintenance and component replacement. Despite these costs, the high efficiency and reduced energy consumption associated with these upgrades can offer substantial savings in the long run. In terms of consumption reduction, an electrical upgrade is estimated to obtain a 4% reduction.

Equipment cost	Total cost	Operational cost (% × installation cost)	Fuel reduction
0.5 MUSD	0.8 MUSD	2 %	4 %

Table 10: Electrical upgrade specifications

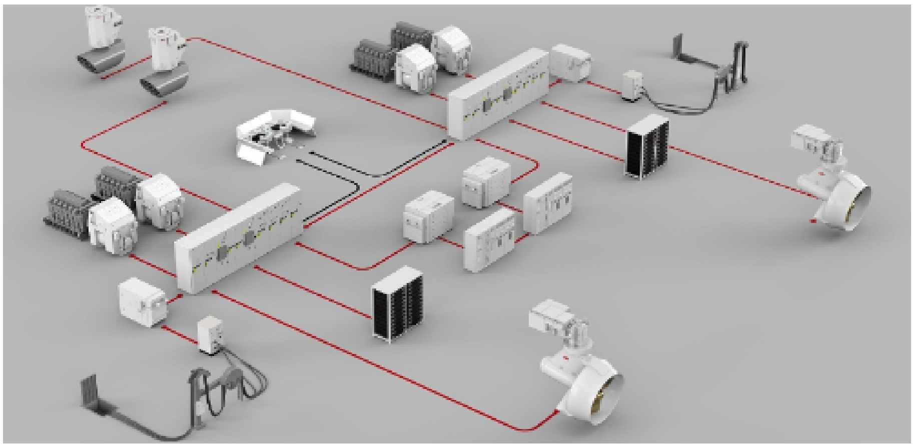

Figure 5.7: ABB electrical solution (ABB [74])

5.4.7 Hybrid

Hybrid propulsion systems paired with auxiliary engines onboard a shipping vessel can significantly cut down on carbon emissions and fuel consumption, offering a sustainable alternative to traditional systems. Hybrid systems blend conventional internal combustion engines with electric propulsion units, enabling efficient energy use and reduced emissions. Auxiliary engines provide backup power and are critical for ship operations like loading and unloading cargo, and hotel load. By integrating these with a battery pack, there is an opportunity to streamline power usage and limit wasteful fuel burn. Hybrid propulsion systems and auxiliary engines can be particularly impactful for large vessels engaged in long-haul shipping, where fuel consumption is extensive.

The lithium ion-cell company Leclanché's battery technology offers compatible battery packs with already-existing propulsion systems for vessels for retrofitting towards hybridization (Leclanché [76]). Leclanché's battery packs are scalable and have the opportunity of being the size order of the ship owner's choice, and hence obtain the potential of saving a corresponding amount of fuel. A hybrid system integrated with a shaft generator from Wärtsila is displayed in Figure 5.8, illustrating a standard propulsion system and how it can be integrated with battery packs and a shaft generator.

Specifications for a hybrid retrofit solution are presented in Table 11. In terms of cost, estimates from GloMEEP suggest that the investment required for a hybrid system ranges from 0.6 to 2.0 MUSD for a hybrid vessel, depending on the system's configuration and ship size (GloMEEP [77]). For a CC in KCC's fleet, the cost of a hybrid system is estimated to be 2.0 MUSD. Accounting for installation costs, the sum accumulates to 2.6 MUSD. The running costs associated with hybrid propulsion technology are expected to be around 5% of the initial investment, which accounts for routine maintenance and the replacement of components like batteries. As these systems are designed for high durability, they require relatively less upkeep compared to traditional engines. The significant fuel savings potential makes hybrid systems an economically viable and environmentally responsible choice, and are estimated to obtain a 15% consumption reduction.

Equipment cost	Total cost	Operational cost (% × installation cost)	Fuel reduction
2.0 MUSD	2.6 MUSD	5 %	15 %

Table 11: Hybrid system specifications

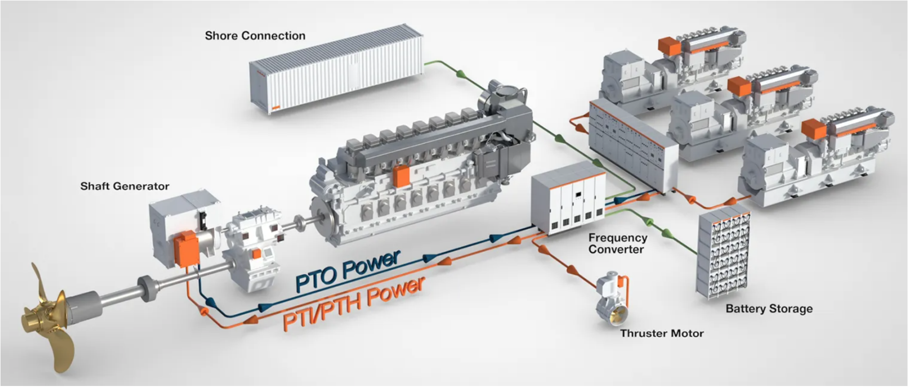

Figure 5.8: Wärtsila hybrid system integrated with shaft generator (Wärtsila [78])

5.4.8 Coating

Coating and re-coating are essential maintenance practices for cargo vessels that help to protect the hull from corrosion, fouling, and other forms of wear and tear. The purpose of the coating is to reduce frictional resistance between the hull and the water, thereby improving the vessel's performance and fuel efficiency. As Figure 5.9 presents, the roughness and smoothness of a surface affect the resistance exponentially with the speed it is exposed to in its environment. With a roughness varying from smooth to 97 μm, the resistance experienced by the surface, increases by almost a factor of 1.7. This is significant and proves the point of the importance and the possessed potential of coating technology. Coatings can be broadly classified into two categories: antifouling coatings and hull coatings. Antifouling coatings are designed to prevent marine organisms such as barnacles and algae from attaching to the hull, while hull coatings are designed to reduce frictional resistance. The functionality of coatings is based on the principle of *surface energy*[3]. When a surface is coated, the coating reduces the surface energy of the hull, making it difficult for marine organisms to attach to it. Similarly, hull coatings that are designed to reduce frictional resistance work by creating a smooth, low-friction surface along the hull. The effect of coating and re-coating on fuel consumption and efficiency is significant. By reducing frictional resistance and preventing fouling, coatings can improve the vessel's performance and reduce its fuel consumption.

Coating and re-coating a ship's hull is not considered a retrofit option in this thesis, as it is not considered a retrofit option in the manner as the ones previously presented. However, it is imperative for ship owners to undertake continuous condition monitoring of their vessels to assess their efficiency in resisting water. Hull cleaning in port or during anchorages can lead to significant fuel savings during sailing by reducing resistance. An innovative solution has been developed by the Norwegian companies Joton ([80]) and Kongsberg ([81]) to enable hull cleaning whenever necessary. The Hull Skater is a drone kept on board the vessel until it reaches an anchorage or harbor, and is then released into the water, attached to the hull, and travels alongside the vessel, cleaning the hull of bio-fouling and other debris (Hull Skater [82]). This technology provides an alternative solution for ship owners to perform regular hull cleaning and improve their vessels' fuel efficiency.

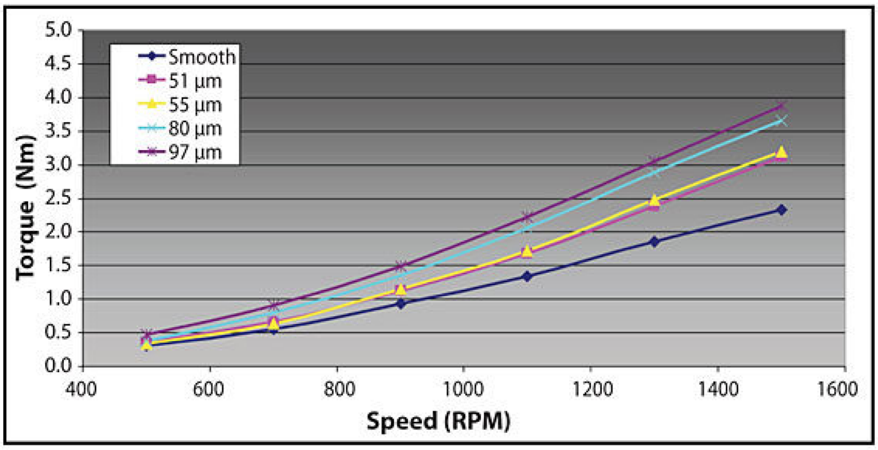

Figure 5.9: Friction drag of grit-blasted aluminum disks with various roughness (PCI [83])

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[3] "The molecular force of attraction between unlike materials determines their adhesion. The strength of attraction depends on the surface energy of the substrate. High surface energy means a strong molecular attraction, while low surface energy means weaker attractive forces." (Definition from Can-Do [79]

5.5 Retrofit options summation

The retrofit options presented above in Section 5.4 are the ones that will be utilized in the case study for Torvald Klaveness in Section 8, with the exception of coating. Each option is represented with an associated cost, both initial and operational, as well as their respective fuel reduction potential. Table 12 summarizes these attributes for each option, which are the values to be utilized in the case study.

Option	Total cost	Operational cost	Fuel reduction
Shaft generator	1.32	3	4
Air-lubrication	1.55	3	6
Propeller duct	1.20	2	8
Wind-assisted propulsion	1.30	6	11
Scrubber	2.60	2	4
Electrical upgrade	0.80	2	4
Hybrid	2.60	5	15
[-]	MUSD	%	%

Table 12: Retrofit options summation

6 Key decision-making factors in vessel design

The design and retrofitting of vessels are complex processes requiring careful decision-making from shipowners. Two crucial factors influencing these decisions are operational efficiency and economic feasibility. Operational considerations involve optimizing various aspects of a vessel's functionality and performance, such as propulsion systems, energy consumption, and adherence to industry regulations. On the other hand, economic considerations encompass investment costs, operating expenses, market trends, and financial risks. For new-builds, these factors influence design choices, material selection, and construction methods. In retrofitting, they guide decisions on upgrades, fuel efficiency, and vessel lifespan extension.

6.1 Concept of operations

Defining the concept of operations (CONOPS) for a vessel is important during the design phase because it helps to ensure that the vessel is designed and optimized to meet its intended purpose and operational requirements. CONOPS provides a detailed plan and framework for how the vessel will be operated, including its intended missions, tasks, and functions. By having a clear understanding of the vessel's intended operations, designers can make informed decisions about the vessel's layout, features, and capabilities to ensure that it will be efficient, safe, and effective in performing its intended tasks. A well-defined CONOPS also helps to facilitate communication between designers, operators, and stakeholders, ensuring that everyone is aligned on the vessel's goals and expectations.

A vessel's re-design phase including retrofit options such as a shaft generator, air-lubrication, or other, should not alter the vessel's operability, safety, restrictions, or constraints unless it is intentional. This includes the vessel's speed, stability, maneuverability, and cargo handling abilities. The vessel should show operational reliability with proper maintenance and crew training. Due to the nature of a shipping ship accommodating only necessary personnel, the maintenance should be relatively simple; it should not be labor-intensive or time-consuming. In addition, maintenance should be possible with parts and training readily available in its sailing region. Additionally, the frequency of the maintenance cycle should not hinder the vessel's normal service greatly. Furthermore, the ship should be fully functional with a crew the size of a conventional shipping ship, and not require additional crew members, as the vessel is originally designed to accommodate just enough personnel. Despite the possible difference in propulsion due to the installed shaft generator, change of fuel type, or installation of a hybrid system, crews trained in operating traditional propulsion vessels should be able to quickly learn to operate this alternative propulsion system with little training.

The primary purpose of a shipping vessel is to create economic value for the shipowner. Thus the ship must show strong economic feasibility during the operation. This means that after considering the vessel's procurement cost, operating cost, and maintenance cost, the ship is still able to make an acceptable revenue for the owner. It is worth noting that with the rising emission taxes and increasing fuel prices due to strengthening regulatory constraints, less-emitting vessels are becoming increasingly attractive for their carbon-reducing characteristics, providing them an advantage over the traditional propulsion vessels regarding operation and voyage costs.

Lastly, due to the dangerous nature of some retrofit alternatives; for example, the gaseous and explosive nature of hydrogen, the toxicity of ammonia as an alternative fuel, or the added mass and weight on deck following a Flettner rotor concerning crew members nearby, safety is a primary concern when installing abatement options onboard a vessel. Safety includes the safety of the crew, the integrity of cargoes, the surrounding environment, and the operability of the vessel. The properties of all abatement options should be considered and evaluated, and necessary means of prevention, detection, and response should be implemented to protect the crew members. In the catastrophic event of a shipwreck, methods should be deployed to minimize the damage to the surrounding environment. Lastly, the ship must meet the regulations of Ship Classification Societies and ports (Sjøfartsdirektoratet [84]).

6.1.1 Owner's requirements

In the context of deep-sea shipping, the current trading routes are well-established and highly optimized. Therefore, any vessel with expensive and weighty abatements or retrofits must be at least as good as the current solution in order to be commercially viable. The owner's requirements for such a retrofitted vessel are critical for its success in the market. Based on the CONOPS for the vessel, the most important owner's requirements are identified as follows:

- Economics
- Operability of the vessel
- Emissions
- Reliability, availability, maintainability, and safety

The *economics* of a retrofitted vessel is perhaps the most important aspect of its operation. A vessel may have zero emissions, but if the economics of the operation is not sustainable, it will not be a viable commercial option. Therefore, locating solutions that make the vessel economically sustainable is crucial. The operational and voyage costs of the vessel should not exceed its revenue, which would be affected by abatement options installed. Essentially, from a business point of view, any alternative retrofit option must provide a positive return on investment (ROI) for any shipowner and stakeholder to consider it.

The *operability of the vessel* is a crucial requirement from an owner's perspective. If the vessel cannot deliver the payload, the operation will not be financially sustainable and heavily affects the economics of the ship owner. Furthermore, the operability of the abatement options installed must show to be problem-free and not cause a significant amount of extra labor for the crew, for the options to be attractive enough for the shipowner.

The *emissions* are as discussed in Section 2.1, aimed to be reduced by significant amounts, with the goal of net-zero by regulatory drivers. This will be enforced through increasing emission taxes, which are often invested in governmental support for sustainable solutions. Thus, emissions and economics are interdependent. The European Maritime Safety Agency (EMSA) facilitates sustainable solutions, and it is expected that emission taxes will increase over time (EMSA ([85])). Rising emission taxes will play a beneficial and central role for shipowners and operators who own and operate vessels with retrofit options that have already reduced the greenhouse gas emissions of their vessels and fleet.

Reliability, availability, maintainability, and safety (RAMS) have become crucial components of the shipping industry. In order to prevent downtime and loss of income, the vessel must be reliable and easy to maintain. Installing retrofit options leads to additional crew training for the correct maintenance, and introducing new technology related to the abatement options can result in unforeseen failures and required maintenance. Safety is a primary concern on a vessel accommodating personnel. In the event of alternative fuel systems, such as ammonia and hydrogen, being installed, the risks associated with pressure and boiling temperature must be carefully considered. Advanced cooling and pressure systems are required to keep ammonia and hydrogen below their respective boiling temperatures. If the system fails, the pressure in the fuel tanks quickly increases, and the consequences can be severe. Safety details related to alternative fuels are discussed in Section 4.1. For other abatement options, such as a Flettner rotor or air lubrication, the risks to human safety are not as great as for alternative fuels, but they may affect the operability of the vessel more significantly and hence be of reliability, availability, and maintainability risk. They may also require more frequent maintenance, as they contain quite young technology and might serve issues more often.

6.2 Economics

The economics of a vessel and a fleet are perhaps considered the most important part of its operations. Without probable economic gain, the stakeholders of the vessel would not be invested in the operation and the vessel would simply not exist. Hence, the CONOPS for the vessel and its business decision criteria are vital elements to have detailed for the market drivers, stakeholders, ship owner, and cargo owner to obtain a functional collaboration and a transparent economic plan. Capital expenditures (CAPEX), operational expenses (OPEX), voyage expenses (VOYEX), and environmental expenses (ENVEX) are all critical components of a ship's financial operation. Each of these costs incurred in building and operating a vessel plays a crucial role in the vessel's overall performance and profitability. The mathematical description of the four expense types for a vessel is listed in Table 13.

CAPEX refers to the expenditures that are necessary to acquire, maintain, or upgrade the ship's physical assets, such as the hull, engines, and equipment. These expenditures are made to ensure the vessel's safe and efficient operation, and they typically have a long-term impact on the ship's value. CAPEX can include the cost of purchasing a new vessel, retrofitting or upgrading existing equipment, or replacing damaged or worn-out components. OPEX, on the other hand, refers to the day-to-day costs associated with operating the vessel, crew expenses, maintenance, insurance, and port charges. These expenses are typically recurring and have a direct impact on the ship's profitability. OPEX can vary based on factors such as vessel size, trading pattern, and regulatory requirements. VOYEX includes expenses that are incurred during a voyage, such as bunker fuel, port fees, and cargo handling costs. These expenses are specific to each voyage and can vary significantly depending on the route, cargo type, and market conditions. VOYEX is directly linked to the ship's revenue, as it is deducted from the freight revenue earned during the voyage. ENVEX encompasses the expenditures related to environmental compliance and sustainability, such as ballast water treatment, emissions control, and waste management. These expenditures are becoming increasingly important in the shipping industry, as regulations aimed at reducing environmental impact become more stringent. ENVEX, including the vessel's emissions taxes, can have a significant impact on a ship's operating costs and may motivate investment in new technology and equipment.

CAPEX = P+U+R	OPEX = CS+M+PF+I+O	VOYEX = F+CH+PC	ENVEX = CH+WM+BWT
P - Purchase Price	**CS** - Crew Salaries	**F** - Fuel	**EC** - Emissions Control
U - Upgrades	**M** - Maintenance	**CH** - Cargo Handling	**WM** - Waste Management
R - Retrofitting	**PF** - Port Fees	**PC** - Port Charges	**BWT** - Ballast Water Treatment
	I - Insurance **O** - Other Expenses		

Table 13: The four expenses for a vessel (self-composed)

In the shipping industry, these four expense categories are interdependent and closely linked. CAPEX can affect OPEX, VOYEX, and ENVEX, as investing in more efficient equipment can lead to reduced fuel consumption, and hence emissions, and maintenance costs. Similarly, investments in environmental compliance can lead to improved operational efficiency and reduced operating costs in the long run. VOYEX and OPEX are also closely related, as higher fuel prices or port fees can significantly impact a voyage's profitability. Similarily, VOYEX and ENVEX, both dependent on the fuel consumption and hence emissions, are heavily correlated. When calculating the four future expenses for Klaveness taking into account retrofit options investments and their effect on the vessel's economy, the net present value (NPV) method is used, respecting an annual discount rate.

In this thesis, focusing on the installation of retrofit options on vessels in a fleet, the four expense categories will only include costs followed or affected by the installations. In other words, for CAPEX, equipment and installation costs will be included, operational costs for OPEX, fuel costs for VOYEX, and ENVEX including only emissions taxes. Costs non-related to the installations will not be a part of the assessment, such as port fees, cargo freight revenue, crew costs, etc.

6.2.1 Payback period

The payback period is a widely used financial metric that measures the time required for an investment to recover its initial cost through generated cash flows. By dividing the initial cost of an investment by its projected annual cash flows, the payback period is determined. The payback period calculation, focusing on installing retrofit options, is presented in Equation 7 with factors described in Table 14. It is commonly employed by businesses and individuals to assess the time needed to recoup their investment. Moreover, the payback period helps evaluate investment risk by considering the length of time until positive returns are achieved. The method offers several advantages. Firstly, it provides a clear timeframe for an investment to pay for itself, aiding decision-makers in evaluating investment opportunities. Additionally, it enables quick comparisons between investment alternatives, allowing investors to prioritize based on recovery timelines. Lastly, the simplicity of the payback period calculation makes it accessible to a wide range of users, regardless of their financial expertise.

$$\begin{aligned}\text{Payback period} &= \frac{\text{Initial cost}}{\text{Annual returns}} \\ &= \sum_{t\in T} \frac{C_I \times (1 + C_{Of})}{(Fc_{vt} \times P_{fuel} + E_{vt} \times P_{co2}) \times y_{vrt}}\end{aligned} \tag{7}$$

Unit	Description
C_I	Investment cost
C_{Of}	Operation cost factor
Fc_{vt}	Annual fuel consumption for vessel v in time period t
P_{fuel}	Fuel price per ton
E_{vt}	Annual emissions for vessel v in time period t
P_{co2}	CO_2 tax per ton
y_{vrt}	1 if retrofit option r in use on vessel v in time period t, 0 otherwise

Table 14: Payback period factors

In the case of a shipowner investing in retrofit alternatives, the initial cost refers to the expenses in relation to the retrofit installation, both investment cost and operational costs. The annual return refers to the reduction in fuel costs and emissions taxes, due to the installation of a retrofit option. A positive payback period indicates that the investment has generated more returns than the initial cost incurred, while a negative payback suggests a loss. It is important to note that payback period calculations may vary depending on the specific retrofitting project, vessel type, operational conditions, and market factors.

6.2.2 Economic subsidies

Governments recognize the high cost of investing in emissions-reducing applications and have established economic subsidiary solutions to intensify the stakeholders' and shipowners' incentive for investing in energy-efficient solutions. The regulatory drivers, therefore, have established specialized agencies to promote environmentally friendly energy production and consumption. One such agency is Enova, established in 2001 and owned by the Norwegian Ministry of Climate and Environment (NMCE) (Enova [86], NMCE [87]). Enova plays a crucial role in implementing the Norwegian government's energy and climate policies by providing financial incentives, support, and advisory services to businesses, industry, and the public sector for energy-efficient and low-emission projects. Enova's key focus areas include energy efficiency in buildings, renewable energy production, electrification of the transport sector, and carbon capture and storage. As a result, Enova is a significant player in Norway's efforts to reduce greenhouse gas emissions and achieve its climate targets. Other, international, agencies focusing on environmental subsidies, are the European Investment Bank with their Climate Bank section ([88]), and the U.S. Environmental Protection Agency ([89]).

Enova offers financial support for emissions-reducing projects, and businesses can apply for support covering a percentage of the value-added tax. Non-emissions maritime transport is one of Enova's key focus areas (Enova maritime sector [86]), and the level of support for a project depends on the project's size and the business. Smaller businesses typically receive a higher percentage of support than larger ones. Appendix Section C provides an overview of the possible support for different energy-efficiency projects, such as pilot projects, investigations, and investments, for small, semi-large, and large businesses. Semi-large businesses can receive up to 50% support for investments in projects that reduce GHG emissions beyond the restrictions set by the EU standards and will be a part of the CAPEX calculations. KCC informed in their sustainability report for 2022 that they received Enova-support for shaft generators and air lubrication installations for two of their vessels. After correspondence with co-supervisor at Klaveness, including Enova-support in this thesis was concluded to be over-complicated, as Enova seldom supports projects not unique or world-leading. It is however important to keep this in mind for stakeholders and the shipowner during economic assessments of possible retrofitting.

6.3 Decision-making factors summation

In the decision-making process for vessel design, the concept of operations and the economics of retrofitting play crucial roles. CONOPS considers the owner's requirements and operational needs, providing a clear understanding of how the vessel will be utilized. This information ensures that the retrofitting design aligns with the intended purpose and optimizes performance. On the other hand, the economic aspects, such as the payback period and subsidies, are vital considerations to determine the financial feasibility of retrofitting. The payback period helps assess the time required for the retrofit investment to recover its cost, while subsidies can significantly influence the economic viability of the project. By incorporating CONOPS and economics into the decision-making process, stakeholders can make informed choices about possible retrofit options that enhance vessel performance and maximize financial returns.

Maximizing financial returns when investing in emissions-reducing abatements, without inflating the fleet's total cost, is indeed a challenging task. A well-developed optimization model can serve as a useful tool in this context for decision-makers. It can act in accordance with emissions limits set by regulatory drivers and respects the vessel's CONOPS, all while keeping costs to a minimum.

7 Linear optimization model for fleet renewal and retrofit

Linear optimization is a mathematical technique used to determine the best solution from a set of feasible solutions. It is a powerful tool for decision-making that helps organizations make optimal choices in the allocation of resources and maximization of profits. The goal of linear optimization is to find the values of the decision variables that maximize or minimize an objective function subject to a set of constraints. Deterministic models rely on certain input data and fixed rules and are therefore often inflexible. A general optimization problem statement, *minimizing the objective function by varying the design variables subject to the constraints and design variable bounds*, is shown in Equation 8 below (Engineering Design Optimization [90]).

$$\begin{aligned} &\min \mathrm{Z} = f(x) \\ &\quad \underline{x_i} \leq x_i \leq \overline{x_i} \qquad i = 1, ..., n_x \\ &\quad \text{s.t.} \\ &g_j(x) \leq 0 \qquad\qquad j = 1, ..., n_g \\ &h_k(x) \leq 0 \qquad\qquad k = 1, ..., n_h \end{aligned} \tag{8}$$

The simplex algorithm is used to improve the objective function iteratively until reaching the optimal solution. The first step in solving a linear optimization problem using the simplex method is to set up the problem using sets, variables, constraints, parameters, and an objective function. The simplex method starts with an initial basic feasible solution, and then iteratively moves to adjacent basic feasible solutions by selecting a non-basic variable to enter the basis and a basic variable to leave the basis until the optimal solution is reached.

7.1 Optimization software

An optimization model solving a linear optimization problem may be developed and solved using the programming language Python and the library Xpress, developed by FICO (Python [91], FICO [92]). Xpress is a high-performance optimization library that provides a comprehensive set of tools for solving linear, mixed-integer, and quadratic optimization problems. It is designed to handle large-scale problems and provides advanced features such as optimization modeling and decomposition. The library is optimized for performance and provides state-of-the-art algorithms and solvers for finding optimal solutions to optimization problems. Xpress also provides robust error handling and error reporting, making it easy to diagnose and resolve issues that may arise during the optimization process. For the case studies regarding Klaveness' fleet in Section 8, the optimization model will be developed using Python and Xpress.

7.2 Development of optimization model for fleet renewal and retrofit

A binary linear programming (BLP) algorithm was implemented using Python, utilizing the Xpress optimization library to formulate the model with inspiration from *Balland, O.* (Optimized selection of air emission controls for vessels [93]). The primary objective of the model is to minimize the total cost of the fleet while adhering to emissions and economic regulations and constraints.

The model utilizes binary variables to indicate vessel retrofitting, as well as sets to define the present vessels and retrofit options. The objective function and constraints are formulated to regulate the model and aim to optimize the fleet with respect to both economics and emissions. An explanation of the model can be found below its formulation.

Sets

V - set of vessels indexed by v

R - set of retrofits indexed by r

Parameters

E^V_v - emissions for vessel v

γ_r - emissions reduction factor for retrofit r

C^{AI}_r - cost for installation of retrofit r

C^{AO}_r - cost for operation of retrofit r

E^{TOT} - allowed emissions

I_{vr} - initial retrofit indicator, 1 if retrofit r is already installed on vessel v, 0 otherwise

Variables

x_{vr} - 1 if vessel v is being retrofitted with retrofit r, 0 otherwise

y_{vr} - 1 if vessel v has been retrofitted with retrofit r, 0 otherwise

Objective function

$$\min \text{ Z} = \min \sum_{v\in V}\sum_{r\in R}(C^{AI}_r x_{vr} + C^{AO}_r y_{vr}) \tag{0}$$

Constraints

$$\sum_{v\in V}(E^V_v - \sum_{r\in R}\gamma_r E^V_v y_{vr}) \leq E^{TOT} \tag{1}$$

$$x_{vr} + I_{vr} \leq y_{vr}, \qquad \forall v \in V, \forall r \in R \tag{2}$$

$$x_{vr},\, y_{vr} \in \{0,1\}, \qquad \forall v \in V, \forall r \in R \tag{3}$$

Model explanation

The optimization model aims to minimize the investment plus operating costs for all vessels and their retrofit options. This objective is represented by a variable x_{vr} that indicates if a retrofit option r is installed on vessel v, and another variable y_{vr} that denotes if this retrofit is operated. The model is subject to several constraints. Constraints (1) ensures that the total emissions from all vessels, after accounting for the emission reduction from retrofit options, do not surpass the total allowable emissions, symbolized as E^{TOT}. The emissions from each vessel v are diminished by the product of the retrofit's reduction factor (γ_r) and the operation of that retrofit y_{vr}. Constraints (2) stipulate that if a retrofit option r is installed on a vessel v (either initially or during the optimization process), it must be operated. To enforce this condition, the sum of $x_{vr} + I_{vr}$ (which shows whether the retrofit is installed) is always set to be greater than or equal to y_{vr} (indicating whether the retrofit is operated), also ensuring that each retrofit option r can only be installed once on each vessel v. Finally, constraints (3) are binary constraints, making sure that x_{vrt} and y_{vrt} can only take binary (0 or 1) values.

7.3 Binary linear optimization model including time domain

IMO's and the EU's emissions regulations will be strengthened in the forthcoming years, making the emissions target for vessels time-dependent. Another challenge when reducing emissions of a vessel is its lifetime. Following, the implementation of emissions-reducing abatements on younger vessels can be far more beneficial than implementing them on older ones. As an example, installing an abatement option today might make the vessel comply with today's emissions regulations. However, with stricter regulations being implemented in the coming years, additional options might be required to be installed for the vessel to comply with the new regulations. Additionally, the installation of stricter options in the first place might have the vessel comply longer into the time horizon, possibly lowering the total cost. Knowing when to install the abatement options, is therefore equally important as figuring out which option to install. Following is the notation and mathematical formulation of the extended optimization model including the time domain with explanations of the model below its formulation. The model is for this thesis constructed and developed using Python through the program Anaconda ([94]) and can be inspected through the author's GitHub profile ([95]). Additionally, the most vital code including the optimization model and the analysis of the model and results, are included in the appendix in Section J. The code is inspired by a base code provided by the supervisor, also available on GitHub ([96]).

Sets

V - set of vessels indexed by v

R - set of retrofits indexed by r

T - set of time periods indexed by t

Parameters

E_v^V - emissions for vessel v at the start of the planning period

γ_r - emissions reduction factor for retrofit r

C_r^{AI} - cost for installation of retrofit r

C_r^{AO} - cost for operation of retrofit r

NPV_r - discount rate for net present value

E_t^{TOT} - allowed fleet emissions in time period t

M - a large number

Y_{vt} - the respective vessel's build year

Y_0 - start year for model

I_{vr} - 1 if vessel v already is outfitted with retrofit option r, 0 otherwise

Age_{vt} - age of vessel v in time period t

Variables

x_{vrt} - 1 if vessel v is being retrofitted with retrofit r in time period t, 0 otherwise

y_{vrt} - 1 if vessel v has been retrofitted with retrofit option r in time period t, 0 otherwise

Objective function

$$\min \text{ Z} = \min \ \sum_{v\in V}\sum_{r\in R}\sum_{t\in T}\frac{(C_r^{AI}x_{vrt}+C_r^{AO}y_{vrt})}{(1+NPV_r)^t} \tag{0}$$

Constraints

$$\sum_{v\in V}(E_v^V-\sum_{r\in R}\gamma_a E_v^V y_{vrt})\leq E_y^{TOT}, \qquad \forall t\in T \tag{1}$$

$$\sum_{t\in T}x_{vrt}+I_{vr}\leq 1, \qquad \forall v\in V,\forall r\in R \tag{2}$$

$$M\sum_{t\in T}x_{vrt}+I_{vr}\geq \sum_{t\in T}, \qquad \forall v\in V,\forall r\in R \tag{3}$$

$$y_{vrt}\geq x_{vrt}, \qquad \forall v\in V,\forall r\in R,\forall t\in T \tag{4}$$

$$y_{vrt}\geq y_{vr(t-1)}, \qquad \forall v\in V,\forall r\in R,\forall t\in T/\{0\} \tag{5}$$

$$y_{vrt}-y_{vr(t-1)}=x_{vrt}, \qquad \forall v\in V,\forall r\in R,\forall t\in T/\{0\} \tag{6}$$

$$y_{vr1}-I_{vr}=x_{vr1}, \qquad \forall v\in V,\forall r\in R\mid Age_{vt}\ \&\ r\neq R/\{-1\} \tag{7}$$

$$x_{vrt}=0, \qquad \forall v\in V,\forall r\in R,\forall t\in T\mid (Age_{vt}-Y_{vt}) \mod 5\neq 0 \tag{8}$$

$$x_{vrt}=1, \qquad \forall r\in R/\{-1\},\forall v\in V,\forall t\in T\mid Age_{vt}>25 \tag{9}$$

$$x_{vrt},\, y_{vrt}\in\{0,1\}, \qquad \forall v\in V,\forall r\in R,\forall t\in T \tag{10}$$

Model explanation

The fleet model's objective function aims to minimize the total cost of retrofitting and operating vessels. This total cost comprises the installation cost C_r^{AI} for retrofitting a vessel with a specific retrofit option and the operational cost C_r^{AO} for operating a vessel v with a particular retrofit option r. Both costs are discounted to the present using a discount factor NPV_r to calculate the net present value. The model is subject to several constraints. Constraints (1) stipulate that the total annual fleet emissions should not exceed the total allowed limits E_t^{TOT}. They take into account the emissions from each vessel v after retrofit options r has been implemented, ensuring that the sum of these emissions is less than or equal to the permitted emission levels. Constraints (2) ensures that each vessel v can only be retrofitted with a specific retrofit option r once. The sum of the decision variable x_{vrt} for each retrofit option and vessel across all time periods T, plus the pre-existing retrofit status of the vessel with that retrofit option I_{vr}, should be less than or equal to 1. Constraints (3) asserts that if a vessel v is retrofitted with a retrofit option r at any time period t (i.e., x_{vrt} equals 1), then it must be operating with that retrofit option (i.e., y_{vrt} equals 1). This condition is ensured by equating x_{vrt} and y_{vrt}, scaled by a large number M, to convert the inequality constraints into equal ones. Constraints (4) dictates that if a vessel is operating with a retrofit option (i.e., y_{vrt} equals 1), it must have been retrofitted with that option (i.e., x_{vrt} equals 1). Constraints (5) insist that once a vessel v is retrofitted with an option (i.e., y_{vrt} equals 1), it will continue operating with that option for the remaining time periods t. Constraints (6) indicate that a change in the operation status of a retrofit option (y_{vrt}) triggers the installation of the retrofit option (x_{vrt}). This means if a vessel v starts operating with a retrofit option r in the current time period t (i.e., y_{vrt} switches from 0 to 1), it must be retrofitted with that option in the current time period (i.e., x_{vrt} equals 1). Constraints (7) specify that if a vessel v is 25 years old, it cannot be retrofitted, except for the last retrofit option r. The underlying assumption (detailed in Section 8.3) is that a vessel is considered a new-build at this age, and the last retrofit option reduces the vessel's emissions by 25% cost-free due to the presumption that vessels become 1% more efficient every year due to improvements in propulsion systems, hull design, and so on. Constraints (8) dictate that a vessel v can only be retrofitted in a time period t if its age is its build year plus a multiple of 5 or 2.5 (docking intervals). Constraints (9) posits that if a vessel's v age is above 25, its emissions must be reduced by 25% from that time period onward. This implies that new vessels will be built with a 25% lower emissions rate than the one it is replacing. Lastly, constraints (10) are binary constraints, ensuring that x_{vrt} and y_{vrt} can only take binary (0 or 1) values.

8 Case study - retrofitting Torvald Klaveness' deep sea shipping fleet

Klaveness' fleet of sixteen vessels stands before an era of more stringent emissions regulations, as discussed in the introduction, Section 1, and will be required to adapt with respect to the regulations thereafter. Ship owners generally do not design their vessels to emit less than the minimum required as it is cost-prohibitive, and thereby operate their fleet maximizing profits within its emission limits. With that in mind, the optimization of a shipowner's fleet would maximize the total allowed emissions, and minimize the total capital, operational, and voyage expenses, respecting legal restrictions as well as staying financially competitive.

In order to respect the upcoming regulations, it is advisable to set emissions goals for every individual vessel in the fleet. Every vessel is different in terms of build year, wear and tear, and operations, and will therefore have different realistic emissions goals. The carbon intensity index introduced in Section 2.4, is a well-constructed indicator representing the emissions of the respective vessel with respect to transported goods and sailing distance and serves as a good indicator of the vessel's performance. The challenge, however, lies in determining the optimal timing for retrofitting each vessel in the fleet, so as to minimize the overall costs of the fleet in a given year as well as reduce its emissions in a large enough manner. In addressing this challenge, linear optimization offers a suitable solution. By analyzing Klaveness' fleet, respecting their current and projected annual emissions, possible retrofit options, build year, and other market parameters affecting the fleet and retrofit options, the optimization model has the potential to determine the optimal retrofitting schedule for each vessel to achieve the company's emission goals whilst minimizing its expenses.

8.1 Torvald Klaveness and its fleet

Torvald Klaveness is a leading Norwegian shipping company founded in 1927 (Klaveness [97]). Based in Oslo, Norway, the company specializes in the transport of dry bulk goods, such as coal, grain, and iron ore, operating a modern fleet of over 100 vessels. The company's subdivision, Klaveness Combination Carriers, operates 16 combination carriers (CCs), allowing them to transport both dry bulk, goods, and liquids. Through their high utilization and efficiency, the vessels emit up to 40% less CO_2 per transported ton compared to standard tanker and dry bulk vessels in current and targeted combination trading patterns, according to themselves (Klaveness Combination Carriers [98]).

Klaveness' fleet of 16 combination carriers, comprises eight specialized CABU combination carriers and eight CLEANBU combination carriers. These CCs were constructed between 2001 and 2021, and are currently fueled by fossil fuel. Their vessels have the capacity to transport caustic soda solutions (CSS), floating fertilizer (UAN), molasses, clean petroleum products (CPP), heavy liquid cargoes, and all types of dry bulk cargo (KCC [99]). Klaveness claims their 40% lower fuel consumption compared to standard tanker and dry bulk vessels in current and targeted trading patterns, is mainly due to KCC's decarbonization efforts. KCC has invested in decision support systems onboard vessels and crew training, optimizing voyage efficiency. Further, they have invested in and are considering further investments in fuel consumption reduction abatements. The abatements are amongst others, a shaft generator from Wärtsila ([60]), an air-lubrication system from Silverstream Technologies ([62]), in-transit hull cleaning, advanced hull coating, scrubbers, and propeller duct from Becker Marine Systems ([65]), straightening and accelerating the hull's wake into the propeller also producing a net forward thrust.

By 2026, Klaveness has ordered three third-generation CABU (CABU III) vessels. "The modern CABU III newbuilds will incorporate Klaveness' decades of experience, deliver large improvements in energy efficiency, and bring KCC closer to offer a zero-emission service to its customers," Klaveness claims in their own news article released May 24^{th} 2023 (KCC [100]). The new generation of CABU vessels will introduce a 35% reduction in carbon footprint compared to the first generation of CABU vessels, due to the new standard of efficiency. The vessels will obtain a 10% higher cargo carrying capacity with a fuel consumption estimated to be 30% lower than the first generation of CABU vessels, through optimized design and installation of several energy-efficiency measures partly tested on KCC's current fleet over the recent years. Additionally, KCC targets the installation of wind-assisted propulsion on the new CABU generation, improving efficiency even further. Lastly, the vessels will be prepared for a later time- and cost-effective conversion for burning zero-emissions fuels, when the technology deems it readily available.

8.1.1 The fleet's challenges

Even though KCC have installed several emissions-reducing abatements onboard some of their vessels, they stand before even tighter and stricter rules and regulations regarding emissions requiring them to further reduce the total emissions of their fleet. Additionally, KCC has set themselves a strict timeline with respect to emissions, depicted in Figure 8.1, gathered from their 2022 performance report (KCC [101]). They target reducing their carbon intensity by 35% compared to their 2018 numbers and reach net-zero across their business within 2050, hence requiring a drastic emissions reduction throughout their operation. Their measures focus mainly on streamlining their diesel oil-fueled vessels. In future fuel reducing decision makings, alternative fuel discussed in Section 4.1, different retrofit options discussed in Section 4.6, and further development of systems support streamlining the fleet's operations, require thorough evaluation, and heavily depends on the operating profile of the respective vessel and its CONOPS discussed in Section 6.1. The vessels must still be operable and make profit, whilst its updated CONOPS may have tightened its emissions restrictions, safety regulations, and operable capabilities. Thus, KCC must carefully evaluate the available fuel-reducing options in light of various vessel specifications, such as common bunkering intervals, sailing areas, available space on or within the vessel, and other key parameters. An updated set of CONOPS reflecting the vessel's capabilities and mission statement will need to be developed to ensure that the chosen measures are effective in reducing emissions while meeting regulatory requirements.

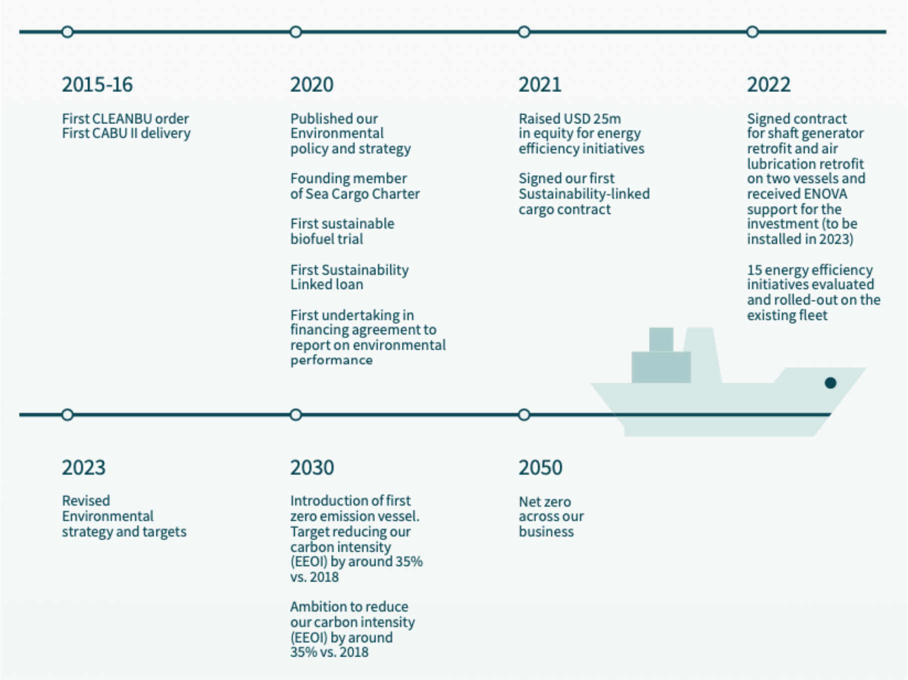


Figure 8.1: KCC decarbonization timeline (KCC [101])

8.2 Data pre-pocessing

Obtaining and organizing data for each vessel in Klaveness' fleet, including their retrofit options, is an integral step in optimizing the fleet's timeline with respect to emissions regulations. The data is sourced from direct communication with the co-supervisor at Klaveness. Theoretically, numerous specifications and variables for each vessel could impact the selection of retrofit options, such as size and positioning on the vessel. However, this case study limits itself to the vessel's annual emissions, fuel consumption, and age, as these factors have the greatest impact on the decision of whether and when a retrofit option should be installed on each vessel. KCC have already started the process of installing retrofit options for the fleet, making it necessary to map which vessel has which option installed, beforehand. The data for the 16 vessels in the fleet, including their names, build year, annual emissions, fuel consumption, and already installed retrofit option is provided by Klaveness Ship Management (KSM) and presented in Table 15. The annual vessel emissions are gathered from 2022 data for KCC's fleet, provided by KSM. Total fuel consumption is based on total emissions, divided by the CO_2 factor for marine gas oil equal to 3.17 (SSB [102]). In Table 15 the emissions and fuel consumption values are rounded to the nearest five hundred, with precise values used in the model. Lastly, mapping of whether a vessel has a retrofit option installed or not is included, represented by a binary value in the for-right column, so it is ensured that a vessel cannot be installed with the same retrofit option twice, marked in the data set read by the optimization model.

Vessel	Built year	Annual emissions	Annual fuel cons	Retrofit option y
Barcagena	2001	$19,000$	$6,000$	$x \in \{0, 1\}$
Banastar	2001	$19,000$	$6,000$	
Bangor	2002	$18,500$	$6,000$	
Bantry	2005	$18,500$	$6,000$	
Bakkedal	2007	$18,000$	$6,000$	
Balboa	2016	$18,000$	$5,500$	
Baffin	2016	$18,000$	$5,500$	
Ballard	2015	$17,500$	$5,500$	
Baru	2019	$17,000$	$5,500$	
Barracuda	2019	$17,000$	$5,500$	
Barramundi	2019	$17,000$	$5,500$	
Baleen	2020	$17,000$	$5,500$	
Bangus	2020	$17,000$	$5,500$	
Baiacu	2021	$16,500$	$5,000$	
Bass	2021	$16,500$	$5,000$	
Balzani	2021	$16,500$	$5,000$	
Unit	year	$\frac{tonfuel}{year}$	$\frac{tonCO_2e}{year}$	[-]

Table 15: Klaveness' fleet

Table 16 outlines the retrofit options available for Klaveness' fleet of vessels. The table presents the installation and operational (percentage of installation) costs and emissions reduction factors associated with each option. It is assumed that these parameters are consistent across all vessels in the fleet, given their similarity in design, for the simplification of this thesis. The values specified for each retrofit option are based on recommendations provided by Klaveness Ship Management and gathered from online sources, as discussed in Section 4.6. However, it is important to note that the actual costs associated with retrofit installation and operation are subject to significant variation depending on vessel-specific factors such as size, type, yard, and supplier. As such, the figures presented in the table should be treated as estimates and may not fully capture the full range of potential costs. It is recommended that future research include upper and lower bounds for each retrofit parameter to provide a more comprehensive analysis, and hence provide a "positive" and "pessimistic" economic result. A sensitivity analysis testing a positive and a pessimistic approach is carried out in the discussion, Section 9.1. Additionally, the emissions reduction factor associated with the chosen retrofit option provides an idea of the effectiveness of every option.

Retrofit	Investment cost	Operational cost (% of investment)	Emissions reduction factor
Flettner rotor	1.30	3%	.15
Scrubber	2.60	2%	.04
Air lubrication	1.55	3%	.08
Electrical upgrade	0.80	2%	.04
Shaft generator	1.32	3%	.04
Propeller duct	1.20	2%	.08
Auxiliary hybrid	3.50	10%	.15
Unit	MUSD	$\frac{MUSD}{year}$	[-]

Table 16: Retrofit options

Some additional parameters are required for the optimization calculations utilizing Table 15, Table 16, and Table 19 to be carried out. The parameters are listed in Table 17 below. The year-today-parameter is created for the sake of later use for Klaveness and other shipowners, so the model will have a more flexible approach. Further, a CO_2 tax proposed by the EU, discussed in Section 3.2, is set to 90 euros per ton CO_2e, converted to 98 USD (June 2023). The MGO fuel price can fluctuate with several percentage points every day, but is set to 600 $\frac{\$}{mt}$, and is gathered from Ship & Bunker ([103]). Although it is highly unlikely, the fuel price and emissions taxes will be constant during the time horizon of which the optimization model will operate, for the simplicity of the model. The expected discount rate r for the calculation of future costs for installation and operations is set to 3%.

Parameter	Annual emissions reduction	Year today	CO_2 tax	Fuel cost	r
Value	x	y_0	98	600	3
Unit	%	year	$\frac{USD}{tonCO_2e}$	$\frac{USD}{ton}$	%

Table 17: Parameters

Finally, the future timeline for Klaveness' fleet is presented, as shown in Table 19. The table contains information on the fleet's annual allowed emissions from the current year until 2050. The year 2050 was chosen due to IMO, the EU, and Klaveness having 2050 as their end-goal for their time horizon and emissions goals. To determine the annual total allowed emissions for the fleet, the fleet's total emissions from Table 15 are adjusted for the required annual emissions reduction, as presented in Table 17 and formulated in Equation 9 with parameters in Table 18. The annual required emissions reduction rate is presented in percent (%) and allows for the user of the optimization model to restrain the fleet's future emissions by their wishes.

$$E_y^{fleet} = E_0^{fleet}(1-x)^{y_n - y_0}, \quad n = 1,\, 2,\, 3\, \ldots\, N \tag{9}$$

Parameter	Description
E_y^{fleet}	Allowed fleet emissions for year y
E_0^{fleet}	Total fleet emissions in year 0
x	Annual fleet reduction parameter
y_n	Respective year
y_0	Year today

Table 18: Notation

Year	Allowed emissions
n	$E_0^{fleet} \times (1-x)^{y_n - y_0}$
$n+1$	$E_0^{fleet} \times (1-x)^{y_{n+1} - y_0}$
$n+2$	$E_0^{fleet} \times (1-x)^{y_{n+2} - y_0}$
$n+3$	$E_0^{fleet} \times (1-x)^{y_{n+3} - y_0}$
$\vdots$	$\vdots$
$N-3$	$E_0^{fleet} \times (1-x)^{y_{N-3} - y_0}$
$N-2$	$E_0^{fleet} \times (1-x)^{y_{N-2} - y_0}$
$N-1$	$E_0^{fleet} \times (1-x)^{y_{N-1} - y_0}$
N	$E_0^{fleet} \times (1-x)^{y_N - y_0}$
	$\frac{ton}{CO_2e}$

Table 19: Time horizon

With the tables presented in this section, the optimization model can be developed using Python with the Xpress library, reading these tables as input data from an Excel file. The output data for the model will present the suggested timeline for the fleet, suggesting when which vessel should be retrofitted with which option. Additionally, the costs of investing and operating the retrofit options as well as the fleet's total emissions will be calculated and presented. The case study consists of 16 vessels and 7 retrofit options, resulting in a staggering total of $8^{16} \approx 2.8E14$ different fleet combinations where each vessel can be outfitted with 0 to 7 retrofit options. This highlights the importance of this study, as deciding when which vessel should be outfitted with which retrofit options for optimizing the fleet's costs-to-emissions-ratio, is near impossible for a human being.

8.2.1 Payback period for retrofit alternatives

To ensure shipowners find retrofit options compelling and worth investing in, it is essential to demonstrate that the investment will yield returns within a shorter time frame than the investment's lifespan. The economic viability of retrofit options is critical for businesses to perceive the investment as worthwhile. Economic gain typically refers to positive profits over time, but it can also encompass emissions reduction for tax benefits or to enhance a company's public image and reputation, thereby creating potential future business opportunities.

Figure 8.2 illustrates the calculated payback period for four distinct scenarios involving the retrofitting of specific vessels: Banastar with a Flettner rotor, Baru with air lubrication, Barracuda with a propeller duct, and Bass with a shaft generator. The payback period calculations were performed using the methodology presented in Section 6.2. It is important to note that while the vessels have different annual fuel consumption rates, the installation cost of each retrofit option remains constant regardless of the vessel. The Flettner rotor emerges as the most effective option, surpassing the propeller duct system and the air lubrication, demonstrating relatively similar payback period results but are significantly superior to the shaft generator. The retrofit options break even after only approximately 2.5, 4, 5.5, and 9 years respectively. The expected popularity of different retrofit options is anticipated to be mirrored in the results for the optimization model, as it is designed to prioritize the selection of the most optimal alternative for each respective vessel.

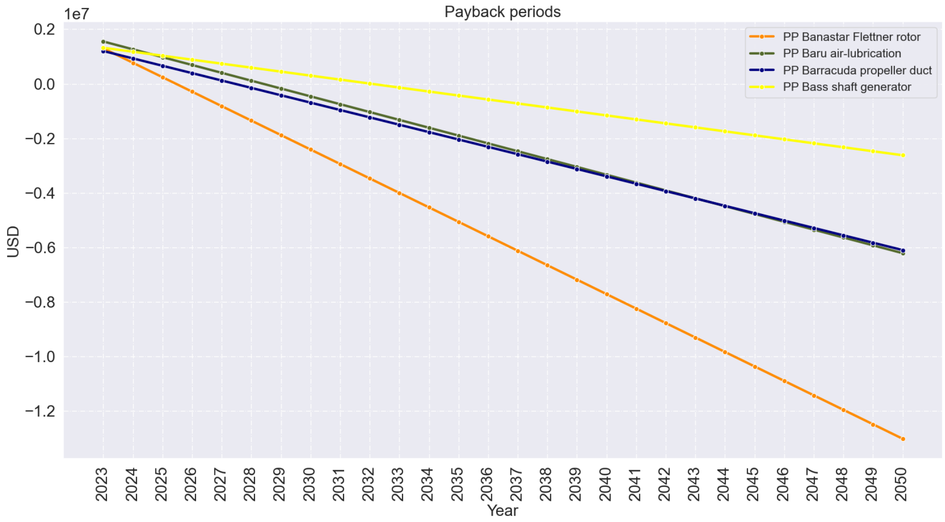


Figure 8.2: Payback periods for retrofit alternatives for KCC vessels

8.3 Assumptions

In order to develop the optimization model utilizing the presented data sets, several assumptions have been made to ensure the feasibility of solving the problem while maintaining a realistic representation that remains relevant to real-life scenarios. These assumptions are outlined below:

1. Homogenous fleet: Although there may be variations in size and age, it is assumed that the fleet consists of vessels that are fundamentally similar in terms of their operational characteristics and vessel design. This assumption allows for simplified analysis and modeling without compromising the overall validity of the results.

2. Improvement in vessel efficiency: It is assumed that a vessel built one year later consumes and emits 1% less CO_2e than a vessel built in the previous year. This assumption is based on advancements in engine technology, electrical systems, hull design, and other relevant factors. The proposal for this assumption originated from the co-supervisor at Klaveness, and it has been adopted for the purposes of this study.

3. Fleet longevity and retrofit options: Vessels in the fleet are assumed to have the potential for continued operation and improvement. It is assumed that after a vessel reaches the end of its original lifespan, 25 years, it can be retrofitted to become 25% more fuel-efficient, respecting assumption 2. Additionally, retrofit options implemented on the respective vessel will be kept with the "new-builds", considering the likelihood of incorporating retrofit capabilities into new-build designs in the time to come. It is also assumed that all vessels will be replaced by the exact age of 25, regardless of their condition and health.

4. CO_2 tax: A CO_2 tax rate of 98 USD per ton of emitted CO_2 is assumed in this study, after the proposal from the EU of introducing a CO_2 tax of 90 euros per CO_2 emitted. This assumption reflects the presence of a pricing mechanism designed to incentivize reduced emissions and encourage environmentally friendly practices. Comment from co-supervisor at Klaveness, informing that seldom will the shipowner retrieve all the positive effects of fuel savings as long as they do not freight solely their own cargo. Hence, the cargo owner would gain a natural economic benefit. For this model, the shipowner is assumed to receive all economic benefits from reducing the vessel's emissions.

5. Reduction in future allowed emissions: The study assumes a constant reduction in the future allowed emissions on an annual basis. This assumption acknowledges the need for ongoing emission reductions to meet environmental targets and regulatory requirements.

6. Future discount rate: A constant future discount rate of 3% is assumed in this study. This assumption is applied to calculate future installation and operational costs using the NPV methodology, accounting for the discount rate. The rate is also assumed to be constant throughout the time horizon.
7. Data accuracy and completeness: It is assumed that the data collected and used for analysis is accurate and comprehensive. This assumption implies that the data provided by Klaveness is reliable and covers all relevant aspects required for the optimization model.
8. Deterministic modeling: It is assumed that the optimization model employs a deterministic approach, meaning it does not consider uncertain or probabilistic factors in its calculations. This assumption simplifies the modeling process but may overlook the impact of randomness or variability in real-world scenarios.
9. Static market conditions: The model assumes that market conditions, including freight rates, fuel prices, freight deals, and regulatory requirements, remain constant throughout the analysis period. This assumption simplifies the modeling process by eliminating the need to incorporate dynamic market factors but may limit the model's accuracy in capturing real-world fluctuations.
10. Determined decision variables: The optimization model assumes that the decision variables, such as vessel routing, speed, and fuel allocation, are completely determined and controllable. This assumption implies that the shipping company has full authority to adjust these variables as needed without external constraints.
11. Uniform performance metrics: The model assumes a consistent and uniform set of performance metrics to evaluate different scenarios and compare results. These metrics may include fuel efficiency, emissions, costs, or a combination of factors to enable a standardized assessment of optimization outcomes.
12. Infinite lifespan: It is assumed that every retrofit option has an infinite lifespan outliving the respective vessel, making it irrelevant to look at the need for replacing the option. Regular maintenance costs are however included.
13. Retrofit budget: The model assumes the vessel fleet owner does not operate with an annual retrofit budget, as this depends heavily on the strongly fluctuating marine market. Should an installation prove to be economically beneficial in the long run, the ship owner should make the investment.
14. Dry dock installation: It is assumed that the ship owner only installs retrofit options during dry-docking, as off-hiring the vessel for the sole reason of a retrofit option installation is too counter-productive and follows with too little economic gain.
15. The four economic costs presented in Section 6.2, include only: CAPEX; installation cost of retrofit option, OPEX; operation cost of the retrofit option, VOYEX; fuel cost, ENVEX; CO_2 tax based on fuel consumption.

8.4 Case studies description

The optimization model for Klaveness' fleet will perform three case studies, presented in the following subsections. The three cases consider an annual total fleet emissions reduction of 3%, 4%, and 5% respectively. The results of each study will be presented in an orderly manner, with tables and graphs presented and discussed. The results will be analyzed individually before they are compared and discussed in the discussion, Section 9, later in the thesis. For every study, the results table including total costs of the fleet optimization with respect to retrofitting, the fleet's emissions next to its allowed, spanning over a time horizon, is presented. Additionally, a graphical representation of the same results is depicted. Further, a table describing when every vessel should be retrofitted with which option throughout the time horizon is presented. With the emissions data already presented, the CII rating of three randomly picked vessels within the fleet is graphically described, before the economic results are further analyzed and visualized. Later, a heatmap of the economic and emissions values is presented and discussed before the popularity of every retrofit option is presented. Lastly, a regression plot comparing the fleet's total emissions and the following total retrofit costs is depicted and analyzed.

For case 1, a comprehensive description and analysis of the results is carried out. As for cases 2 and 3 containing the same illustrations and tables only with different data, a not-so-comprehensive description will be carried out, keeping the focus mainly on the analysis part, to avoid unnecessary repetition.

8.5 Case study 1: 3% annual emissions reduction

The focus of case study 1 is an assessment of a strategic operational pathway that seeks a 3% annual reduction in fleet emissions. This ambitious trajectory, which projects a 56% decrease in emissions by 2050 in contrast to the 2022 levels, necessitates the fleet to embrace a series of retrofit options as outlined in Table 16. The application of these retrofit options throughout the duration of the operation must adhere to the boundaries delineated by the optimization model.

8.5.1 Comprehensive results overview

The advanced optimization model yields a detailed computational ecosystem, consisting of $7,168$ variables along with $13,364$ constraints. It facilitates a comprehensive analysis of the annual emissions and associated costs that stem from the installation of retrofit options. Finally, it lays out the optimal sequence for retrofitting specific vessels in a particular year. The salient outcomes of the optimization process, including cost and emissions data rounded to the nearest thousand, are summarized in Table 20 starting at 2023, with five years intervals from 2025. A complete representation of the results can be accessed in the appendix, Figure A7, presented in an Excel format.

The total annual costs, accounting for the accumulated annual CAPEX, OPEX, VOYEX, and ENVEX, are strictly associated with the retrofit options installed. Therefore, the model does not incorporate expenses incurred in the course of regular business activities, such as cargo handling, port fees, maintenance costs, crew salaries, or vessel build costs. The analysis verifies that in each year of retrofit option implementation, the fleet's emissions remain below the allowed limit, decreasing by 3% annually.

Year	Total cost	Emissions	Allowed emissions
2023	79.0	274	278
2025	75.8	261	261
2030	54.0	224	225
2035	43.6	193	193
2040	33.2	165	166
2045	20.4	128	142
2050	16.0	116	122
Unit	$E6 \times \frac{\$}{year}$	$E3 \times \frac{tonCO_2e}{year}$	$E3 \times \frac{tonCO_2e}{year}$

Table 20: Case 1 results (1)

The illustration of the economic and emissions findings is provided in Figure 8.3, where both CAPEX and OPEX are graphically represented as bars, their scale quantified by the left-hand-side (LHS) y-axis. These metrics are computed annually after each retrofit. The right-hand-side (RHS) y-axis portrays the annual and annual allowed emissions, exhibited as line plots. For this analysis, only CAPEX and OPEX are integrated into the plot to emphasize the impact of material and operational expenditures on the total emissions produced by the fleet.

It is apparent that an increase in CAPEX inherently causes a surge in OPEX. This is because the maintenance requirement escalates with the introduction of additional retrofit options. In the final third of the time horizon, there is a noticeable reduction in retrofit investments, consequently leading to a drop in OPEX, which is computed as the net present value as of 2023. This decline in retrofit investments can be attributed to the natural aging of the fleet's vessels. When a vessel's age reaches 25, it is replaced within the model by a new, identical vessel equipped with the same retrofit options and 25% lower emission rate, as detailed in the assumptions in Section 8.3.

This transition is particularly evident between the years 2043 and 2046, where a significant drop in the fleet's emissions is observed. In 2023, the emissions produced by the fleet start below the permissible limit, due to the implementation of pre-installed retrofit options, discussed in Section 8.2.

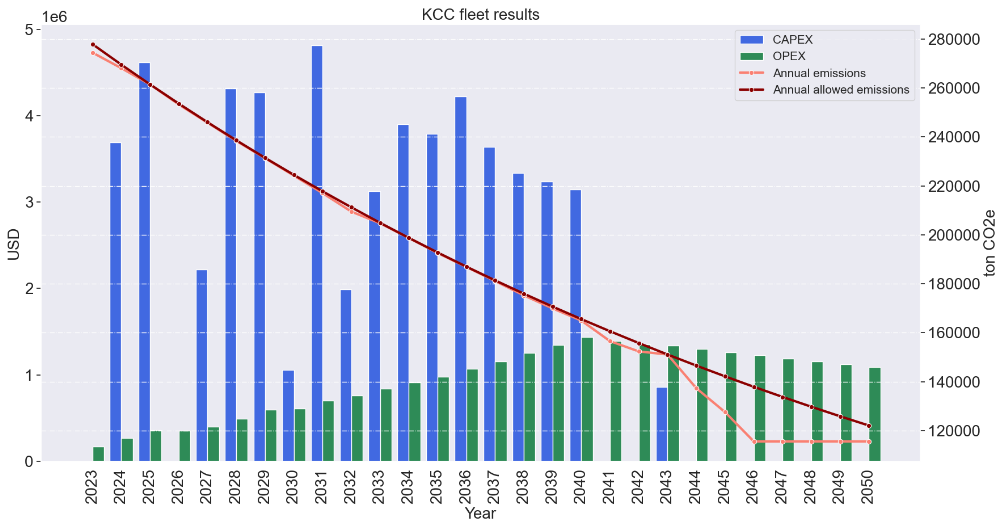


Figure 8.3: Case 1 results - Time Horizon

The results depicted in Figure 8.3 indicate the outcomes of installing specific retrofit options on vessels in a given year. Detailed information regarding the optimal timing and selection of retrofit options for each vessel — with the objective to adhere to the annual fleet emissions restrictions while minimizing associated costs — is provided in Table 21. For a comprehensive view, the table is made available in appendix Figure A8 in the form of an Excel sheet. It is evident that the retrofit options Flettner rotor and the propeller duct are the most attractive installations providing the most efficient fuel reduction per cost unit, as not before most of the vessels are fitted with either, retrofit options such as air lubrication, shaft generator, and electrical upgrades are installed.

It is worth noting that in certain years, multiple retrofit options are applied to some vessels, leading to a substantial decrease in their emissions. This might be beneficial for the ship owner, as simultaneous installations of several retrofits could utilize common personnel, equipment, expertise, and other resources, thereby potentially optimizing the retrofit process even further.

Year	Vessel(s)	Retrofit installation
2023	[-]	[-]
2025	Bantry	Flettner rotor, Propeller duct
	Bakkedal	Propeller duct
	Ballard	Propeller duct
2030	Ballard	Flettner rotor
	Bantry	New build
2035	Bangor	Flettner rotor
	Bakkedal	Flettner rotor, Electrical upgrade
	Baleen	Electrical upgrade
2040	Ballard	Hybrid
	Bakkedal	Hybrid
2045	Baleen	New build
	Bangus	New build
2050	[-]	[-]

Table 21: Case 1 results (2)

8.5.2 Carbon intensity index rating

Adopting the methodology delineated in Section 2.4 and deploying the associated equations, the CII ratings for specific vessels within Klaveness' fleet, namely Barcagena, Bantry, and Barramundi, can be computed. This procedure provides a key measurement of vessel efficiency, and the annual fuel consumption data, which factored in installed retrofits, played a central role in these calculations. The findings were as follows: in 2023, Barramundi and Barcagena received a CII rating of D, while Bantry was rated E. According to the criteria detailed in Section 2.4, any vessel that receives an E rating or a D rating for three consecutive years is required to formulate an emissions reduction plan to improve its rating to C or better. Therefore, action will be mandatory for Bantry. By 2024, Barramundi was outfitted with a Flettner rotor and a propeller duct, which lowered its CII rating to C. However, no measures were taken for Barcagena and Bantry. In 2025, Bantry had a Flettner rotor and a propeller duct installed, affecting its rating to D, while Barcagena's rating increased to E (action plan required) and Barramundi maintained a steady C. In the final year, 2026, Barcagena is replaced with a new build changing the CII rating to C, Barramundi receives a D, and Bantry's grade returns to E (second action plan required).

The primary objective of this optimization model is to maintain the fleet's emissions below the allowable limit while minimizing the total cost. Therefore, it does not adhere to the CII rating system and has not prioritized vessels with lower ratings. This limitation warrants further discussion, which is provided in Section 10.1.

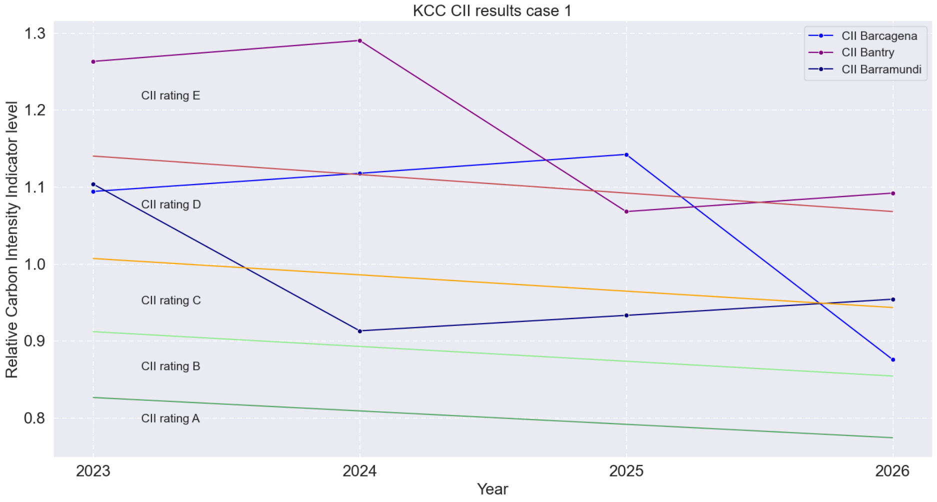


Figure 8.4: Case 1 CII rating

8.5.3 Economic analysis

Figure 8.5 delineates CAPEX and OPEX on the LHS y-axis, and VOYEX and ENVEX on the RHS y-axis. CAPEX is illustrated as bar plots while the other expenses are portrayed as line plots. The detailed individual presentations of OPEX, VOYEX, ENVEX, and the cumulative cost of all four components can be referred to in appendix Figure A9, Figure A10, Figure A11, and Figure A12, respectively.

The CAPEX bars and the OPEX line plot, recognizable from Figure 8.3, exhibit a consistent pattern. Notably, the VOYEX and ENVEX line plots, which are exclusively dependent on a vessel's fuel consumption and emissions respectively, display a marked correlation with the emissions line plot from Figure 8.3. These metrics depict an almost linear decline until the investments in additional retrofit options (CAPEX) cease, following which the rate of decrease moderates.

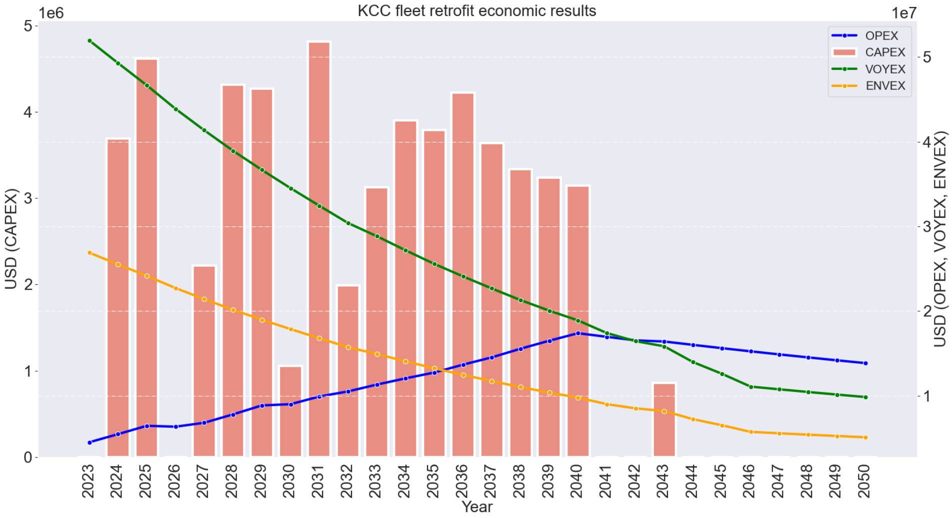
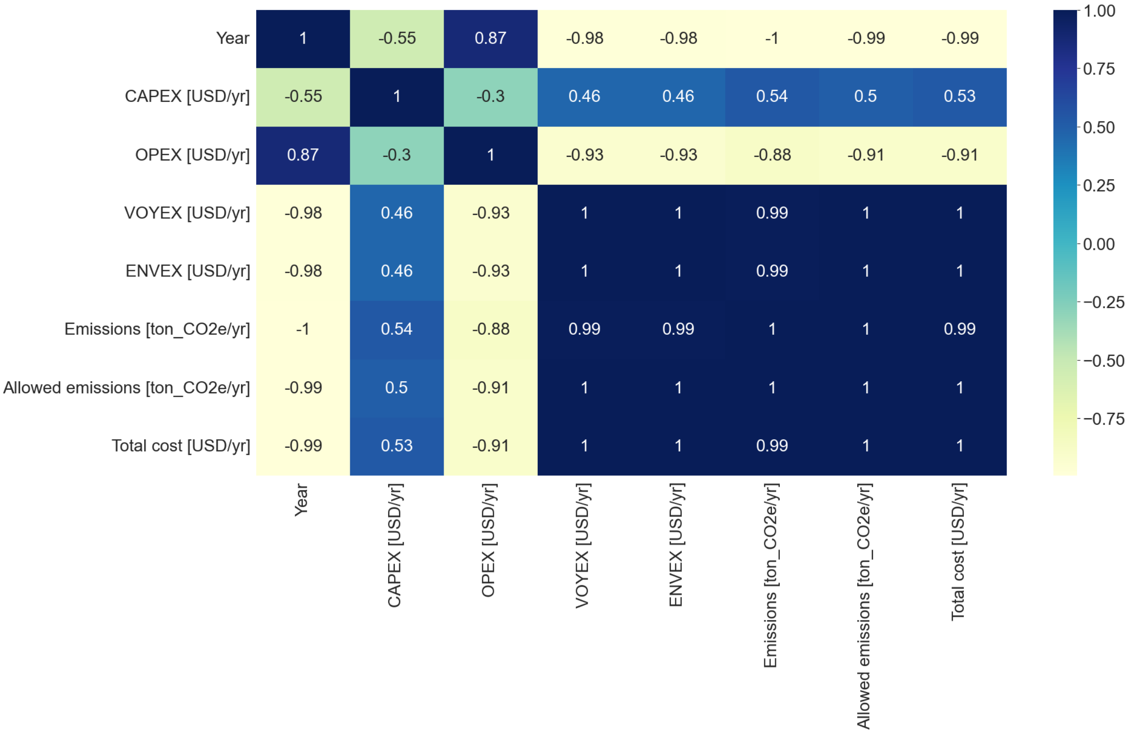


Figure 8.5: Case 1 economic results

8.5.4 Heatmap analysis

The resulting dataframe, encompassing information pertaining to costs, emissions, and time periods, is visually represented as a heatmap in Figure 8.6. A heatmap constitutes a graphical representation of data wherein matrix values are exhibited as colors. It enables the identification of patterns within the provided dataset, such as the detection of high and low values, and illuminates correlations or relationships between variables.

A value of 1 implies a strong correlation between two columns, and conversely. It is expected that VOYEX and ENVEX should have a strong correlation with the vessel's fuel consumption and emissions, which is corroborated by the heatmap, demonstrating correlations of 0.99 to 1. As shown in Figure 8.3, rising OPEX leads to a decrease in emissions, which is affirmed by a negative correlation of -0.91 between the two. The "Year" column exhibits either a positive or negative correlation of ±0.87 to ±1 with all other columns except CAPEX. While costs and emissions adjust annually, investments in retrofit options occur approximately half of the years in the time horizon, indicated by a correlation value of -0.55 between the "CAPEX" column and the rest.



	Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
Year	1	-0.55	0.87	-0.98	-0.98	-1	-0.99	-0.99
CAPEX [USD/yr]	-0.55	1	-0.3	0.46	0.46	0.54	0.5	0.53
OPEX [USD/yr]	0.87	-0.3	1	-0.93	-0.93	-0.88	-0.91	-0.91
VOYEX [USD/yr]	-0.98	0.46	-0.93	1	1	0.99	1	1
ENVEX [USD/yr]	-0.98	0.46	-0.93	1	1	0.99	1	1
Emissions [ton_CO2e/yr]	-1	0.54	-0.88	0.99	0.99	1	1	0.99
Allowed emissions [ton_CO2e/yr]	-0.99	0.5	-0.91	1	1	1	1	1
Total cost [USD/yr]	-0.99	0.53	-0.91	1	1	0.99	1	1

Figure 8.6: Case 1 heatmap

In appendix Figure A13, the clustermap with the same data as the heatmap as input is presented. A clustermap is a hierarchical clustering heatmap displaying both rows and columns of the data, clustered using a dendrogram algorithm (Java T Point [104]). Clustermaps are used to visualize clusters of similar rows and columns and to identify patterns of similarities and differences in the data. They can be used to visualize the correlation matrix and other types of data, such as gene expression data. While a heatmap is used to visualize patterns and correlations in a matrix of data, a clustermap provides a more detailed and hierarchical view of the data by clustering the rows and columns and displaying them using a dendrogram.

8.5.5 Analysis of retrofit counts

Table 22 presents the frequency of installation for each retrofit option within the fleet throughout the defined time horizon. The number of new builds reaches its maximum, as anticipated, given it constitutes the retrofit option yielding the most significant emission reduction and carries a zero cost from the retrofit perspective. The rationale behind this is that the expense associated with new builds is an unavoidable cost for KCC, irrespective of retrofitting activities, as detailed in Section 8.3. Similarly, the count for the installation of Flettner rotors is also maximized, indicating that by the end of the time horizon, every vessel in the fleet will be equipped with a Flettner rotor. Propeller duct, electrical upgrade, and hybrid retrofit options follow with 14, 11, and 10 installations, respectively. Further, the installation of air lubrication occurs only 3 times throughout the entire time horizon, and the shaft generator only 2. Scrubbers are never installed. However, as per initial values, the air lubrication system and the shaft generator are both installed twice beforehand of the time horizon.

Flettner rotor	Propeller duct	Hybrid	Electrical upgrade	Air lubrication	Shaft generator	Scrubber	New build
16	14	10	11	3	2	0	16

Table 22: Case 1 retrofit counts

8.5.6 Regression plot analysis

The regression plot elucidating the relationship between the total cost and total emissions of the fleet is presented in Figure 8.7. The regression plot exhibits an upward-sloping trend, indicative of a positive relationship between emissions and cost. However, the strength of this relationship appears to weaken as cost escalates. This might suggest a phenomenon of diminishing returns on cost-reduction efforts towards emission reduction. It is plausible to consider that the installation of additional retrofit options lowers fuel costs and, consequently, emissions taxes. While the initial costs accompany the installation of retrofit options, it appears that fuel and emissions-related costs supersede them. The illustration proposes that installations of retrofit options are both economically and environmentally beneficial for Klaveness' fleet for this case study.

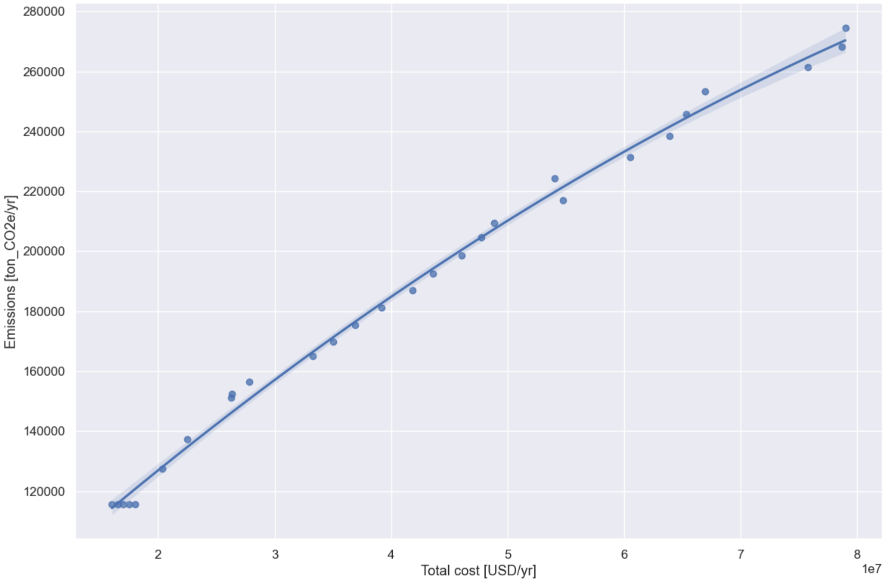


Figure 8.7: Case 1 linear regression

8.6 Case study 2: 4% annual emissions reduction

Case study 2 conforms to a yearly reduction in fleet emissions of 4%, by applying retrofit alternatives as detailed in Table 16 throughout the study period, in compliance with the constraints defined within the optimization model. This incremental strategy anticipates a significant decrease of 67% in emissions by 2050 when compared against the emission levels of 2022 for KCC's fleet.

8.6.1 Comprehensive results overview

Upon running the optimization model, it evaluates the annual emissions and associated costs stemming from the implementation of retrofit options. Moreover, it stipulates which ship should undergo retrofitting with a specific option during a particular year. Table 23 displays the economic outcomes and emissions statistics derived from the model, in conjunction with the yearly permissible total emissions. A comprehensive visualization of the findings is provided in appendix Figure A14, made available in an Excel format for further perusal.

Year	Total cost	Emissions	Allowed emissions
2023	79.0	274	278
2025	76.8	256	256
2030	51.6	209	209
2035	41.0	170	170
2040	30.6	139	139
2045	16.7	99	113
2050	12.9	87	92
Unit	$E6 \times \frac{\$}{year}$	$E3 \times \frac{tonCO_2e}{year}$	$E3 \times \frac{tonCO_2e}{year}$

Table 23: Case 2 results (1)

The illustration in Figure 8.8 depicts the economic and emissions results graphically. These metrics are calculated annually after each retrofit installed on each vessel. CAPEX and OPEX are both graphically presented as bars with their scale quantified on the LHS y-axis, portraying costs in million USD. The annual and allowed fleet emissions are portrayed on the RHS y-axis, scaled in ton CO_2e. It is evident that with an increase in CAPEX, OPEX inherently follows, due to the inherent rise in maintenance requirements that comes with an increased number of installed retrofit options. In the final third of the time horizon, there is a noticeable decrease in the number of investments in retrofit options and hence a drastic reduction in CAPEX costs. Following, the OPEX is steadily decreasing, due to the natural calculation of OPEX in NPV as of 2023. The drastic drop in the number of investments is a natural consequence of the fleet's vessels aging; a vessel reaching the age of 25 years old will be replaced with a new, similar vessel with the same retrofit options installed and a 25% lower emissions rate, as argued in the assumptions Section 8.3.

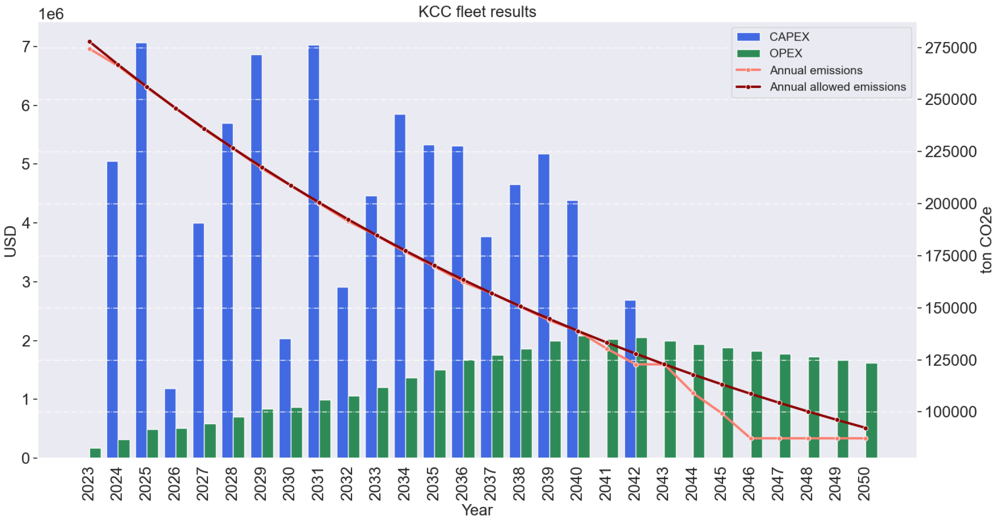


Figure 8.8: Case 2 results - time horizon

The result presented in Figure 8.8 arises from the strategic installation of retrofit options on specific vessels during particular years, as detailed in Table 24, with the aim of complying with the fleet's emission limits. A more exhaustive account, including the entire study period, is provided in appendix Figure A15 in an Excel format for further analysis. It becomes obvious that the Flettner rotor and the propeller duct emerge as the most viable retrofit options, offering the highest efficiency among the available choices. Almost only when the majority of the fleet's vessels are equipped with either of these options do other retrofit alternatives such as the shaft generator and air lubrication begin to be installed.

Year	Vessel(s)	Retrofit installation
2023	[-]	[-]
2025	Bantry	Flettner rotor, Propeller duct
	Bakkedal	Flettner rotor, Propeller duct
	Ballard	Flettner rotor, Propeller duct
2030	Bangor	Flettner rotor, Propeller duct
	Bantry	New build
2035	Bangor	Electrical upgrade
	Bakkedal	Electrical upgrade, Hybrid
	Ballard	Electrical upgrade, Hybrid
2040	Ballard	Air lubrication
	Bakkedal	Air lubrication
	Bangor	Air lubrication, Hybrid
2045	Baleen	New build
	Bangus	New build
2050	[-]	[-]

Table 24: Case 2 results (2)

8.6.2 Carbon intensity index rating

The CII for three specific vessels; Banastar, Ballard, and Baffin, has been calculated and graphically illustrated in Figure 8.9. The computation of CII constitutes a crucial assessment of a vessel's efficiency, taking into account the vessel's freight capacity and emissions influenced by the installed retrofit options. In the year 2023, both Ballard and Baffin are assigned a CII score of E, necessitating the development of an emissions reduction plan, while Banastar is designated a score of C. In 2024, Ballard retains the same score, whereas Baffin is upgraded to a score of D upon being equipped with a Flettner rotor. Banastar, similarly outfitted, is elevated to score A. In 2025, Ballard is fitted with a Flettner rotor and a propeller duct, resulting in a revised score of D. Baffin and Banastar are assigned scores of E (action plan required) and B respectively. In 2026, Banastar is replaced by a new vessel and upgraded to an A rating, while Ballard and Baffin are assigned scores of D and E respectively.

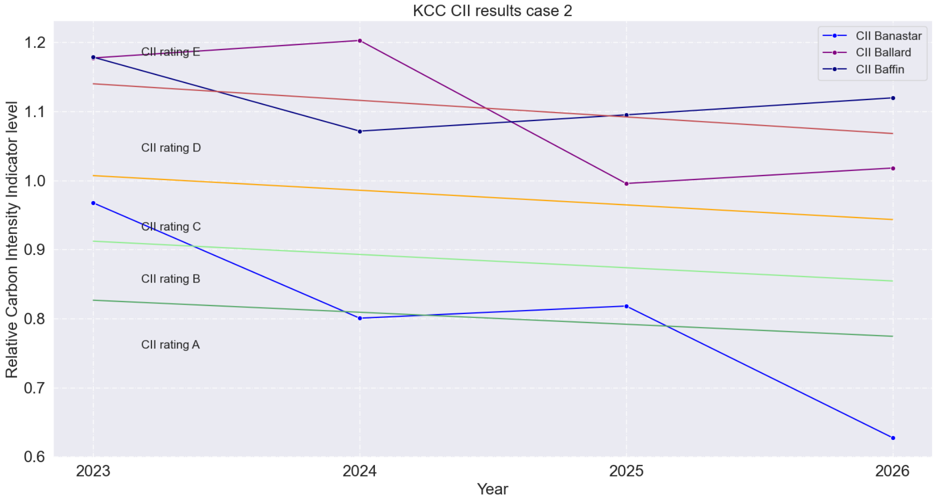


Figure 8.9: Case 2 CII rating

8.6.3 Economic analysis

In Figure 8.10, CAPEX and OPEX are depicted on the LHS y-axis, while VOYEX and ENVEX are demonstrated on the RHS. CAPEX is rendered as bar plots, while the others are represented as line plots. These along with the accumulated total cost are separately displayed in appendixFigure A16, Figure A17, Figure A18, and Figure A19, for detailed examination.

The patterns evident in the CAPEX and OPEX plots, as seen in Figure 8.8, display remarkable consistency. Likewise, the line plots for VOYEX and ENVEX accurately mirror the emissions line plot in Figure 8.8. Given that both metrics are heavily influenced by a vessel's fuel consumption and consequent emissions, this graphical representation is deemed fitting. Both line plots exhibit a nearly linear decrease in the first two-thirds of the study period but flatten considerably as the number of retrofit investments begins to decline. This further underlines the profound correlation between retrofit investments and their impact on a vessel's fuel consumption and emissions.

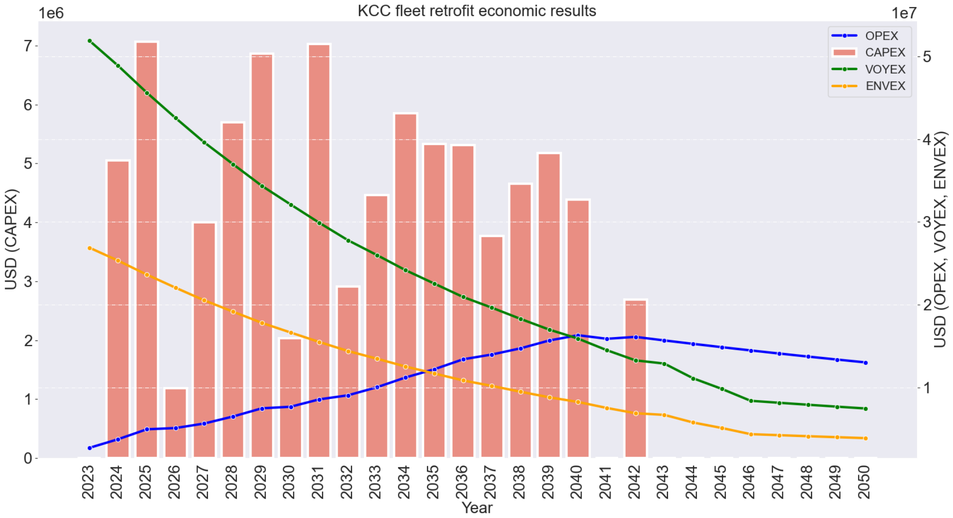
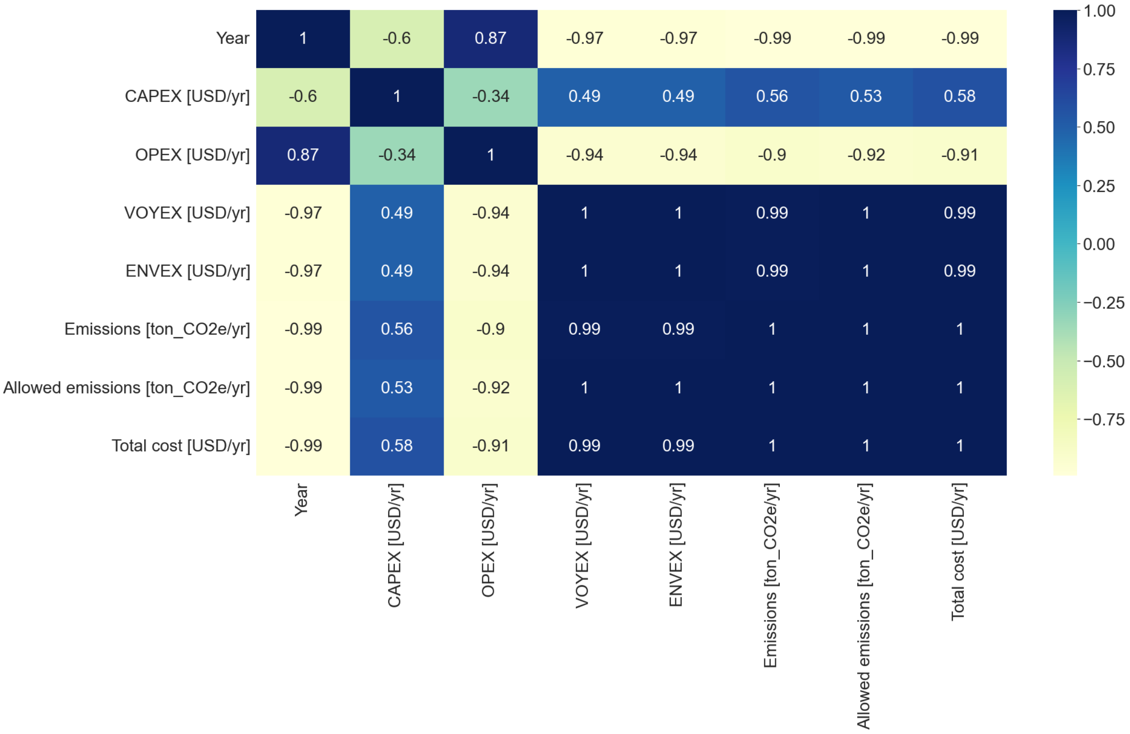


Figure 8.10: Case 2 economic results

8.6.4 Heatmap analysis

The constructed dataframe, incorporating information related to costs, emissions, and temporal periods, is visually represented as a heatmap in Figure 8.11. It is anticipated that environmental and fuel-related expenditures (VOYEX and ENVEX) would have a strong correlation with a vessel's emissions, which are directly tied to its fuel consumption and hence emissions. This is manifested in the correlation between the fleet's allowable and actual emissions, as well as the environmental costs, ranging from 0.99 to 1.0. As portrayed in Figure 8.10, an increase in OPEX leads to a reduction in emissions and environmental costs, denoted by values fluctuating between -0.9 and -0.94. While every attribute experiences change with each time step, denoted by the "Year" column equating to nearly ±1.0 for every attribute, CAPEX is only influenced by approximately half of the time period. This is represented by its average correlation of about 0.5 with each of the other attributes.



	Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
Year	1	-0.6	0.87	-0.97	-0.97	-0.99	-0.99	-0.99
CAPEX [USD/yr]	-0.6	1	-0.34	0.49	0.49	0.56	0.53	0.58
OPEX [USD/yr]	0.87	-0.34	1	-0.94	-0.94	-0.9	-0.92	-0.91
VOYEX [USD/yr]	-0.97	0.49	-0.94	1	1	0.99	1	0.99
ENVEX [USD/yr]	-0.97	0.49	-0.94	1	1	0.99	1	0.99
Emissions [ton_CO2e/yr]	-0.99	0.56	-0.9	0.99	0.99	1	1	1
Allowed emissions [ton_CO2e/yr]	-0.99	0.53	-0.92	1	1	1	1	1
Total cost [USD/yr]	-0.99	0.58	-0.91	0.99	0.99	1	1	1

Figure 8.11: Case 2 heatmap

8.6.5 Analysis of retrofit counts

Table 25 presents the frequency of retrofit option installations across the fleet throughout the defined study period. The count of new builds and installations of the Flettner rotor, propeller duct, electrical upgrades, and hybrid systems reach their maximum and are applied to every vessel in the fleet. Moreover, the air lubrication system and shaft generator are installed 12 and 3 times, respectively, of which two of each installation is done in beforehand of the time horizon. The scrubber is never installed. It is not unexpected that the count of new builds is maximized, given it is the most "efficient" retrofit option in terms of emissions and cost. Conversely, the air lubrication system and the shaft generator appear to be less appealing options for model implementation within the fleet.

Flettner rotor	Propeller duct	Hybrid	Electrical upgrade	Air lubrication	Shaft generator	Scrubber	New build
16	16	16	16	12	3	0	16

Table 25: Case 2 retrofit counts

8.6.6 Regression plot analysis

The regression plot illustrating the correlation between the fleet's total cost and its emissions is displayed in Figure 8.12. The plot exhibits an almost linear upward trend, indicating a positive relationship between the fleet's cost and emissions. However, this relationship appears to weaken as the cost increases, suggesting diminishing returns on investment in cost-reduction efforts geared towards emissions reduction. This means that installing retrofit options not only reduces the fleet's total costs by offsetting fuel and emissions-related expenses but also lowers the fleet's total emissions and associated costs. This suggests that retrofit option installations are advantageous both economically and environmentally for KCC's fleet for this case study.

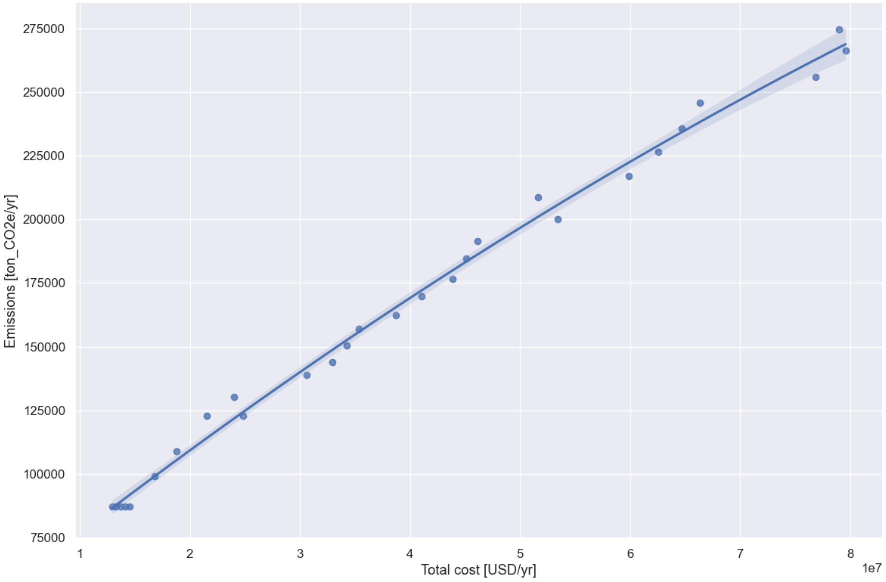


Figure 8.12: Case 2 linear regression

8.7 Case study 3: 5% annual emissions reduction

Case study 3 respects an annual fleet emissions reduction of 5%, installing retrofit options detailed in Table 16 throughout the time horizon respecting the constraints set within the optimization model. The 5% annual emissions decrease from 2022 to 2050 suggests a total of 75% less emissions for the respective fleet.

8.7.1 Comprehensive results overview

Upon execution, the optimization model ascertains the yearly emissions and the associated costs induced by the application of the retrofit options and designates the appropriate vessel for the installation of a specific retrofit option at a given time. Table 26 illustrates the economic results and emissions data generated by the model, in tandem with the allowable total emissions. A more comprehensive depiction of the results can be found in appendix Figure A21 in an Excel format for detailed inspection.

Year	Total cost	Emissions	Allowed emissions
2023	79.0	274	278
2025	76.7	251	251
2030	50.5	194	194
2035	37.8	150	150
2040	30.3	116	116
2045	14.0	76	90
2050	10.6	64	69
Unit	$E6 \times \frac{\$}{year}$	$E3 \times \frac{tonCO_2e}{year}$	$E3 \times \frac{tonCO_2e}{year}$

Table 26: Case 3 results (1)

Figure 8.13 provides a graphical representation of economic and emissions results. These values are computed annually following the installation of each retrofit on every vessel. Both CAPEX and OPEX are visually displayed as bars, their scale determined on the LHS y-axis, signifying costs in million USD. The annual and permissible emissions of the fleet are plotted on the RHS y-axis, scaled in ton CO_2e. As CAPEX rises, an associated increase in OPEX is apparent, a natural result of the growth in maintenance needs accompanying a rise in retrofit installations. In the final third of the study period, there is a noticeable drop in retrofit investments, leading to a significant reduction in CAPEX costs. Consequently, OPEX exhibits a steady decline due to the inherent calculation of OPEX in NPV starting from 2023. The sharp fall in investment count can be attributed to the aging of the fleet's vessels. When a vessel reaches the age of 25 years, it will be replaced by a new, similar vessel equipped with the same retrofit options but exhibiting a 25% lower emissions rate, as outlined in the assumptions Section 8.3.

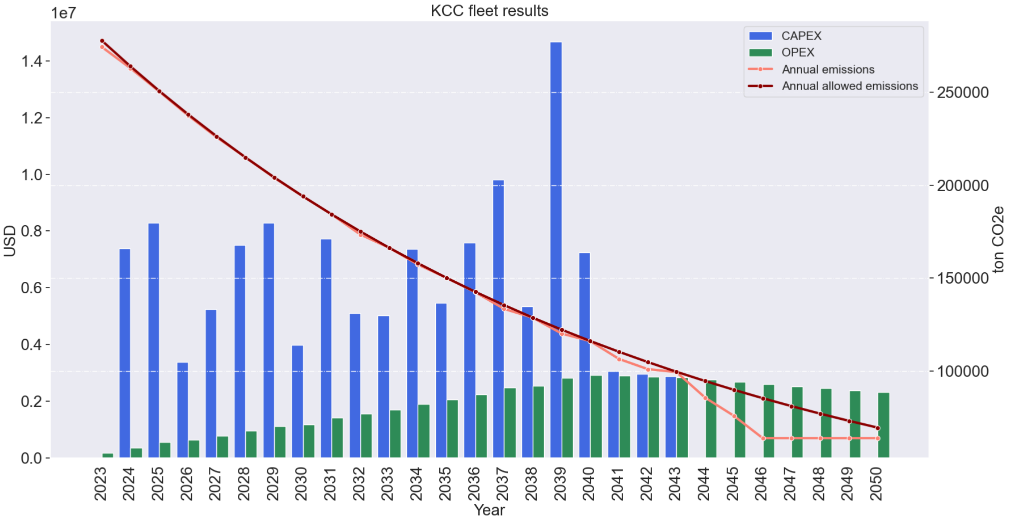


Figure 8.13: Case 3 results - time horizon

The outcome showcased in Figure 8.13 is due to the careful placement of retrofit options on certain vessels during specific years. This is detailed in Table 27, all with the objective of sticking to the emission restrictions set for the fleet whilst minimizing the total costs. A more thorough rundown including the entire time frame is provided in appendix Figure A22, available in an Excel format for deeper inspection. It is clear from the results that the Flettner rotor and the propeller duct stand out as the top retrofit options, delivering the best efficiency among all options. It is only when most vessels in the fleet are fitted with one or the other that other retrofit options, like the shaft generator and air lubrication, start getting installed.

Year	Vessel(s)	Retrofit installation
2023	[-]	[-]
2025	Bantry	Flettner rotor, Propeller duct
	Bakkedal	Flettner rotor, Propeller duct
	Ballard	Flettner rotor, Propeller duct
	Baleen	Flettner rotor
2030	Bangor	Flettner rotor, Electrical upgrade, Propeller duct
	Bantry	New build
	Bakkedal	Electrical upgrade
	Ballard	Electrical upgrade
2035	Bangor	Hybrid
	Ballard	Hybrid
2040	Ballard	Scrubber, Shaft generator
	Bakkedal	Scrubber
	Bangor	Air lubrication
2045	Baleen	New build
	Bangus	New build
2050	[-]	[-]

Table 27: Case 3 results (2)

8.7.2 CII rating

The CII for three specific vessels - Bakkedal, Balboa, and Balzani, is computed and displayed graphically in Figure 8.14. The CII delivers an essential measure of a vessel's efficiency, factoring in its cargo capability and emissions output. In 2023, Bakkedal and Balboa both receive a CII score of E, necessitating an emissions reduction plan, while Balzani secures a C rating. In 2024, Balboa receives a Flettner rotor retrofit and is given a CII score of D, whereas Bakkedal remains stable and Balzani's score drops to D. In 2025, Bakkedal is equipped with a Flettner rotor and a propeller duct, receiving a CII score of D, while Balboa's rating drops to E (action plan required) and Balzani remains at D. By 2026, Balzani gets a Flettner rotor and a propeller duct, boosting its CII score to C, Balboa receives a propeller duct earning a score of D, and Bakkedal reverts to a CII score of E.

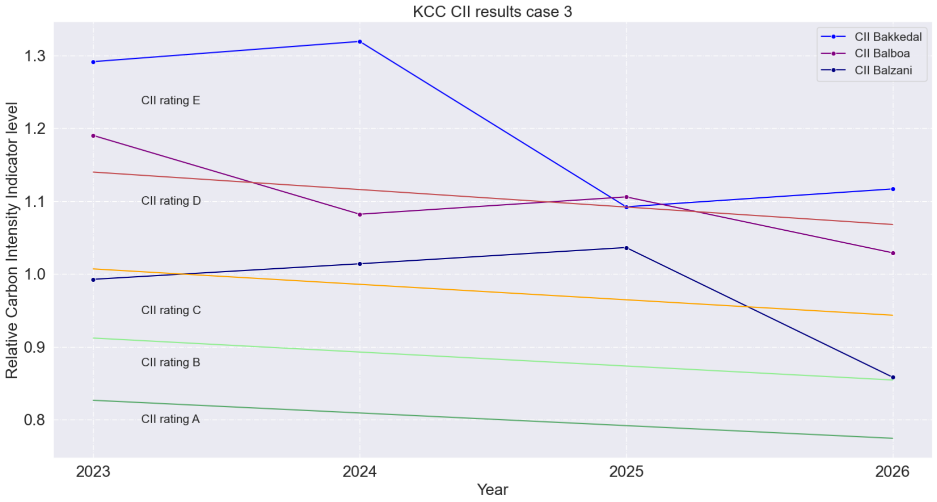


Figure 8.14: Case 3 CII rating

8.7.3 Economic analysis

In Figure 8.15, CAPEX and OPEX are illustrated on the LHS y-axis, with VOYEX and ENVEX on the RHS. CAPEX is depicted as bar plots while the others are presented as line plots. Each of these, along with the total accumulated cost, are individually showcased in appendix Figure A23, Figure A24, Figure A25, Figure A26 for in-depth exploration.

The CAPEX and OPEX plots, as seen in Figure 8.13, exhibit a consistent trend depicted in Figure 8.15. The line plots for VOYEX and ENVEX similarly mimic the emissions line plot in Figure 8.13. As both metrics are closely tied to the vessel's fuel consumption and resultant emissions, the graphic representation proves to be apt. Both line plots show an almost linear reduction in the first two-thirds of the time span, which notably levels off as retrofit investments start to decrease. This underlines the strong correlation between retrofit investments and their effects on a vessel's fuel consumption and emissions.

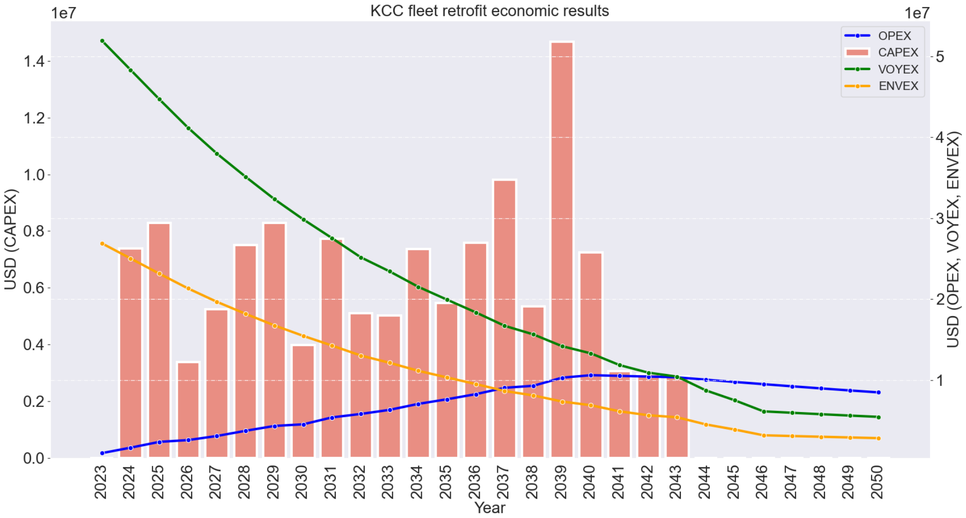
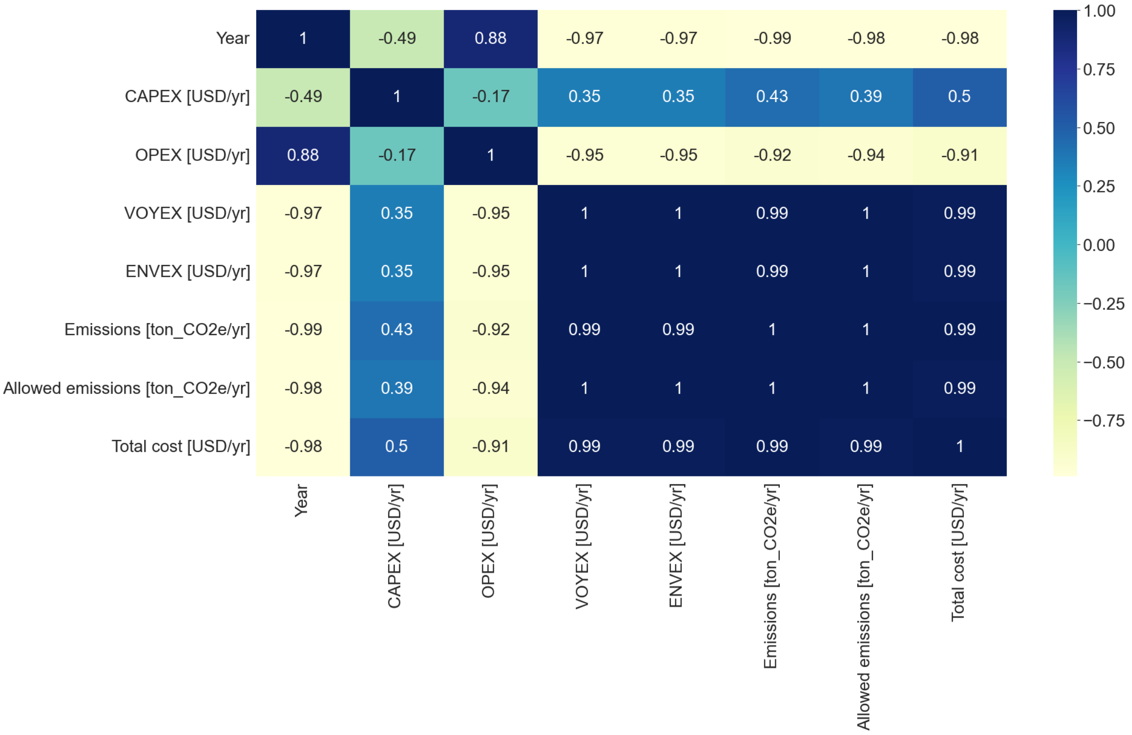


Figure 8.15: Case 3 economic results

8.7.4 Heatmap analysis

The created dataframe, which packs together information about costs, emissions, and time periods, is shown as a heatmap in Figure 8.16. The environmental and fuel-related costs (VOYEX and ENVEX) are naturally closely tied to a vessel's emissions, as these are directly connected to its fuel consumption. This becomes evident in the strong correlation between the fleet's allowed and actual emissions, and the environmental costs, ranging from 0.99 to 1.0. As shown in Figure 8.15, when OPEX goes up, emissions and environmental costs drop, with values between −0.92 and −0.95. Although every parameter changes with each time step, the "Year" column is close to ±1.0 for every attribute - CAPEX only really changes for about half of the time periods. This is presented by its average correlation of about 0.5 with each of the other attributes.



	Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
Year	1	-0.49	0.88	-0.97	-0.97	-0.99	-0.98	-0.98
CAPEX [USD/yr]	-0.49	1	-0.17	0.35	0.35	0.43	0.39	0.5
OPEX [USD/yr]	0.88	-0.17	1	-0.95	-0.95	-0.92	-0.94	-0.91
VOYEX [USD/yr]	-0.97	0.35	-0.95	1	1	0.99	1	0.99
ENVEX [USD/yr]	-0.97	0.35	-0.95	1	1	0.99	1	0.99
Emissions [ton_CO2e/yr]	-0.99	0.43	-0.92	0.99	0.99	1	1	0.99
Allowed emissions [ton_CO2e/yr]	-0.98	0.39	-0.94	1	1	1	1	0.99
Total cost [USD/yr]	-0.98	0.5	-0.91	0.99	0.99	0.99	0.99	1

Figure 8.16: Case 3 heatmap

8.7.5 Analysis of retrofit counts

The frequency of retrofit installations across the fleet during the study period is shown in Table 28. New builds and installations of the Flettner rotor, electrical upgrades, air lubrication, and scrubber systems are all maxed out and are installed on every vessel in the fleet. The propeller duct, hybrid system, and shaft generator are installed 15, 15, and 14 times, respectively. Naturally, with the requirement of an annual 5% emissions reduction for the fleet, almost every vessel will be required to be outfitted with almost every option available. The air lubrication and the shaft generator are both pre-installed twice before the time horizon in the fleet.

Flettner rotor	Propeller duct	Hybrid	Electrical upgrade	Air lubrication	Shaft generator	Scrubber	New build
16	15	16	15	16	16	14	16

Table 28: Case 3 retrofit counts

8.7.6 Regression plot analysis

Figure 8.17 shows a regression plot representing the relationship between the total cost of the fleet and its emissions. The plot shows an almost perfect linear upward trend, which suggests a positive relationship between the fleet's cost and emissions. This relationship never seems to either weaken or be strengthened as the cost goes up, suggesting a steady return on efforts to reduce costs and, in turn, emissions. It suggests that installing retrofit options, which reduce the total fleet costs as fuel and emissions-related costs are balanced by installation costs, also lowers the fleet's total emissions and costs. This means retrofit installations can be a win-win, economically and environmentally for KCC's fleet for this case study.

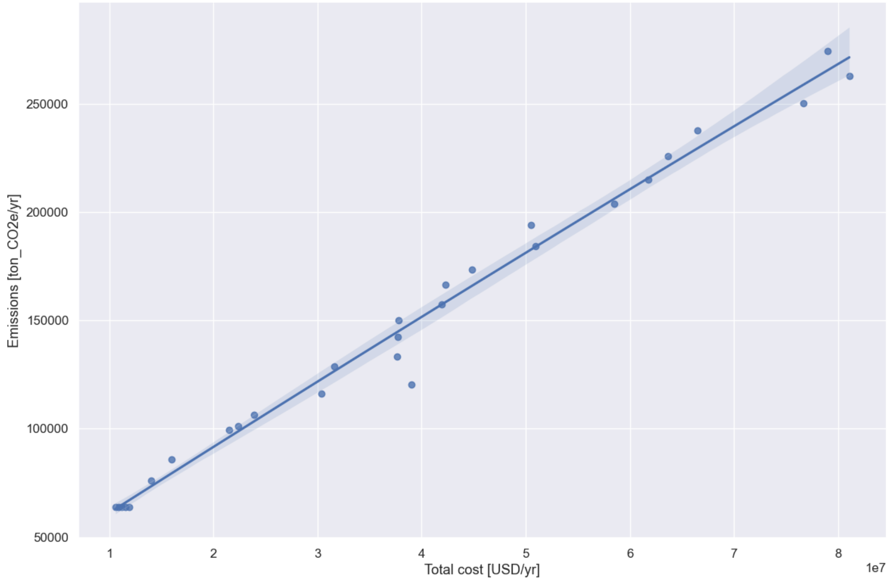


Figure 8.17: Case 3 linear regression

8.8 Case studies summation

The three case studies respecting an annual emissions reduction rate of 3%, 4%, and 5% respectively have been outlined and their results presented. It becomes evident that the model with the provided dataset is able to find an optimal and feasible solution for all three narratives, deciding when each vessel in the fleet should be retrofitted with which retrofit option, as well as calculating annual emissions and costs for each. Each case study proves itself to be both an economically and environmentally beneficial action plan for KCC's fleet. However, by targeting the emissions reduction rate at 6%, the model is unable to locate a feasible solution and returns the fleet untouched by retrofit options with unaltered emissions and costs. For the fleet to adhere to stricter emissions requirements than for case 1, 2, or 3, other options must be evaluated, for instance, alternative retrofit options or a complete upgrade of the propulsion system, including implementation of alternative fuels, discussed in Section 4.1.

9 Discussion: Retrofitting a deep sea shipping fleet

The decision of when which vessel in a vessel fleet shall be retrofitted with a specific retrofit option, is a complex study for any shipowner striving towards lower emissions for their fleet as well as minimizing their total costs. However, gathering a vast amount of data and evaluating several aspects of the problem, is an important path towards making the decisions.

This section discusses the reasons and drivers for a less-emitting and more efficient worldwide shipping fleet, followed by retrofitting possibilities for the shipping company Torvald Klaveness' fleet for complying with future emissions regulations set by regulatory drivers. Three scenarios with respect different to annual emissions reduction are carried out in the thesis and will be analyzed and compared for the intention of being able to set a goal for Klaveness as a pioneering and forthcoming shipping company, obtaining great focus on reducing their emissions and operating a highly efficient fleet. How the fleet's barriers and opportunities can be used to increase the interest for retrofitting of a fleet's vessels with other, similar shipping companies, will also be discussed. Before comparing the three case study results, a sensitivity analysis of the model developed for this thesis is carried out, to obtain an idea of how trustworthy the economic and environmental results are.

9.1 Sensitivity analysis of the model

As discussed in Section 8.3, several assumptions have been made throughout this thesis and study, some of which substantially affect the results of the optimization study. To investigate the robustness of the found optimal solution, several scenarios have been studied where input parameters have been altered and compared to the original input, hereby referred to as the base case.

9.1.1 Alternations in retrofit parameters

The parameters containing data for installation and operation cost as well as fuel reduction potential for each retrofit found in Section 5.4, were gathered from extensive internet research and will with all probability deviate from real-world values. Hence, it would be beneficial to test the model for different extremes of the input variables. The model is therefore tested for all three cases with the retrofit options values altered ±10% to create an *optimistic* and a *pessimistic* scenario. Optimistic refers to the installation costs being lowered and the fuel reduction potential being increased by 10% respectively, and vice versa for the pessimistic view. The results for the *pessimistic*, *normal*, and *optimistic* scenarios are presented in Table 29, where the *normal* values are the values from the original dataset presented in Section 8.2. The total fleet's emissions and its total cost are calculated for the total time period of 2023 to 2050.

Case		Pessimistic	Optimistic	Unit	Deviation from normal
Case 1	$\sum$ Emissions	5.227	5.174	E^6 ton CO_2e	(+0.51%, -0.51%)
	$\sum$ Total costs	1.211	1.156	E^9 USD	(+2.64%, -2.03%)
Case 2	$\sum$ Emissions	4.648	4.602	E^6 ton CO_2e	(+0.47%, -0.51%)
	$\sum$ Total costs	1.172	1.082	E^9 USD	(+4.97%, -3.01%)
Case 3	$\sum$ Emissions	7.781	4.104	E^6 ton CO_2e	(+88.62%, -0.51%)
	$\sum$ Total costs	1.543	1.024	E^9 USD	(+42.08%, -5.71%)

Table 29: Alternations in retrofit parameters pessimistic and optimistic view

For the three cases, the accumulated emissions and total cost over the time horizon are calculated, for the pessimistic and the optimistic scenario. The accumulated results are compared to the values from the original dataset to calculate the deviation. For the pessimistic case 1 and 2, the fleet's accumulated emissions were only increased by $\sim 0.5\%$, and the costs between 2.5 and 5%, approximately. Likewise for the optimistic narrative for all three cases, only a $\sim 0.5\%$ emissions decrease and 2 to 5.7% economic decrease. However, an interesting find is for the pessimistic narrative for case 3, the optimization model could not find a feasible solution and returned the fleet and time horizon without any retrofit options installed and an unaltered fleet. In other words, with a 10% increase in installation costs and reduction in fuel reduction factor, the model cannot find any feasible solution. It is important to note that the only actual constrain the model is required to handle in this case, is the requirement of an annual 5% emissions reduction for the fleet, whilst it is only ordered to minimize the fleet's total cost, but does not obtain any form of retrofit installation budget or such. So naturally, an optimistic view of lower costs and more fuel reduction will obtain a feasible solution.

Observing the narratives with feasible solutions, a 10% increase or reduction in the retrofit parameters will only affect the emissions by half a percentage point due to the nature of the model only striving for respecting the emissions restrictions set for the fleet. However, the costs will fluctuate up to about ten-fold the percentage value and are affected significantly heavier. Although the emissions do not get heavily affected, the number of combinations of retrofit options installed is somewhat altered. The retrofit installation combination for the optimistic narrative for case 3 is shown in appendix Figure A28, for comparison.

To summarize, the alternation of retrofit cost and emissions-reducing parameters will not affect the model significantly, as the model is designed to only reduce the fleet's emissions to a constant value every year, and will try to maximize its allowed emissions rate, whilst also minimizing the fleet's total cost.

9.1.2 Alternations in economic parameters

The fuel price used in the optimization model is set to be constant throughout the time horizon, which in reality is highly unlikely. The fuel price can fluctuate up to several percentage points every day, and will additionally most likely increase in the coming years due to stricter emissions-related regulations and the international goal of moving away from fossil fuel. Moreover, the CO_2 tax is also set to be constant throughout the time horizon, which is just as unlikely. The tax will with all probability increase steadily over time to reflect the same arguments as for higher fossil fuel prices. The optimization model is therefore tested for two new scenarios; *increased fuel prices and* CO_2 *taxes* by 20% (strict), and *significantly increase in fuel prices and* CO_2 *taxes* by 40% (very strict), to reflect the possible narrative of fossil fuel being restrained and heavily restrained, respectively.

Case		Strict	Very strict	Unit	Deviation from normal
Case 1	$\sum$ Emissions	5.201	5.200	e^6 ton CO_2e	(±0.00%, −0.01%)
	$\sum$ Total costs	1.399	1.619	e^9 USD	(+18.60%, +37.19%)
Case 2	$\sum$ Emissions	4.626	4.626	e^6 ton CO_2e	(±0.00%, ±0.00%)
	$\sum$ Total costs	1.316	1.515	e^9 USD	(+17.82%, +35.63%)
Case 3	$\sum$ Emissions	4.125	4.126	e^6 ton CO_2e	(±0.00%, +0.01%)
	$\sum$ Total costs	1.267	1.448	e^9 USD	(+16.65%, +33.30%)

Table 30: Alternations in economic parameters strict and very strict view

With increasing fuel prices and CO_2 taxes, both 20% and 40%, the variation in the accumulated fleet's emissions are negligible, whilst the costs are increased by an approximate average of 17% and 35%, remarkably close to the cost increase values. As for the above sensitivity analysis, due to the nature of the model, it has got no incentive for lowering the emissions even further, only keeping them within bounds, whilst minimizing the costs. This reflects how much of the fleet's total cost is dependent on the fuel cost and emissions taxes, emphasizing the importance of reducing the fleet's total fuel consumption and emissions.

In sum, alternating fuel costs and emissions taxes affect the fleet's emissions rate a negligible amount, but will however increase the fleet's total cost almost proportional to the cost increase, proving the weight of the fuel cost and emissions taxes for the total cost of the fleet.

9.2 Comparison of case study results

In this thesis, an in-depth analysis of three emissions cases is conducted, each representing a different annual emissions reduction target - 3%, 4%, and 5% - for Klaveness Combination Carrier's vessel fleet. The focus of this comparison is to expose the effects of these three scenarios on the reduction in costs and emissions associated with each.

9.2.1 Case 1: 3% Annual Emissions Reduction

In the first scenario, targeting a 3% annual reduction in emissions, it was found that the total cost of the fleet throughout the whole time horizon including everything in between installation costs and emissions taxes, accumulating to 1.18 billion USD, was the highest among the three cases. Likewise for the accumulated emissions of the fleet: 5.20 million tons CO_2e. This suggests that under a relatively moderate emissions reduction target, the associated costs of retrofitting and other necessary alterations to the fleet operations were not significantly offset. Thus, the net savings in terms of costs were significant, the fleet has greater potential.

9.2.2 Case 2: 4% Annual Emissions Reduction

The second case, targeting a 4% annual reduction in emissions, showed a slightly more cost reduction compared to the first case. Total costs throughout the time horizon summarize to 1.12 billion USD, and emissions to 4.63 million tons CO_2e. This implies that a more aggressive emissions reduction target can lead to more substantial cost savings, despite necessitating additional, more extensive, or more costly retrofitting options. The reasons for this may be multifaceted, and could potentially include increased fuel efficiency, reduced penalties or charges associated with emissions, and others.

9.2.3 Case 3: 5% Annual Emissions Reduction

The third and final case set an even more ambitious target of a 5% annual reduction in emissions. Accumulated costs over the time horizon equal to 1.09 billion USD, whilst emissions to 4.13 million tons CO_2e. Excitingly, this case resulted in the greatest reduction in total costs and emissions among all three scenarios. The biggest driver behind this larger cost reduction is by all accounts greater fuel efficiency, hence larger reductions in emissions-related charges and lower fuel costs. Further, this may lead to potential benefits associated with enhanced environmental and technological reputation.

9.2.4 Comparison

A summation of the emissions and cost data for the three cases is presented in Table 31. It becomes evident, that a stricter emissions policy, forcing the fleet owner to reduce its emissions even further, actually is economically beneficial, as well as environmentally. The graphical representation of the outcomes of the three cases is displayed in Figure 9.1 with costs depicted on the LHS y-axis, and total emissions on the RHS. The comparison reveals a trend of increasing cost reductions with higher emissions reduction targets. However, it is critical to recognize the potential complexities and uncertainties that underlie these findings. As the ambition of the emissions reduction target increases, so too may the required upfront investment and operational changes. A comprehensive understanding of these trade-offs is essential for effective decision-making.

	Case 1	Case 2	Case 3	Unit
$\sum$ Emissions	5.20	4.63	4.13	$E6\times$ tons CO_2e
$\sum$ Total cost	1.18	1.12	1.09	$E9\times$ USD

Table 31: Case 1, 2, and 3, emissions and total cost comparison

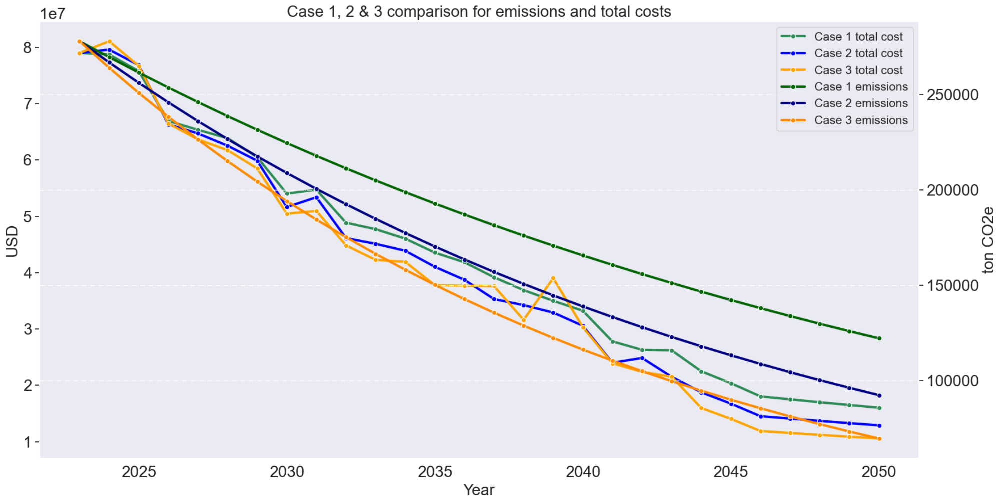


Figure 9.1: Emissions and total costs comparison of case 1, 2, & 3

The results depicting all three cases of economic and emissions results (Figure 8.3, Figure 8.8 and Figure 8.13), all show noticeable similarities and almost mirror each other's behavior. For all of them, in the first two-thirds, the investment rate in retrofit options is quite high, pushing up the CAPEX and OPEX. Following the remaining time horizon, the number of investments dabber heavily off, followed by a drastic drop in CAPEX, and stagnation of OPEX, slowly dropping due to it being calculated as NPV. Conversely, the fleet's emissions steadily decrease with investments made in the first two-thirds, before they drop even more drastically in the last third. The last third of the time horizon with respect to both costs and emissions, acting in the abnormal way that they are, is due to the natural aging of the fleet's vessels. At age 25, every vessel is replaced with a new one, 25% more efficient, as argued in Section 8.3. In that specific time horizon, a vast amount of the fleet's vessels are of age and will be replaced. Even though KCC's fleet is within its emissions restrictions, it does not mean they should hold off with investments in emissions-reducing measures. This is of course an assessment required to be carried out by KCC, where past investments and their effects on the fleet's environmental footprint and economic results should play a major role in the evaluations made. As for the optimization model, its goal is to keep the fleet respecting its restrictions, whilst minimizing costs related to retrofitting, and therefore does not push the costs higher to reduce emissions even further.

The quantity each retrofit option is installed within the fleet for the three respective cases is depicted in Figure 9.2, presenting the popularity of each. It is evident that besides new builds which obviously are maxed out for every case, the Flettner rotor, the propeller duct, the hybrid solution, and the electrical upgrade, are the most attractive retrofit options. The air lubrication system, the shaft generator, and the scrubber are all less attractive options with the scrubber only being installed in case 3. Furthermore, for all options in case 3, every retrofit option is almost maxed out with the exception of three, highlighting the extreme demand a 5% annual emissions reduction is for the fleet. This highlights the case study results, evaluating the dataset accounting for 6% annual reduction to not obtain a feasible solution. This scenario would require more powerful retrofit options or a larger pool of options for this specific model.

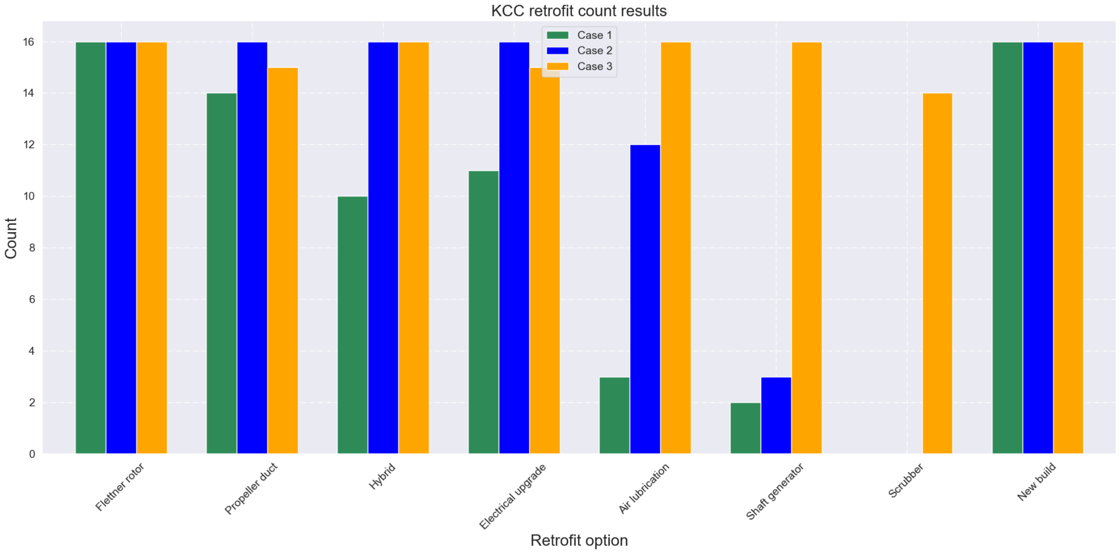


Figure 9.2: KCC retrofit counts

As for the carbon intensity index rating of three randomly selected vessels out of 16, for all three narratives, no conspicuous case led to better ratings for the vessels than another. Through all three cases, all three vessels are rated quite poorly, often above a CII rating of *D* or *E*, and will be required to come up with an emissions-reducing action plan. As pointed out, the optimization model presented in Section 7.3 does not account for the CII rating of the individual vessels when optimizing the fleet with retrofit options, and therefore ”allows” every vessel to acquire a poor rating. Further, the economic analysis analyzing the CAPEX, OPEX, VOYEX, and ENVEX of the fleet in the given time horizon, is remarkably similar in the plot's shape and figure for all cases. The three cases mirroring each other in their results also become oblivious in the heatmap and linear regression plots, where every attribute in the resulting dataframe has very similar correlations with one another, as well as the upward sloping almost linear regression plot expressing the positive correlation between the cost of the fleet and its total emissions. However, in the retrofit counts bar plots, it comes to show that neither of the three cases installs the same amount of retrofit options, with the exception of the Flettner rotor and hybrid for cases 2 and 3, and not even the same percentage of each option with respect to the available. The installation ratio of every option does not follow any logical pattern other than increasing the number of installations with increasing annual emissions reduction.

To sum up, while all three cases showed a reduction in costs alongside emissions, the extent of cost reduction was noticeably higher in the cases with more ambitious emissions reduction targets. This highlights the potential financial benefits that can be gained in addition to environmental when implementing more rigorous emissions reduction strategies within the vessel fleet.

9.3 Background theory and regulatory constraints

In light of the escalating urgency of addressing climate change, numerous regulatory bodies including the International Maritime Organisation, the European Union, and also KCC's internal policies, have established ambitious emissions reduction targets for the years 2030 and 2050. These goals necessitate significant emission reductions from maritime operations, imposing a tangible pressure on the industry to transform its practices. As delineated earlier, the IMO has outlined a target to curtail the maritime shipping industry's total emissions by 40% by 2030 and 70% by 2050, compared to 2008 levels. Meanwhile, the EU has mandated a 55% reduction in net greenhouse gas emissions by 2030 compared to 2008 levels and reaching net zero emissions by 2050. KCC, in an effort to contribute positively towards this industry-wide transformation, has set an internal target of a 35% reduction in emissions by 2030 compared to their 2018 levels and aspires to reach net zero emissions by 2050.

While direct comparisons between the EU's and KCC's 2030 emissions targets are not completely analogous due to their difference in baseline comparison year, it is feasible to estimate KCC's emissions reduction from the beginning of the model's time horizon. By 2030, for cases 1, 2, and 3, the fleet - after the execution of retrofit installations - has achieved a total reduction in CO_2e emissions by 18%, 24%, and 30% respectively, compared to 2022 levels. This shows promising results with respect to the IMO's and the EU's 2030 goals, only with different base years. By 2050, these cases have culminated in emissions reductions of 58%, 68%, and 77% respectively. The comparison of these three narratives is succinctly summarized in Table 32.

	Base year	2030	2050
IMO	2008	40%	70%
EU	2008	55%	Net-zero
KCC	2018	35%	Net-zero
KCC case 1	2022	18%	58%
KCC case 2	2022	24%	68%
KCC case 3	2022	30%	77%

Table 32: Drivers and cases comparison

With lacking emissions data for similar base years as for the IMO or the EU, the three scenarios cannot be directly compared to regulatory restrictions. However, by 2050, cases 2 and 3 demonstrate emission reductions compared to 2022 that almost hit and exceed respectively, the IMO's target of 70%. These findings indicate that the more aggressive retrofit strategies represented by cases 2 and 3 could potentially be part of an effective approach to meeting the industry's long-term decarbonization goals. It is crucial to remember, however, that while these case studies provide valuable insights, they represent idealized scenarios. The practical implementation of such strategies would likely encounter numerous technological, operational, and financial challenges. These must be factored into future research and decision-making processes.

Nevertheless, neither of the narratives carries the fleet towards net zero, implying that KCC even with the outlined retrofit strategy, will have to look for better energy-reducing measures within their operation. Alternative fuel options discussed in Section 4.1, would be a natural choice when conducting further research towards more efficient emissions-reducing measures. With more advanced developed engine technology and fuel infrastructure, alternative fuel shows great potential for helping the marine industry reach net zero within 2050.

9.4 Implications for the shipping industry

The results of these case studies offer several important implications for the shipping industry. They can be broadly categorized into economic, operational, and policy implications.

9.4.1 Economic implications

The economic implications are perhaps the most direct and quantifiable. Retrofitting vessels with new technologies to reduce emissions presents an upfront cost. However, these initial investments can be recuperated over time through fuel cost savings and reduced emissions taxes. The pace of this return on investment varies depending on the retrofit option chosen. For instance, a Flettner rotor or an air lubrication system upgrade, enhancing fuel efficiency, may provide faster returns compared to a scrubber or an electrical upgrade, obtaining a longer payback period due to their operational characteristics and installation costs, as discussed in Section 6.2. This comes to show when the model prioritized for instance Flettner rotors before scrubbers. An economic analysis that considers these variables is therefore crucial to guide retrofitting decisions.

Additionally, economic subsidies should be considered during the economic analysis of possible investments in upgrades of a vessel such as retrofitting for lower emissions and higher efficiency. As mentioned in Section 6.2, inventions, installations, and development of solutions promoting lower emissions, obtain the possibility of receiving subsidies. Klaveness, as discussed, did receive support from the Norwegian agency Enova, for the installation of air lubrication and shaft generators on two of their existing vessels. However, as these subsidies are mostly relevant if the installation is unique or world-leading, after recommendation from the co-supervisor, this support was not accounted for during this thesis.

9.4.2 Operational implications

Operational implications too are significant as the introduction of new technologies inevitably impacts the daily operations of the vessels and overall fleet management. For instance, the installation of retrofit options such as a hybrid system or a Flettner rotor will require crew members to undergo training to effectively operate and maintain these systems. This could potentially increase the workload of the crew and necessitate adjustments to daily routines and schedules. Furthermore, the downtime required for a retrofit installation could disrupt operations and result in short-term losses, which should be factored into the overall operational planning.

9.4.3 Policy implications

Lastly, policy implications, as the adoption of retrofitting strategies is heavily influenced by the regulatory environment. Current regulations set by organizations like the IMO and the EU are driving the need for emissions reduction. However, additional policy measures might be necessary to facilitate the widespread adoption of these retrofitting technologies. These could include incentives like tax benefits or subsidies for retrofit installations, or stricter emissions standards that make retrofitting a more economically viable option. As such, joint industry initiatives such as Enova discussed in Section 6.2, are vital organizations for a more energy-efficient industry to grow.

Moreover, regulations that ensure the safety and efficiency of new retrofit technologies are crucial. For example, the operation of an air lubrication system or a shaft generator must comply with navigation safety regulations, and the effectiveness of a scrubber in reducing emissions should be validated by environmental regulations. All of these aspects when installing a retrofit option must be integrated into the concept of operations of the vessel, as discussed in Section 6.1. Respecting all four aspects; the economics, the operability of the vessel, the environmental aspect, and the RAMS section, for the option to be viable as an installation to the respective vessel. As such, close cooperation between policymakers, and regulatory and market bodies, is essential to facilitate the transition to a more sustainable shipping industry.

9.5 Limitations of thesis

Despite the valuable insights generated from this study, it is important to acknowledge the limitations that come with the approach taken, which may impact the findings and their applications.

One of the primary limitations was the availability of data. There was a lack of access to historic emissions data for the fleet, which could have allowed for more accurate comparisons and calculations toward the IMO's and the EU's emissions goals. Furthermore, precise cost and fuel reduction potential data for the various retrofit options were gathered through various internet resources, which could have affected the accuracy of the results and conclusions. In the context of KCC's fleet, all vessels were assumed to be homogeneous, apart from their fuel consumption and age during the optimization process. This assumption implies that all vessels are equally suitable for installation with all retrofit options. In reality, the suitability and effectiveness of retrofit options may vary based on several vessel characteristics, including design, and operating conditions.

The complexity of the model itself represents another limitation. Developing a comprehensive and accurate mathematical model of a vessel fleet is a challenging endeavor due to the myriad factors involved, including vessel sizes, capacities, operational constraints, sailing area conditions, and restrictions, and the array of potential retrofitting options. Inevitably, simplifications and assumptions had to be made to create a manageable linear optimization model, which may not capture all nuances of the real-world problem. The dynamic nature and inherent uncertainties of real-world vessel fleet optimization also pose a limitation. Variables such as fluctuating fuel prices, regulatory changes, shifting market demands, and unforeseen events are difficult to incorporate into a static model. Such uncertainties could significantly impact the practicality and effectiveness of the recommended retrofitting strategies, especially since the model has a time horizon of 27 years allowing for potentially a completely different real-world situation somewhere along the horizon.

Constraints and trade-offs are other aspects that can complicate the modeling and decision-making process. Operational, financial, and environmental constraints and business objectives need to be balanced in the model, which can be challenging. Interpreting the solutions generated by the model and implementing them in practice is another potential limitation. While the model may suggest an optimal solution, practical considerations such as vessel availability, retrofitting logistics, and compatibility with existing operations can affect the applicability and effectiveness of the proposed strategies. Lastly, while linear optimization is a powerful and versatile tool, it has inherent limitations. It assumes linear relationships between variables and constraints, which may not always hold true in real-world scenarios. Nonlinear aspects, such as non-linear costs or relationships, may need to be approximated or excluded, potentially affecting the accuracy of the optimization results.

In light of these limitations, future research should aim to incorporate more comprehensive data, refine the modeling approach to better capture real-world complexities, and incorporate dynamic and uncertainty considerations. Furthermore, the exploration of advanced optimization techniques that can handle non-linearities and uncertainties could prove beneficial. Practical considerations and stakeholder inputs should also be incorporated into the decision-making process to ensure the feasibility and effectiveness of the proposed retrofitting strategies.

9.6 Value of the optimization model

The presented linear optimization model for fleet retrofitting determines the most cost-effective and environmentally conscious retrofitting strategy for KCC's fleet of vessels, taking into account constraints related to emissions, costs, and operational parameters. The primary strength of the model is its adaptability; it can be modified and tailored to suit the decision-making process of any shipping company, increasing its versatility and relevance in addressing common industry challenges. For Torvald Klaveness, this model provides a methodical approach to managing their vessel fleet, with consideration of key performance indicators applicable to the company. It offers significant strategic planning advantages, assisting the firm in preparing for substantial financial commitments and in navigating regulatory compliance. From a broader market perspective, the appeal of this model spans various shipping companies operating within today's highly competitive and tightly regulated environment. The model provides a structured framework for these companies to better manage the complex decisions between profitability, compliance with environmental regulations, and operational feasibility. Thus, it offers a structured solution to the intricate decision-making problem of fleet retrofitting.

Despite these benefits, the simplicity of the model can also be perceived as a limitation. The optimization model, while powerful, may not capture all the nuances inherent in real-world fleet retrofitting problems. For instance, it assumes linear relationships among variables and constraints, which may not always accurately represent real-world scenarios. To enhance the value of the model, consideration could be given to incorporating elements of non-linear programming or adding constraints that better mimic real-world conditions. An important extension to the model would be the integration of future uncertainties. The current model does not explicitly consider uncertainties such as fluctuating fuel prices, regulatory shifts, or changes in market demand. By adding a component that considers various potential future scenarios, the model's robustness can be improved, enhancing its strategic value in long-term planning. To integrate this feature, decision variables could be expanded to include a time dimension, capturing the selection of a specific retrofit alternative over different future periods. This extension would require comprehensive preliminary work, including calculating weight factors for each criterion for each potential future scenario. Moreover, it may require revisiting the criteria, as the importance of different factors may evolve over time.

10 Conclusion

This thesis assesses the decision basis for a shipping vessel fleet decarbonization strategy, including criteria and barriers for selection. A binary integer optimization problem model was developed to assess the alternatives and recommend a decarbonization strategy with respect to the alternatives proposed. The optimization model is flexible and able to include a wide range of data with different criteria, perspectives, and constraints, allowing for multiple fleet owners to be assisted with their decision-making towards the decarbonization of their fleet.

The selection process for the decarbonization strategy evaluating individual retrofit options for shipping vessels was outlined with the assistance of linear optimization theory. The model developed evaluates data for the deep sea shipping company Torvald Klaveness and their fleet. In general, technical, economic, and environmental criteria and aspects were evaluated and considered the determining decision factors. All three case studies carried out utilizing the optimization model, suggest that with the correct planning and decision-making, investments can be carried out to reduce the fleet's total annual greenhouse gas emissions. The emissions can be reduced up until a certain level, as well as reducing the total costs for the fleet proportionally.

The thesis argues that with correct and precise decision-making and quality research toward relevant alternatives for the decarbonization of a fleet, the fleet shows the potential of reducing its total annual emissions at a significant rate. With the outlined timeline for the fleet, it is able to follow the emissions target for the International Maritime Organization for the year 2050. However, the European Union's emissions target of reaching net-zero within 2050 will require additional carbon-reducing measures beyond retrofitting the fleet with energy-enhancing abatements. To reach net-zero, better communication and cooperation between administrative and market drivers are necessary, to boost investments in carbon-reducing research, infrastructure, and technology.

The research question this thesis endeavors to answer, introduced in the introductory chapter, was: *How can an optimization model considering several energy-efficiency alternatives towards a deep sea shipping fleet, respecting a total annual emissions reduction by a set value over a given time horizon, contribute to solving a shipping fleet's challenges towards decarbonization?*

The question is answered by the statement: as proposed in this thesis, well-planned and well-executed decision-making in terms of energy-efficient alternatives for vessels, utilized by a binary linear optimization model, obtain the potential of decarbonizing the fleet by reducing its emissions by a set value periodically over a given time horizon. For the case study of KCC's fleet, an annual reduction rate of up to 5% is possible with the presented energy-efficiency abatements and the data provided for the fleet. Nevertheless, additional and more comprehensive measures will be required for a stricter reduction rate. Thus, as a result, further research, investments, and development in even more energy-efficient attributes are necessary to reach the European Union's net-zero goal.

10.1 Further work

While the thesis provides valuable insights and sets a foundation for understanding the dynamics of retrofitting a vessel fleet, there is scope for future work to refine the model further and enhance its practical applicability. In addition to the suggested expansions for the model in Section 9.6, a list of additional extensions possible to incorporate with the model is presented below.

- An area that warrants further research, is the implementation of alternative fuels as retrofit options. Either as "drop-in-fuels" or in the context of replacing the whole propulsion system. Carbon-neutral or zero-carbon fuels obtain the potential of converting a vessel's operations into being carbon-neutral and might be the solution for Klaveness to reach the EU's and their own carbon-neutrality goal for 2050.
- One potential area of further research involves integrating the evaluation of the vessel's carbon intensity indicator level into the model. By including the anticipated CII rating as a constraint in the optimization model, the analysis can prioritize retrofitting vessels that project poorer scores, aligning with international goals to reduce carbon intensity in shipping.
- Additionally, the model could be adapted to allow specific retrofit options to be installed multiple times, such as Flettner rotors or electrical upgrades. This feature would offer greater flexibility and potential for emissions reductions.
- Supplementary, future work could explore the integration of dynamic fuel prices and emissions taxes over the time horizon. Whether modeled stochastically or based on predictive models, this feature would bring the model closer to the realities of market fluctuations and regulatory changes.
- Consideration of the fleet's annual cargo freight requirement as a constraint would also enhance the model's real-world relevance. This could ensure that the fleet maintains sufficient freight capacity annually, even as vessels undergo retrofitting. Alternatively, the model could explore the economic feasibility of chartering additional vessels to compensate for any reduction in capacity due to off-hire periods.
- Further, incorporating a risk analysis for each retrofit option could offer a more comprehensive perspective. This analysis would assess the potential operational and economic risks associated with each retrofit option, providing additional information for decision-making.
- Lastly, performing more detailed economic and dimension calculations for the various retrofit options would be beneficial. For instance, identifying the specific size and cost of retrofit options such as the Flettner rotor, shaft generator, and scrubber, can yield a more precise estimation of the investment required and the potential returns.

All these enhancements would help the model provide a more comprehensive, accurate, and practical tool for guiding retrofitting decisions, supporting the shipping industry's transition toward a sustainable future.

In summary, this thesis acts as an introductory roadmap for Torvald Klaveness, as well as other shipping companies, emphasizing the efficacy of energy-efficient retrofits through the application of an optimization model. It further highlights the importance of a holistic strategy that embraces propulsion technologies, cleaner energy sources, and a wider array of sophisticated retrofit solutions, in order to achieve the European Union's net-zero emissions goals. The aspiration is that, through this research, Klaveness and the wider shipping industry will be better prepared to tackle forthcoming hurdles, minimize their ecological footprint, and steer toward a more sustainable future.

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Appendix

A IMO timeline

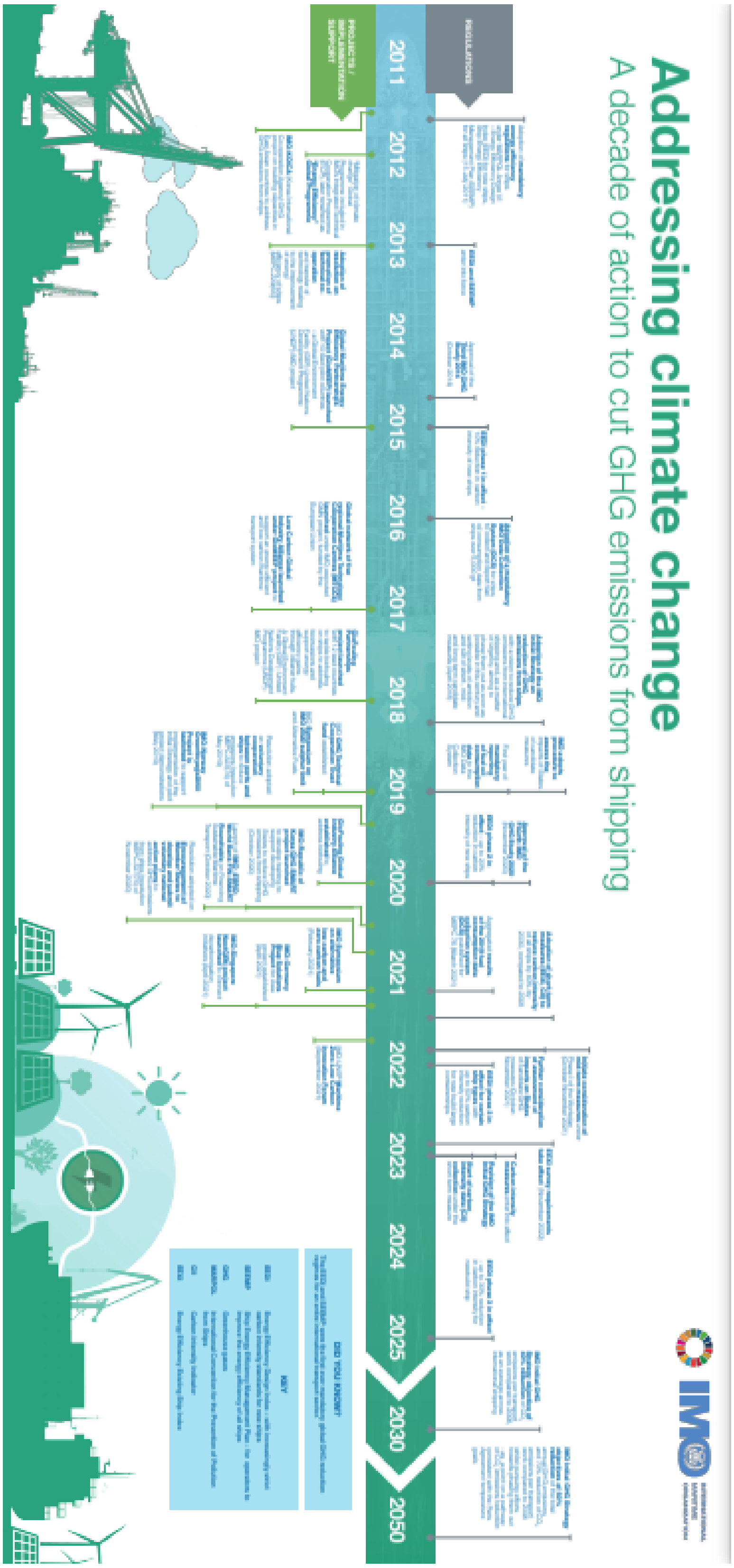
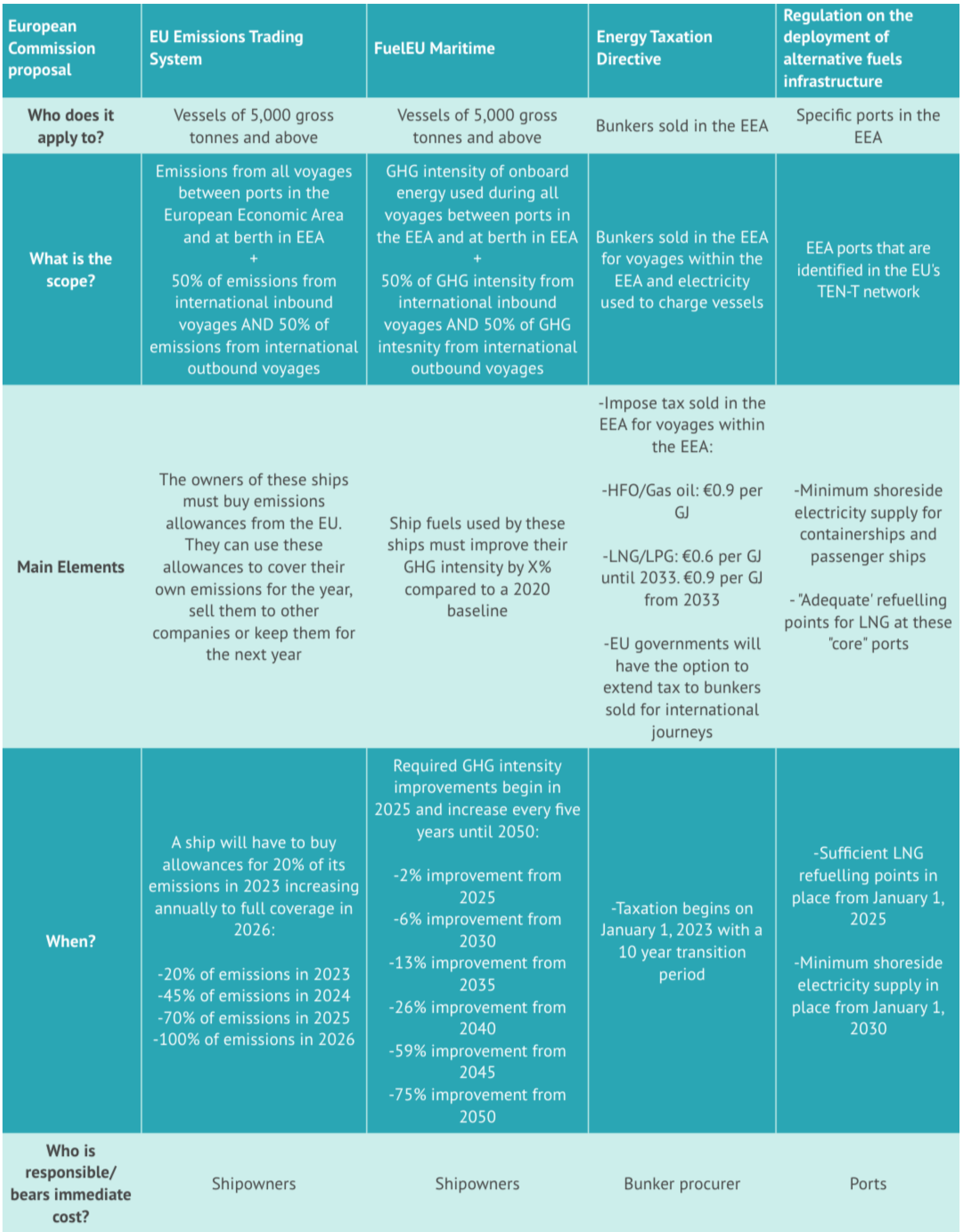


Figure A1: IMO timeline figure [105]

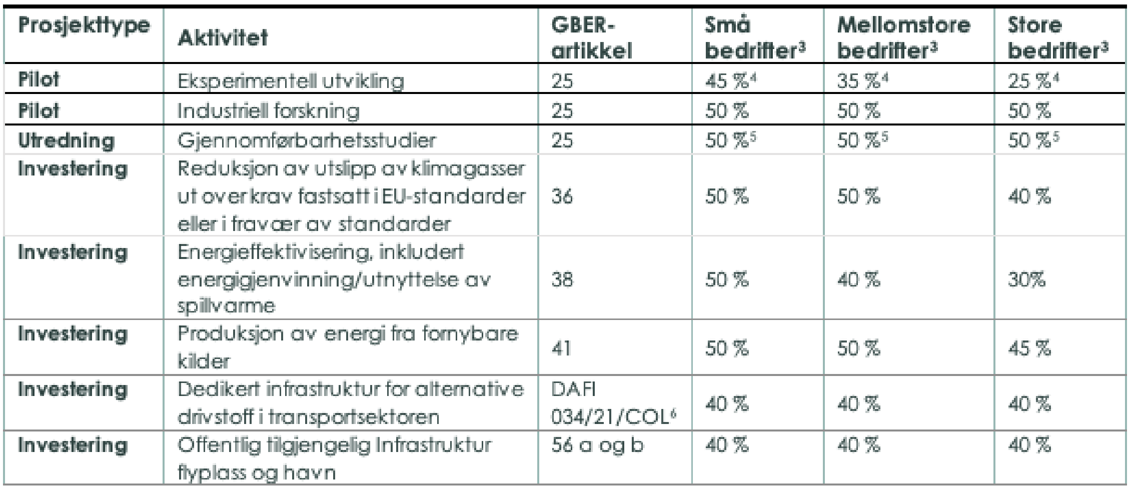
B Lloyd's List



European Commission proposal	EU Emissions Trading System	FuelEU Maritime	Energy Taxation Directive	Regulation on the deployment of alternative fuels infrastructure
Who does it apply to?	Vessels of 5,000 gross tonnes and above	Vessels of 5,000 gross tonnes and above	Bunkers sold in the EEA	Specific ports in the EEA
What is the scope?	Emissions from all voyages between ports in the European Economic Area and at berth in EEA + 50% of emissions from international inbound voyages AND 50% of emissions from international outbound voyages	GHG intensity of onboard energy used during all voyages between ports in the EEA and at berth in EEA + 50% of GHG intensity from international inbound voyages AND 50% of GHG intesnity from international outbound voyages	Bunkers sold in the EEA for voyages within the EEA and electricity used to charge vessels	EEA ports that are identified in the EU's TEN-T network
Main Elements	The owners of these ships must buy emissions allowances from the EU. They can use these allowances to cover their own emissions for the year, sell them to other companies or keep them for the next year	Ship fuels used by these ships must improve their GHG intensity by X% compared to a 2020 baseline	-Impose tax sold in the EEA for voyages within the EEA: -HFO/Gas oil: €0.9 per GJ -LNG/LPG: €0.6 per GJ until 2033. €0.9 per GJ from 2033 -EU governments will have the option to extend tax to bunkers sold for international journeys	-Minimum shoreside electricity supply for containerships and passenger ships - 'Adequate' refuelling points for LNG at these "core" ports
When?	A ship will have to buy allowances for 20% of its emissions in 2023 increasing annually to full coverage in 2026: -20% of emissions in 2023 -45% of emissions in 2024 -70% of emissions in 2025 -100% of emissions in 2026	Required GHG intensity improvements begin in 2025 and increase every five years until 2050: -2% improvement from 2025 -6% improvement from 2030 -13% improvement from 2035 -26% improvement from 2040 -59% improvement from 2045 -75% improvement from 2050	-Taxation begins on January 1, 2023 with a 10 year transition period	-Sufficient LNG refuelling points in place from January 1, 2025 -Minimum shoreside electricity supply in place from January 1, 2030
Who is responsible/ bears immediate cost?	Shipowners	Shipowners	Bunker procurer	Ports

Figure A2: Lloyd's list taxes proposals [32]

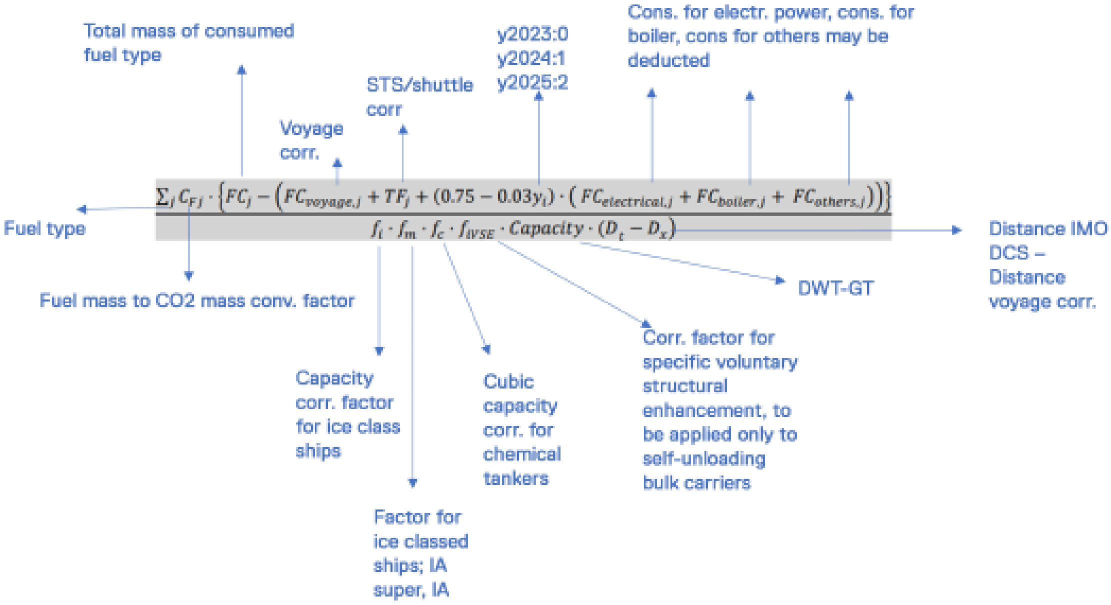
C Enova support



Prosjekttype	Aktivitet	GBER-artikkel	Små bedrifter[3]	Mellomstore bedrifter[3]	Store bedrifter[3]
Pilot	Eksperimentell utvikling	25	45 %[4]	35 %[4]	25 %[4]
Pilot	Industriell forskning	25	50 %	50 %	50 %
Utredning	Gjennomførbarhetsstudier	25	50 %[5]	50 %[5]	50 %[5]
Investering	Reduksjon av utslipp av klimagasser ut over krav fastsatt i EU-standarder eller i fravær av standarder	36	50 %	50 %	40 %
Investering	Energieffektivisering, inkludert energigjenvinning/utnyttelse av spillvarme	38	50 %	40 %	30%
Investering	Produksjon av energi fra fornybare kilder	41	50 %	50 %	45 %
Investering	Dedikert infrastruktur for alternative drivstoff i transportsektoren	DAFI 034/21/COL[6]	40 %	40 %	40 %
Investering	Offentlig tilgjengelig Infrastruktur flyplass og havn	56 a og b	40 %	40 %	40 %

Figure A3: Enova support [86]

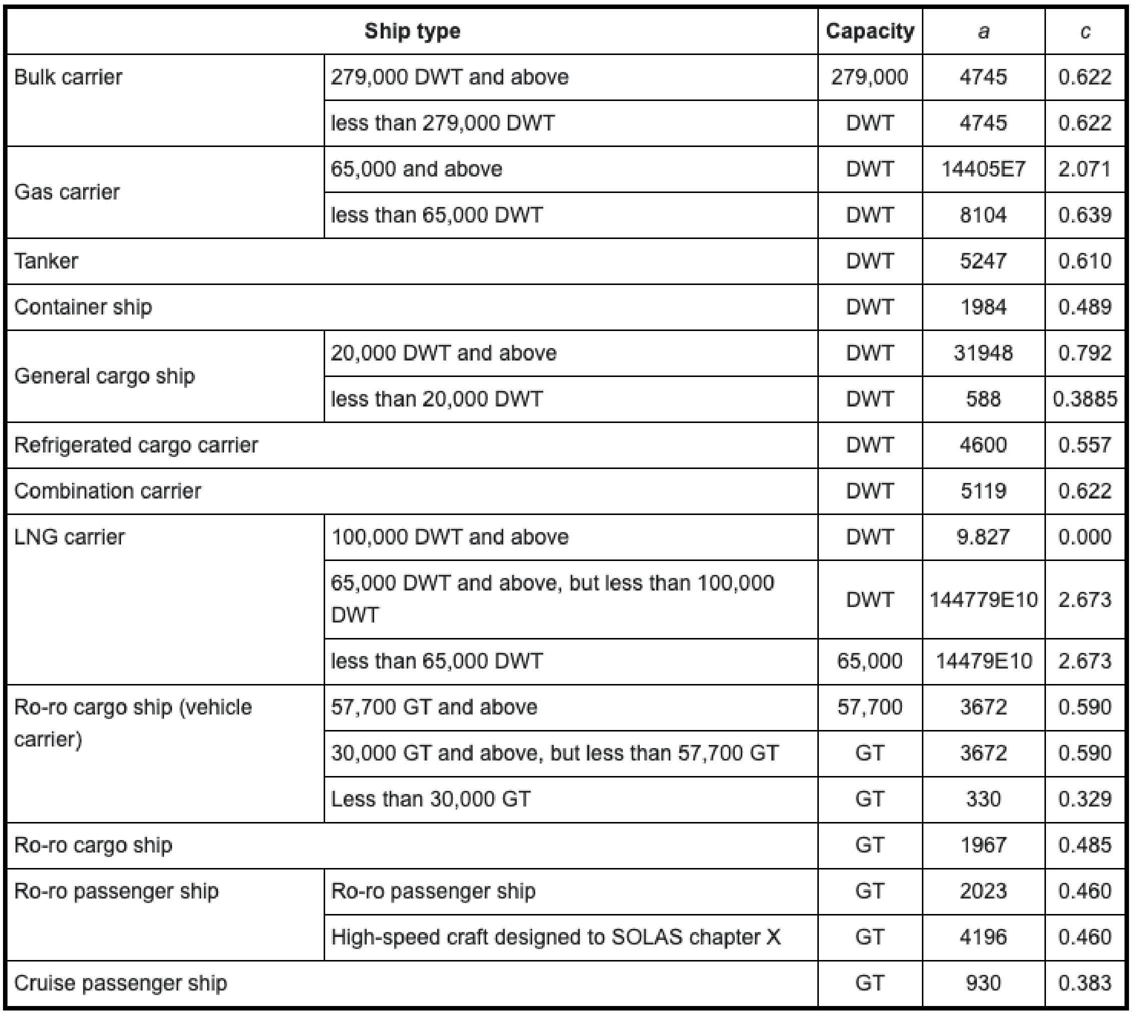
D CII



$$\frac{\sum_j C_{Fj}\cdot\left\{FC_j-\left(FC_{voyage,j}+TF_j+(0.75-0.03y_i)\cdot\left(FC_{electrical,j}+FC_{boiler,j}+FC_{others,j}\right)\right)\right\}}{f_i\cdot f_m\cdot f_c\cdot f_{iVSE}\cdot Capacity\cdot(D_t-D_x)}$$

Figure A4: CII calculation [24]

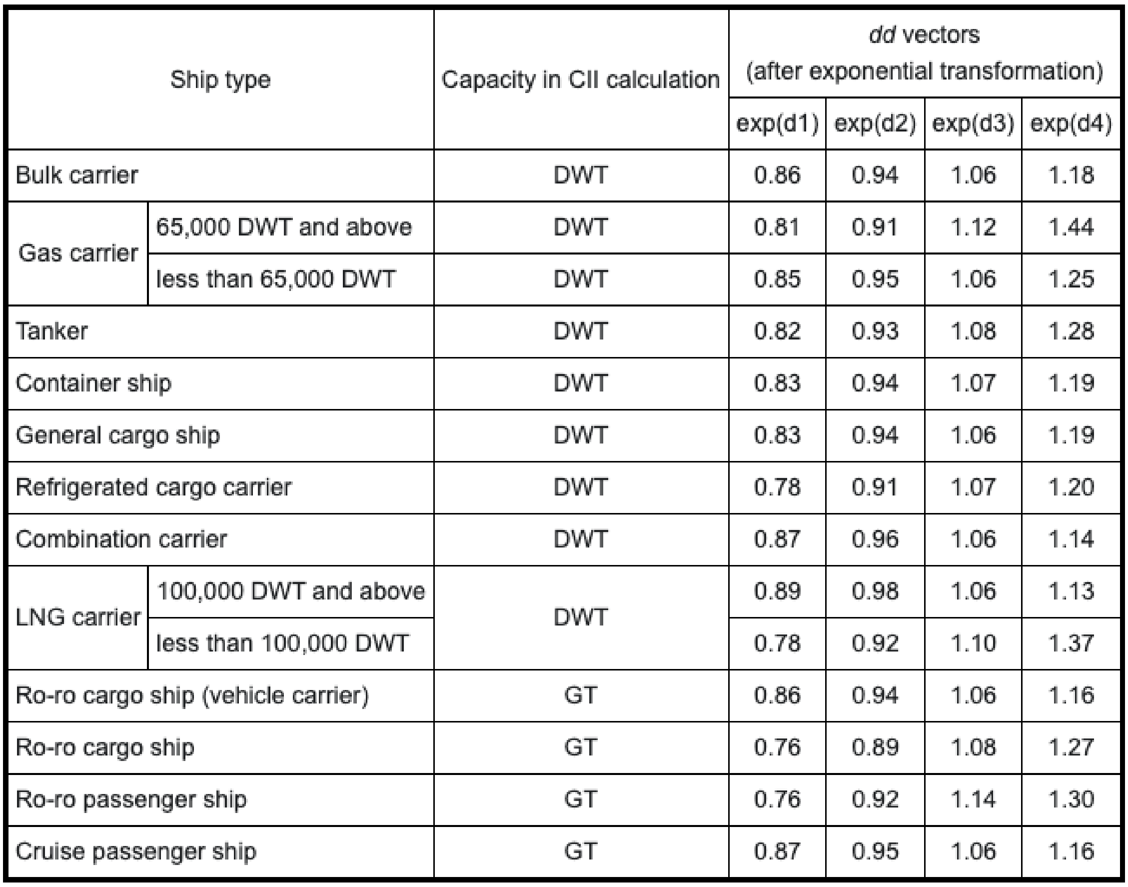
E CII reference



Ship type		Capacity	*a*	*c*
Bulk carrier	279,000 DWT and above	279,000	4745	0.622
	less than 279,000 DWT	DWT	4745	0.622
Gas carrier	65,000 and above	DWT	14405E7	2.071
	less than 65,000 DWT	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	5119	0.622
LNG carrier	100,000 DWT and above	DWT	9.827	0.000
	65,000 DWT and above, but less than 100,000 DWT	DWT	144779E10	2.673
	less than 65,000 DWT	65,000	14479E10	2.673
Ro-ro cargo ship (vehicle carrier)	57,700 GT and above	57,700	3672	0.590
	30,000 GT and above, but less than 57,700 GT	GT	3672	0.590
	Less than 30,000 GT	GT	330	0.329
Ro-ro cargo ship		GT	1967	0.485
Ro-ro passenger ship	Ro-ro passenger ship	GT	2023	0.460
	High-speed craft designed to SOLAS chapter X	GT	4196	0.460
Cruise passenger ship		GT	930	0.383

Figure A5: CII reference [106]

F CII score

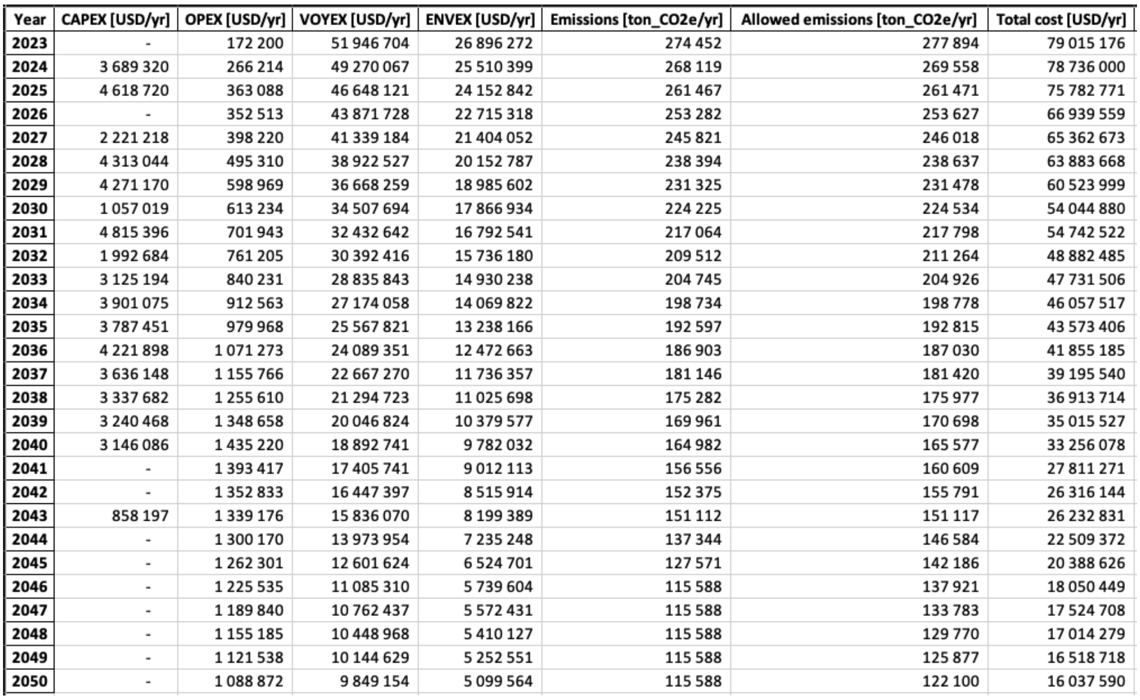


Ship type		Capacity in CII calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		GT	0.76	0.89	1.08	1.27
Ro-ro passenger ship		GT	0.76	0.92	1.14	1.30
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

Figure A6: CII results [25]

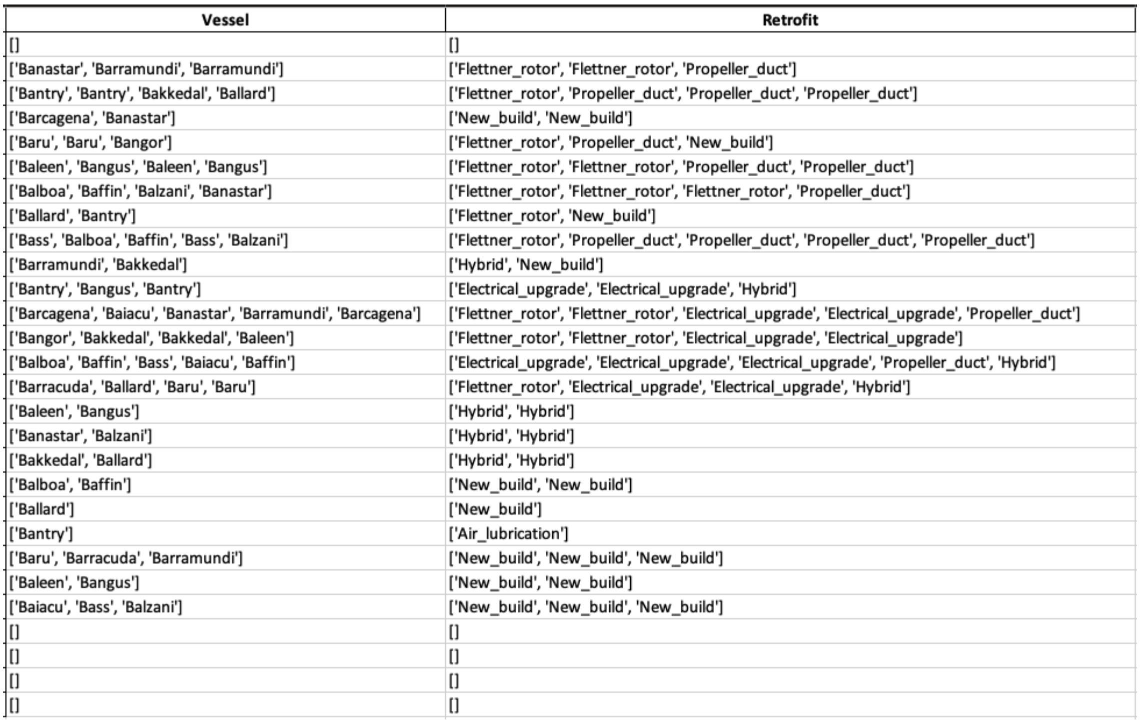
G Case studies additional results

G.1 Case 1 additional results



Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
2023	-	172 200	51 946 704	26 896 272	274 452	277 894	79 015 176
2024	3 689 320	266 214	49 270 067	25 510 399	268 119	269 558	78 736 000
2025	4 618 720	363 088	46 648 121	24 152 842	261 467	261 471	75 782 771
2026	-	352 513	43 871 728	22 715 318	253 282	253 627	66 939 559
2027	2 221 218	398 220	41 339 184	21 404 052	245 821	246 018	65 362 673
2028	4 313 044	495 310	38 922 527	20 152 787	238 394	238 637	63 883 668
2029	4 271 170	598 969	36 668 259	18 985 602	231 325	231 478	60 523 999
2030	1 057 019	613 234	34 507 694	17 866 934	224 225	224 534	54 044 880
2031	4 815 396	701 943	32 432 642	16 792 541	217 064	217 798	54 742 522
2032	1 992 684	761 205	30 392 416	15 736 180	209 512	211 264	48 882 485
2033	3 125 194	840 231	28 835 843	14 930 238	204 745	204 926	47 731 506
2034	3 901 075	912 563	27 174 058	14 069 822	198 734	198 778	46 057 517
2035	3 787 451	979 968	25 567 821	13 238 166	192 597	192 815	43 573 406
2036	4 221 898	1 071 273	24 089 351	12 472 663	186 903	187 030	41 855 185
2037	3 636 148	1 155 766	22 667 270	11 736 357	181 146	181 420	39 195 540
2038	3 337 682	1 255 610	21 294 723	11 025 698	175 282	175 977	36 913 714
2039	3 240 468	1 348 658	20 046 824	10 379 577	169 961	170 698	35 015 527
2040	3 146 086	1 435 220	18 892 741	9 782 032	164 982	165 577	33 256 078
2041	-	1 393 417	17 405 741	9 012 113	156 556	160 609	27 811 271
2042	-	1 352 833	16 447 397	8 515 914	152 375	155 791	26 316 144
2043	858 197	1 339 176	15 836 070	8 199 389	151 112	151 117	26 232 831
2044	-	1 300 170	13 973 954	7 235 248	137 344	146 584	22 509 372
2045	-	1 262 301	12 601 624	6 524 701	127 571	142 186	20 388 626
2046	-	1 225 535	11 085 310	5 739 604	115 588	137 921	18 050 449
2047	-	1 189 840	10 762 437	5 572 431	115 588	133 783	17 524 708
2048	-	1 155 185	10 448 968	5 410 127	115 588	129 770	17 014 279
2049	-	1 121 538	10 144 629	5 252 551	115 588	125 877	16 518 718
2050	-	1 088 872	9 849 154	5 099 564	115 588	122 100	16 037 590

Figure A7: Case 1 annual emissions and costs results for Klaveness' fleet



Vessel	Retrofit
[]	[]
['Banastar', 'Barramundi', 'Barramundi']	['Flettner_rotor', 'Flettner_rotor', 'Propeller_duct']
['Bantry', 'Bantry', 'Bakkedal', 'Ballard']	['Flettner_rotor', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
['Barcagena', 'Banastar']	['New_build', 'New_build']
['Baru', 'Baru', 'Bangor']	['Flettner_rotor', 'Propeller_duct', 'New_build']
['Baleen', 'Bangus', 'Baleen', 'Bangus']	['Flettner_rotor', 'Flettner_rotor', 'Propeller_duct', 'Propeller_duct']
['Balboa', 'Baffin', 'Balzani', 'Banastar']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Propeller_duct']
['Ballard', 'Bantry']	['Flettner_rotor', 'New_build']
['Bass', 'Balboa', 'Baffin', 'Bass', 'Balzani']	['Flettner_rotor', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
['Barramundi', 'Bakkedal']	['Hybrid', 'New_build']
['Bantry', 'Bangus', 'Bantry']	['Electrical_upgrade', 'Electrical_upgrade', 'Hybrid']
['Barcagena', 'Baiacu', 'Banastar', 'Barramundi', 'Barcagena']	['Flettner_rotor', 'Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct']
['Bangor', 'Bakkedal', 'Bakkedal', 'Baleen']	['Flettner_rotor', 'Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade']
['Balboa', 'Baffin', 'Bass', 'Baiacu', 'Baffin']	['Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'Hybrid']
['Barracuda', 'Ballard', 'Baru', 'Baru']	['Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Hybrid']
['Baleen', 'Bangus']	['Hybrid', 'Hybrid']
['Banastar', 'Balzani']	['Hybrid', 'Hybrid']
['Bakkedal', 'Ballard']	['Hybrid', 'Hybrid']
['Balboa', 'Baffin']	['New_build', 'New_build']
['Ballard']	['New_build']
['Bantry']	['Air_lubrication']
['Baru', 'Barracuda', 'Barramundi']	['New_build', 'New_build', 'New_build']
['Baleen', 'Bangus']	['New_build', 'New_build']
['Baiacu', 'Bass', 'Balzani']	['New_build', 'New_build', 'New_build']
[]	[]
[]	[]
[]	[]
[]	[]

Figure A8: Case 1 retrofit results for Klaveness' fleet

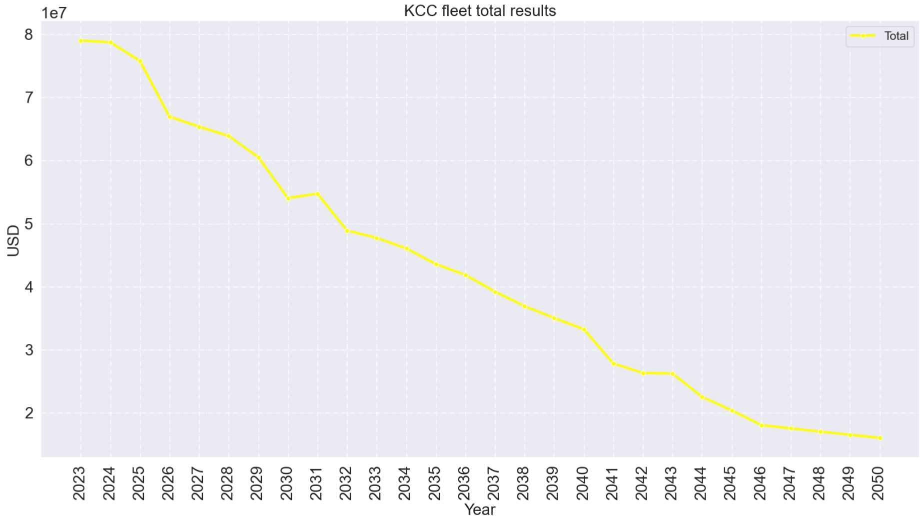


Figure A9: Case 1 total costs

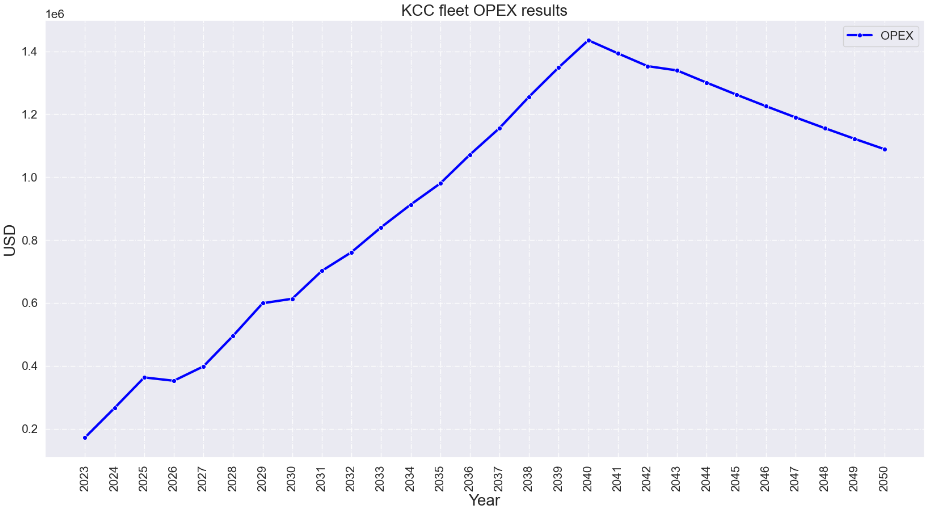


Figure A10: Case 1 OPEX

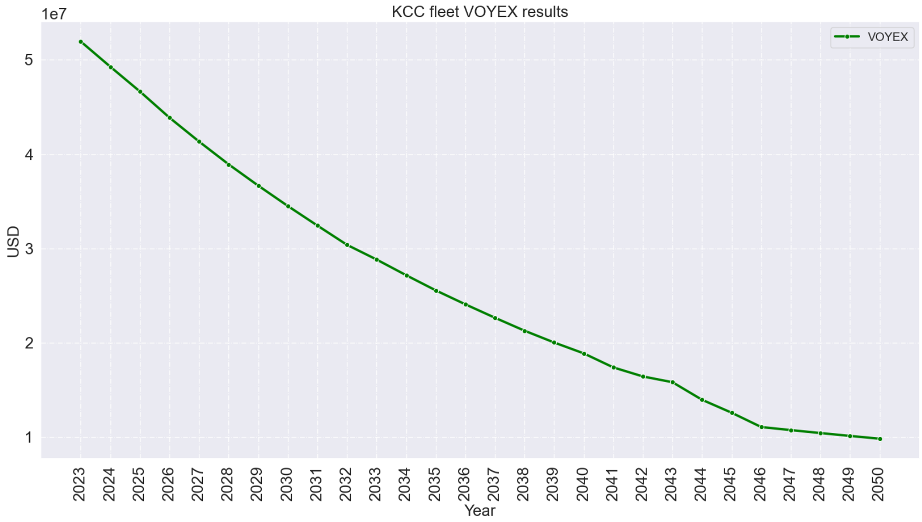


Figure A11: Case 1 VOYEX

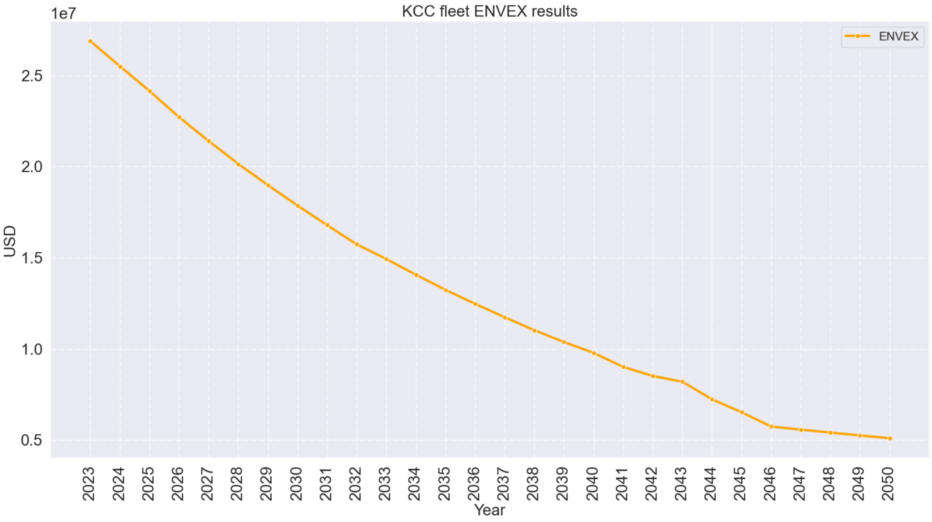


Figure A12: Case 1 ENVEX

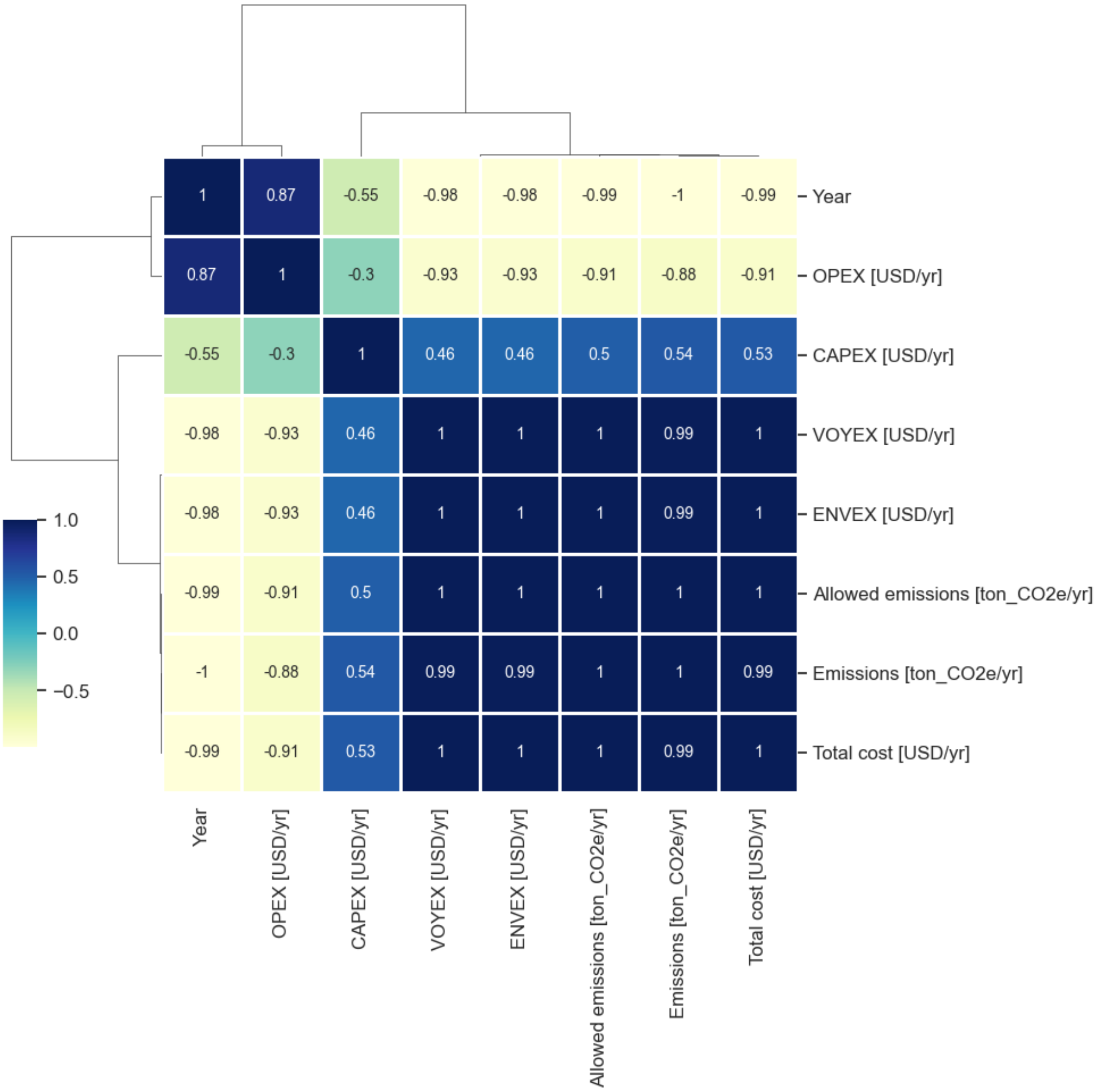
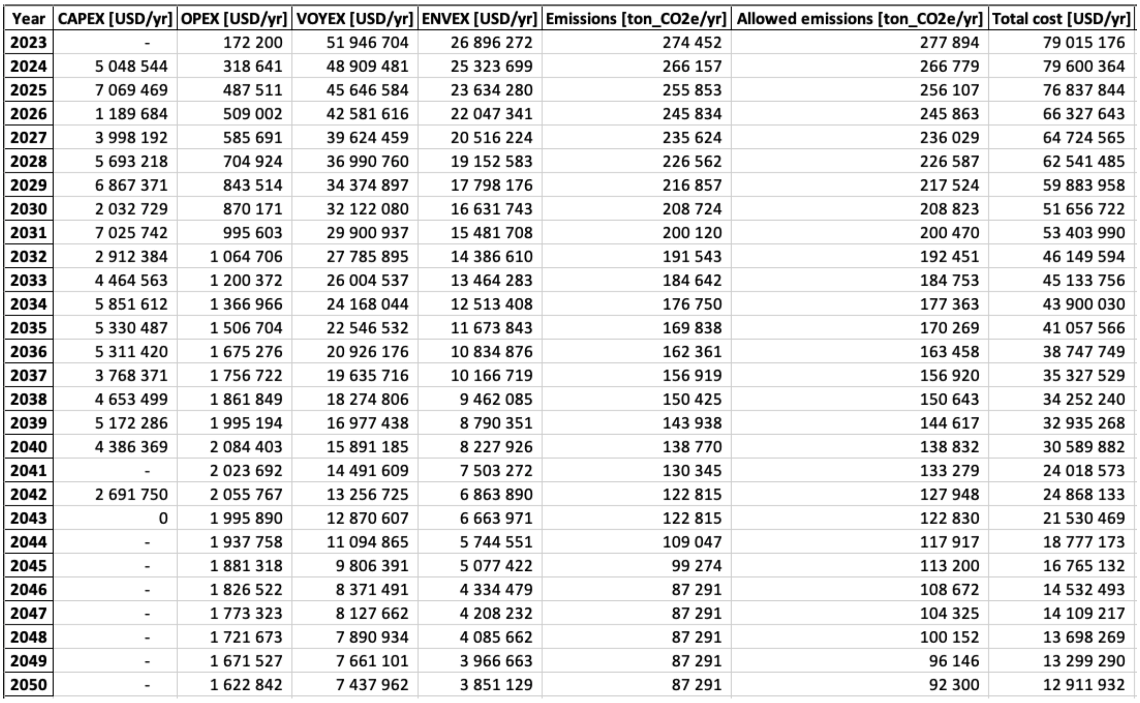


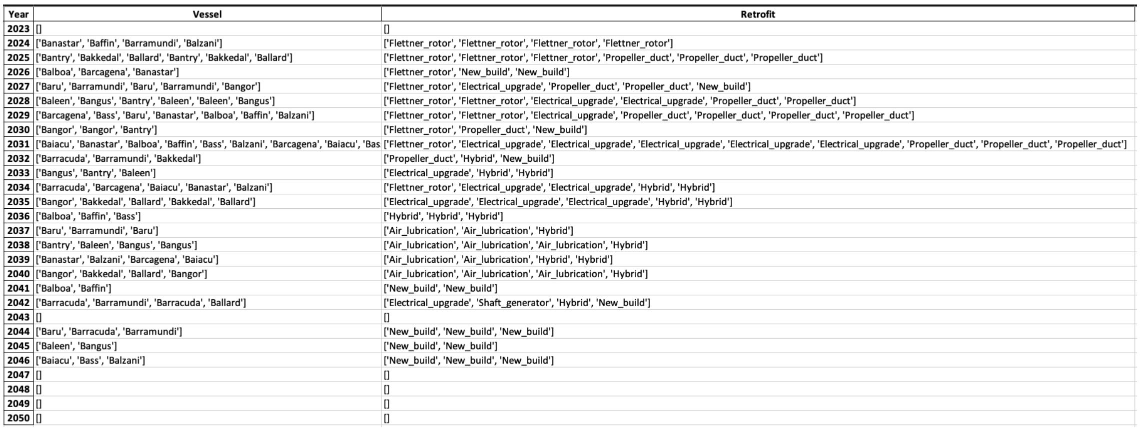
Figure A13: Case 1 clustermap

G.2 Case 2 additional results



Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
2023	-	172 200	51 946 704	26 896 272	274 452	277 894	79 015 176
2024	5 048 544	318 641	48 909 481	25 323 699	266 157	266 779	79 600 364
2025	7 069 469	487 511	45 646 584	23 634 280	255 853	256 107	76 837 844
2026	1 189 684	509 002	42 581 616	22 047 341	245 834	245 863	66 327 643
2027	3 998 192	585 691	39 624 459	20 516 224	235 624	236 029	64 724 565
2028	5 693 218	704 924	36 990 760	19 152 583	226 562	226 587	62 541 485
2029	6 867 371	843 514	34 374 897	17 798 176	216 857	217 524	59 883 958
2030	2 032 729	870 171	32 122 080	16 631 743	208 724	208 823	51 656 722
2031	7 025 742	995 603	29 900 937	15 481 708	200 120	200 470	53 403 990
2032	2 912 384	1 064 706	27 785 895	14 386 610	191 543	192 451	46 149 594
2033	4 464 563	1 200 372	26 004 537	13 464 283	184 642	184 753	45 133 756
2034	5 851 612	1 366 966	24 168 044	12 513 408	176 750	177 363	43 900 030
2035	5 330 487	1 506 704	22 546 532	11 673 843	169 838	170 269	41 057 566
2036	5 311 420	1 675 276	20 926 176	10 834 876	162 361	163 458	38 747 749
2037	3 768 371	1 756 722	19 635 716	10 166 719	156 919	156 920	35 327 529
2038	4 653 499	1 861 849	18 274 806	9 462 085	150 425	150 643	34 252 240
2039	5 172 286	1 995 194	16 977 438	8 790 351	143 938	144 617	32 935 268
2040	4 386 369	2 084 403	15 891 185	8 227 926	138 770	138 832	30 589 882
2041	-	2 023 692	14 491 609	7 503 272	130 345	133 279	24 018 573
2042	2 691 750	2 055 767	13 256 725	6 863 890	122 815	127 948	24 868 133
2043	0	1 995 890	12 870 607	6 663 971	122 815	122 830	21 530 469
2044	-	1 937 758	11 094 865	5 744 551	109 047	117 917	18 777 173
2045	-	1 881 318	9 806 391	5 077 422	99 274	113 200	16 765 132
2046	-	1 826 522	8 371 491	4 334 479	87 291	108 672	14 532 493
2047	-	1 773 323	8 127 662	4 208 232	87 291	104 325	14 109 217
2048	-	1 721 673	7 890 934	4 085 662	87 291	100 152	13 698 269
2049	-	1 671 527	7 661 101	3 966 663	87 291	96 146	13 299 290
2050	-	1 622 842	7 437 962	3 851 129	87 291	92 300	12 911 932

Figure A14: Case 2 annual emissions and costs results for Klaveness' fleet



Year	Vessel	Retrofit
2023	[]	[]
2024	['Banastar', 'Baffin', 'Barramundi', 'Balzani']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor']
2025	['Bantry', 'Bakkedal', 'Ballard', 'Bantry', 'Bakkedal', 'Ballard']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
2026	['Balboa', 'Barcagena', 'Banastar']	['Flettner_rotor', 'New_build', 'New_build']
2027	['Baru', 'Barramundi', 'Baru', 'Barramundi', 'Bangor']	['Flettner_rotor', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct', 'New_build']
2028	['Baleen', 'Bangus', 'Bantry', 'Baleen', 'Baleen', 'Bangus']	['Flettner_rotor', 'Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct']
2029	['Barcagena', 'Bass', 'Baru', 'Banastar', 'Balboa', 'Baffin', 'Balzani']	['Flettner_rotor', 'Flettner_rotor', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
2030	['Bangor', 'Bangor', 'Bantry']	['Flettner_rotor', 'Propeller_duct', 'New_build']
2031	['Baiacu', 'Banastar', 'Balboa', 'Baffin', 'Bass', 'Balzani', 'Barcagena', 'Baiacu', 'Bas	['Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
2032	['Barracuda', 'Barramundi', 'Bakkedal']	['Propeller_duct', 'Hybrid', 'New_build']
2033	['Bangus', 'Bantry', 'Baleen']	['Electrical_upgrade', 'Hybrid', 'Hybrid']
2034	['Barracuda', 'Barcagena', 'Baiacu', 'Banastar', 'Balzani']	['Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Hybrid', 'Hybrid']
2035	['Bangor', 'Bakkedal', 'Ballard', 'Bakkedal', 'Ballard']	['Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Hybrid', 'Hybrid']
2036	['Balboa', 'Baffin', 'Bass']	['Hybrid', 'Hybrid', 'Hybrid']
2037	['Baru', 'Barramundi', 'Baru']	['Air_lubrication', 'Air_lubrication', 'Hybrid']
2038	['Bantry', 'Baleen', 'Bangus', 'Bangus']	['Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Hybrid']
2039	['Banastar', 'Balzani', 'Barcagena', 'Baiacu']	['Air_lubrication', 'Air_lubrication', 'Hybrid', 'Hybrid']
2040	['Bangor', 'Bakkedal', 'Ballard', 'Bangor']	['Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Hybrid']
2041	['Balboa', 'Baffin']	['New_build', 'New_build']
2042	['Barracuda', 'Barramundi', 'Barracuda', 'Ballard']	['Electrical_upgrade', 'Shaft_generator', 'Hybrid', 'New_build']
2043	[]	[]
2044	['Baru', 'Barracuda', 'Barramundi']	['New_build', 'New_build', 'New_build']
2045	['Baleen', 'Bangus']	['New_build', 'New_build']
2046	['Baiacu', 'Bass', 'Balzani']	['New_build', 'New_build', 'New_build']
2047	[]	[]
2048	[]	[]
2049	[]	[]
2050	[]	[]

Figure A15: Case 2 retrofit results for Klaveness' fleet

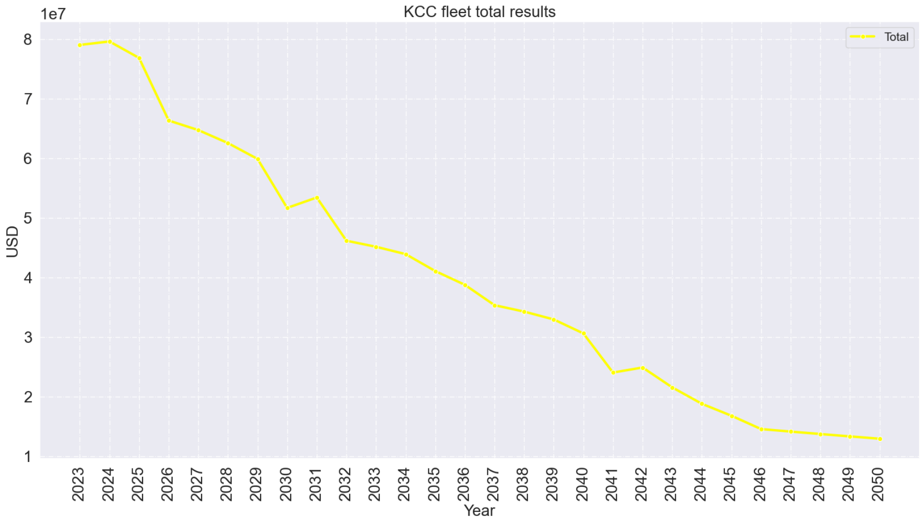


Figure A16: Case 2 total costs

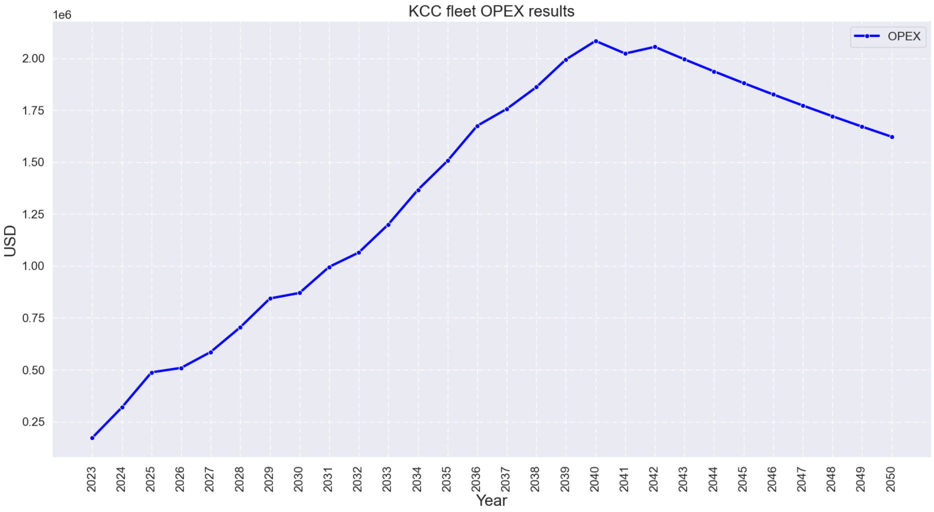


Figure A17: Case 2 OPEX

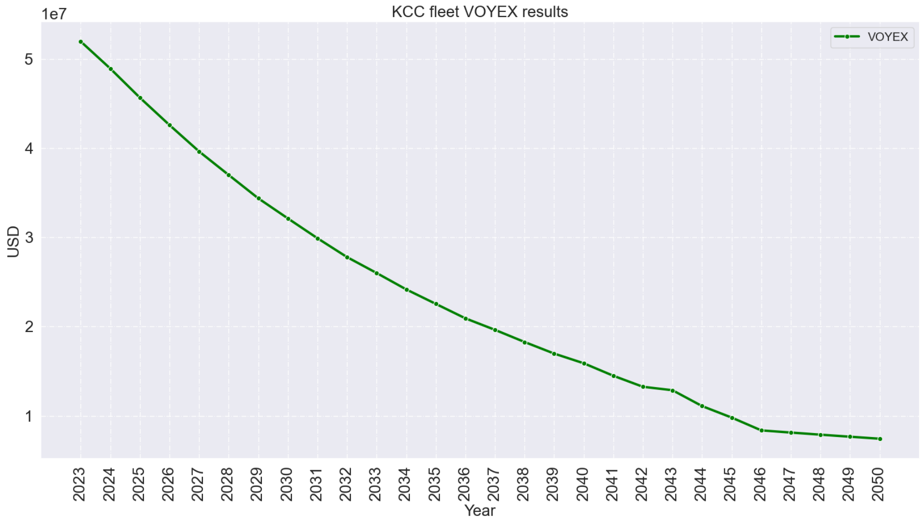


Figure A18: Case 2 VOYEX

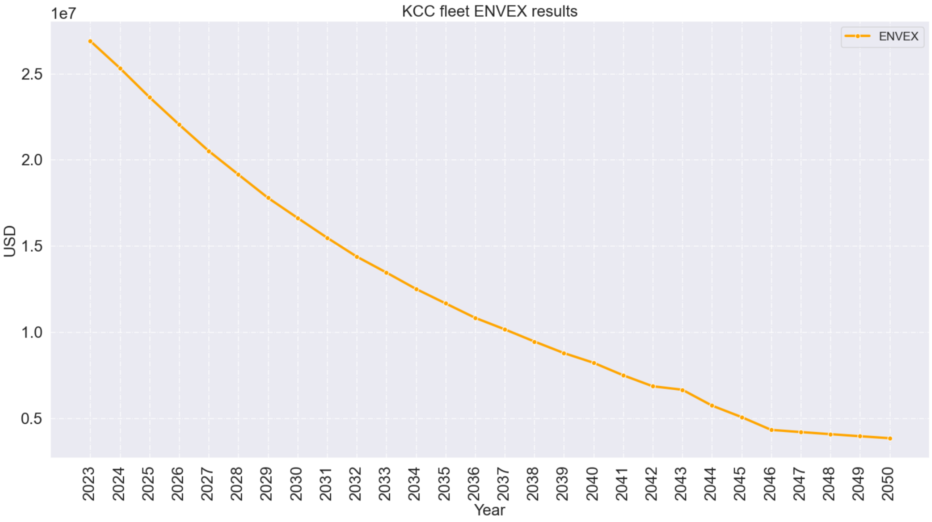


Figure A19: Case 2 ENVEX

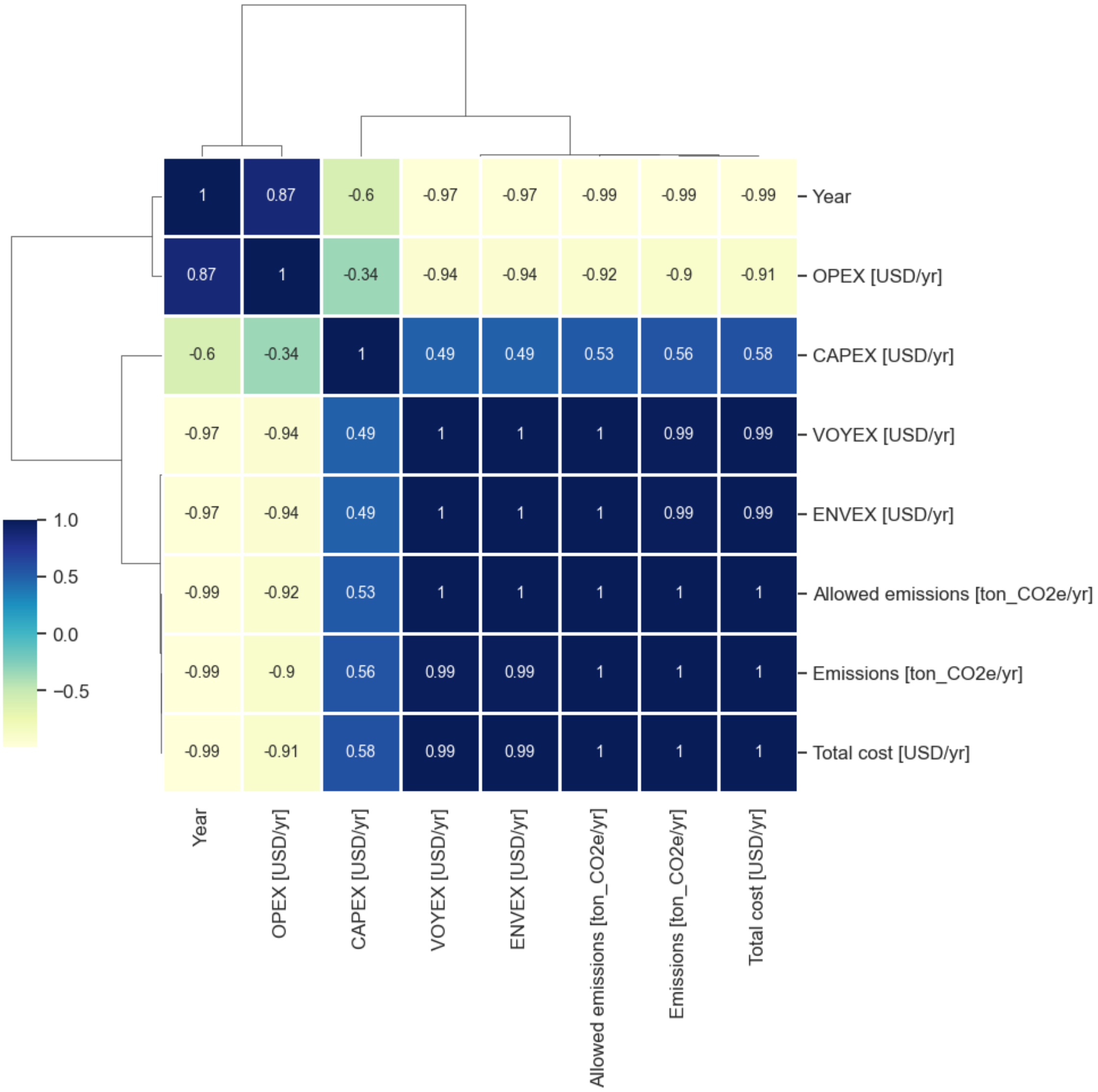
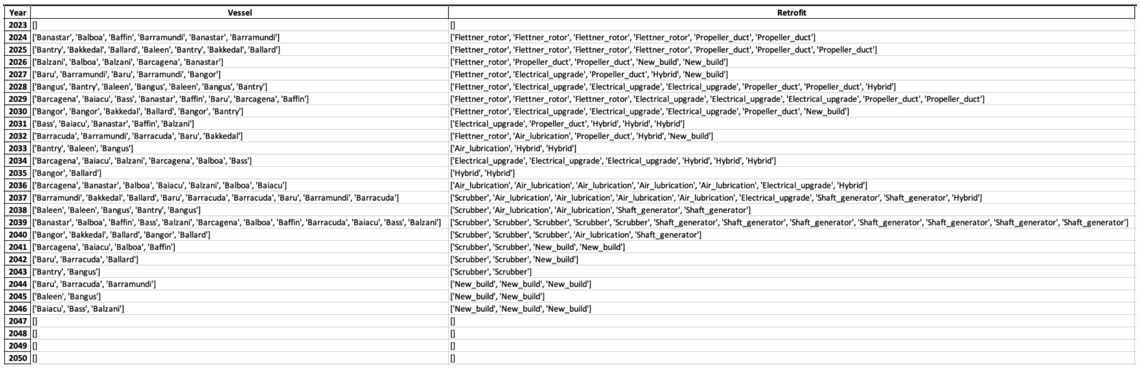


Figure A20: Case 2 clustermap

G.3 Case 3 additional results

Year	CAPEX [USD/yr]	OPEX [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]	Total cost [USD/yr]
2023	-	172 200	51 946 704	26 896 272	274 452	277 894	79 015 176
2024	7 378 641	365 243	48 324 126	25 020 622	262 972	264 000	81 088 632
2025	8 294 844	569 516	44 688 843	23 138 393	250 485	250 800	76 691 597
2026	3 386 024	632 546	41 163 466	21 313 071	237 647	238 260	66 495 107
2027	5 242 074	776 715	37 978 004	19 663 744	225 834	226 347	63 660 537
2028	7 504 696	960 256	35 107 751	18 177 623	215 029	215 029	61 750 326
2029	8 291 094	1 130 771	32 344 725	16 747 020	204 049	204 278	58 513 610
2030	3 984 148	1 188 089	29 853 596	15 457 197	193 984	194 064	50 483 031
2031	7 736 210	1 431 357	27 539 740	14 259 159	184 317	184 361	50 966 467
2032	5 096 671	1 553 297	25 166 742	13 030 500	173 488	175 143	44 847 210
2033	5 022 634	1 697 427	23 430 170	12 131 361	166 363	166 386	42 281 592
2034	7 368 697	1 908 059	21 517 937	11 141 270	157 369	158 066	41 935 963
2035	5 470 763	2 071 315	19 929 037	10 318 591	150 121	150 163	37 789 706
2036	7 592 607	2 251 021	18 357 763	9 505 038	142 433	142 655	37 706 429
2037	9 810 988	2 474 498	16 701 734	8 647 601	133 472	135 522	37 634 820
2038	5 353 129	2 546 331	15 638 155	8 096 915	128 722	128 746	31 634 530
2039	14 681 813	2 831 608	14 180 113	7 341 990	120 222	122 309	39 035 524
2040	7 254 147	2 919 567	13 295 971	6 884 211	116 108	116 193	30 353 896
2041	3 054 452	2 895 620	11 842 779	6 131 796	106 520	110 384	23 924 647
2042	2 965 487	2 870 592	10 907 561	5 647 571	101 052	104 864	22 391 211
2043	2 879 114	2 844 565	10 421 005	5 395 649	99 440	99 621	21 540 333
2044	-	2 761 713	8 716 610	4 513 170	85 672	94 640	15 991 494
2045	-	2 681 275	7 497 406	3 881 907	75 899	89 908	14 060 589
2046	-	2 603 180	6 129 759	3 173 785	63 916	85 413	11 906 723
2047	-	2 527 359	5 951 222	3 081 344	63 916	81 142	11 559 925
2048	-	2 453 746	5 777 885	2 991 597	63 916	77 085	11 223 228
2049	-	2 382 278	5 609 598	2 904 463	63 916	73 231	10 896 338
2050	-	2 312 891	5 446 211	2 819 867	63 916	69 569	10 578 969

Figure A21: Case 3 annual emissions and costs results for Klaveness' fleet



Year	Vessel	Retrofit
2023	[]	[]
2024	['Banastar', 'Balboa', 'Baffin', 'Barramundi', 'Banastar', 'Barramundi']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Propeller_duct', 'Propeller_duct']
2025	['Bantry', 'Bakkedal', 'Ballard', 'Baleen', 'Bantry', 'Bakkedal', 'Ballard']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Propeller_duct', 'Propeller_duct', 'Propeller_duct']
2026	['Balzani', 'Balboa', 'Balzani', 'Barcagena', 'Banastar']	['Flettner_rotor', 'Propeller_duct', 'Propeller_duct', 'New_build', 'New_build']
2027	['Baru', 'Barramundi', 'Baru', 'Barramundi', 'Bangor']	['Flettner_rotor', 'Electrical_upgrade', 'Propeller_duct', 'Hybrid', 'New_build']
2028	['Bangus', 'Bantry', 'Baleen', 'Bangus', 'Baleen', 'Bangus', 'Bantry']	['Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct', 'Hybrid']
2029	['Barcagena', 'Baiacu', 'Bass', 'Banastar', 'Baffin', 'Baru', 'Barcagena', 'Baffin']	['Flettner_rotor', 'Flettner_rotor', 'Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'Propeller_duct']
2030	['Bangor', 'Bangor', 'Bakkedal', 'Ballard', 'Bangor', 'Bantry']	['Flettner_rotor', 'Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Propeller_duct', 'New_build']
2031	['Bass', 'Baiacu', 'Banastar', 'Baffin', 'Balzani']	['Electrical_upgrade', 'Propeller_duct', 'Hybrid', 'Hybrid', 'Hybrid']
2032	['Barracuda', 'Barramundi', 'Barracuda', 'Baru', 'Bakkedal']	['Flettner_rotor', 'Air_lubrication', 'Propeller_duct', 'Hybrid', 'New_build']
2033	['Bantry', 'Baleen', 'Bangus']	['Air_lubrication', 'Hybrid', 'Hybrid']
2034	['Barcagena', 'Baiacu', 'Balzani', 'Barcagena', 'Balboa', 'Bass']	['Electrical_upgrade', 'Electrical_upgrade', 'Electrical_upgrade', 'Hybrid', 'Hybrid', 'Hybrid']
2035	['Bangor', 'Ballard']	['Hybrid', 'Hybrid']
2036	['Barcagena', 'Banastar', 'Balboa', 'Baiacu', 'Balzani', 'Balboa', 'Baiacu']	['Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Electrical_upgrade', 'Hybrid']
2037	['Barramundi', 'Bakkedal', 'Ballard', 'Baru', 'Barracuda', 'Barracuda', 'Baru', 'Barramundi', 'Barracuda']	['Scrubber', 'Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Air_lubrication', 'Electrical_upgrade', 'Shaft_generator', 'Shaft_generator', 'Hybrid']
2038	['Baleen', 'Baleen', 'Bangus', 'Bantry', 'Bangus']	['Scrubber', 'Air_lubrication', 'Air_lubrication', 'Shaft_generator', 'Shaft_generator']
2039	['Banastar', 'Balboa', 'Baffin', 'Bass', 'Balzani', 'Barcagena', 'Balboa', 'Baffin', 'Barracuda', 'Baiacu', 'Bass', 'Balzani']	['Scrubber', 'Scrubber', 'Scrubber', 'Scrubber', 'Scrubber', 'Shaft_generator', 'Shaft_generator', 'Shaft_generator', 'Shaft_generator', 'Shaft_generator', 'Shaft_generator', 'Shaft_generator']
2040	['Bangor', 'Bakkedal', 'Ballard', 'Bangor', 'Ballard']	['Scrubber', 'Scrubber', 'Scrubber', 'Air_lubrication', 'Shaft_generator']
2041	['Barcagena', 'Baiacu', 'Balboa', 'Baffin']	['Scrubber', 'Scrubber', 'New_build', 'New_build']
2042	['Baru', 'Barracuda', 'Ballard']	['Scrubber', 'Scrubber', 'New_build']
2043	['Bantry', 'Bangus']	['Scrubber', 'Scrubber']
2044	['Baru', 'Barracuda', 'Barramundi']	['New_build', 'New_build', 'New_build']
2045	['Baleen', 'Bangus']	['New_build', 'New_build']
2046	['Baiacu', 'Bass', 'Balzani']	['New_build', 'New_build', 'New_build']
2047	[]	[]
2048	[]	[]
2049	[]	[]
2050	[]	[]

Figure A22: Case 3 retrofit results for Klaveness' fleet

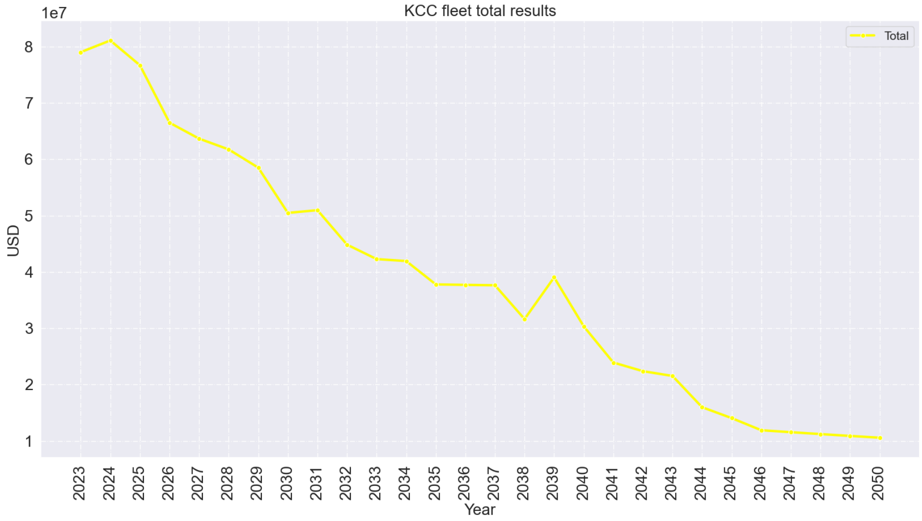


Figure A23: Case 3 total costs

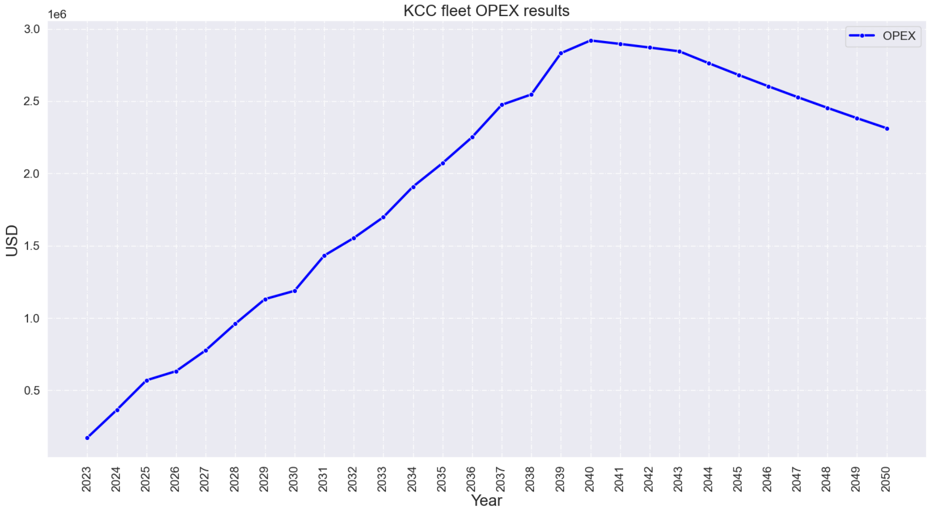


Figure A24: Case 3 OPEX

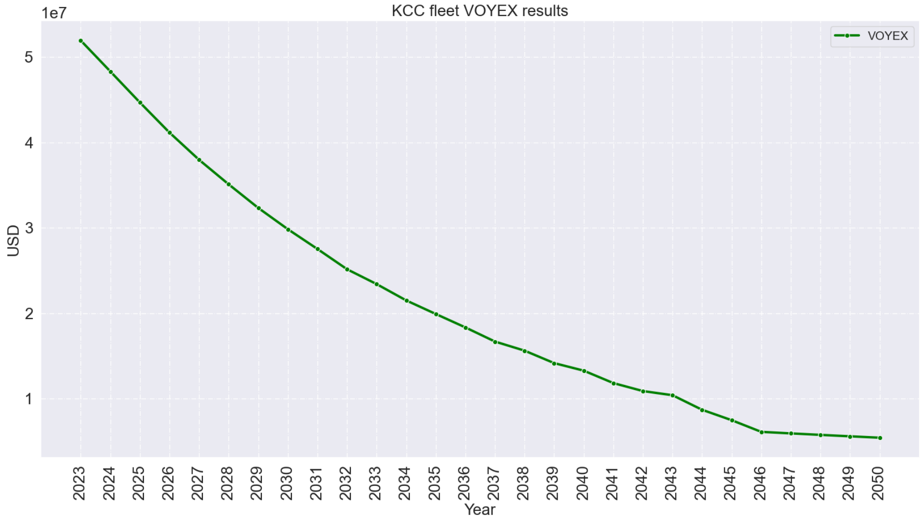


Figure A25: Case 3 VOYEX

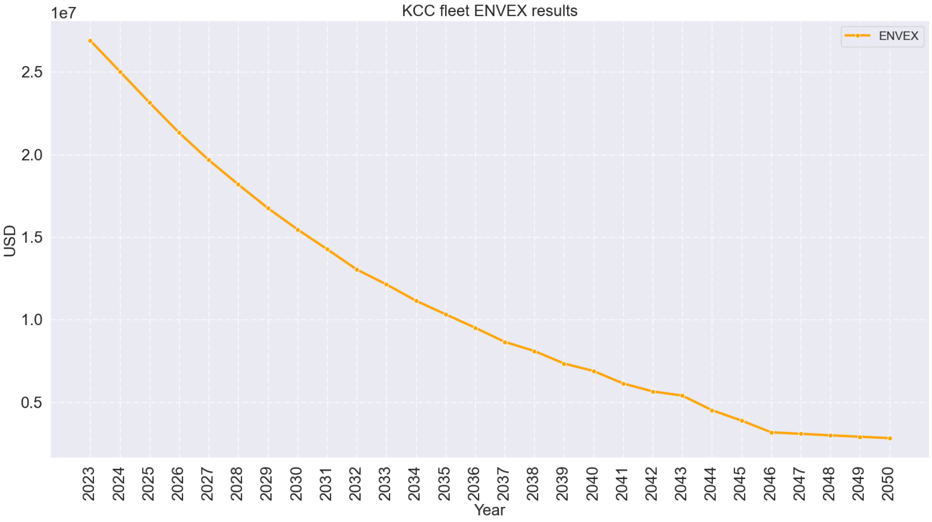
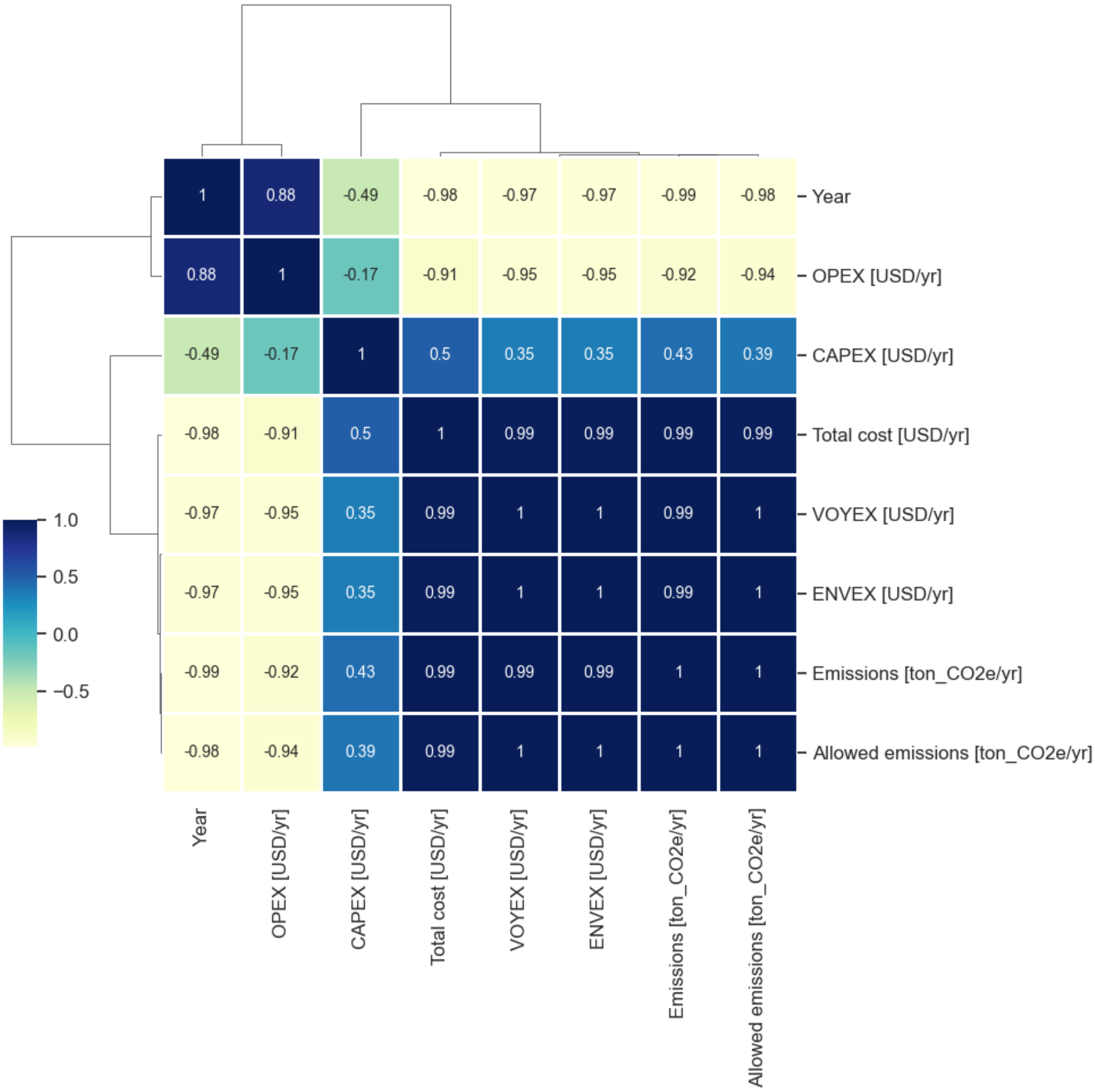


Figure A26: Case 3 ENVEX



	Year	OPEX [USD/yr]	CAPEX [USD/yr]	Total cost [USD/yr]	VOYEX [USD/yr]	ENVEX [USD/yr]	Emissions [ton_CO2e/yr]	Allowed emissions [ton_CO2e/yr]
Year	1	0.88	-0.49	-0.98	-0.97	-0.97	-0.99	-0.98
OPEX [USD/yr]	0.88	1	-0.17	-0.91	-0.95	-0.95	-0.92	-0.94
CAPEX [USD/yr]	-0.49	-0.17	1	0.5	0.35	0.35	0.43	0.39
Total cost [USD/yr]	-0.98	-0.91	0.5	1	0.99	0.99	0.99	0.99
VOYEX [USD/yr]	-0.97	-0.95	0.35	0.99	1	1	0.99	1
ENVEX [USD/yr]	-0.97	-0.95	0.35	0.99	1	1	0.99	1
Emissions [ton_CO2e/yr]	-0.99	-0.92	0.43	0.99	0.99	0.99	1	1
Allowed emissions [ton_CO2e/yr]	-0.98	-0.94	0.39	0.99	1	1	1	1

Figure A27: Case 3 clustermap

H Sensitivity analysis retrofit count

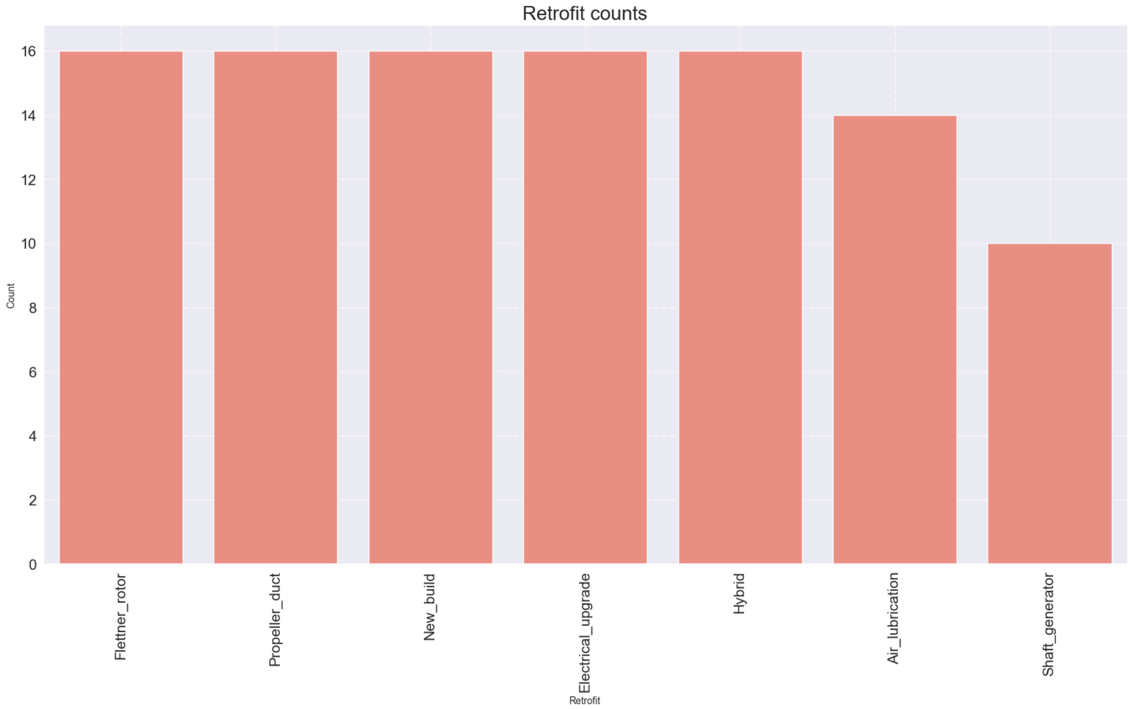


Figure A28: Retrofit counts case 3 optimistic narrative

I Poster

Master Thesis in Marine Technology
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Supervisor: Professor Stein Ove Erikstad
Co-supervisor: Martin Wattum (Torvald Klaveness)

Retrofitting a Deep Sea Shipping Fleet; Keeping Up With the IMO's and the EU's Emissions Targets

Problem

Retrofitting shipping vessels in the world's shipping fleet obtain the potential of its required decarbonization towards the IMO's future emissions targets. However, it must be economically and technologically viable options, attractive enough for both regulatory and market drivers to invest in.

Introduction

As a major contributor to global greenhouse gas emissions, the shipping industry is confronting stringent decarbonization targets set by the International Maritime Organization (IMO) [1] and the European Union (EU) [2]. Amid this regulatory pressure and growing public demand for sustainable transport, retrofitting vessels with emission-reducing technologies have emerged as a practical approach to greener shipping.

Retrofitting involves integrating green technology into existing ships, offering a potentially cost-effective alternative to building new, eco-friendly vessels from scratch. The challenge, however, lies in determining which retrofit option is suitable for each vessel within a diverse fleet. To address this complexity, this thesis proposes a linear optimization model to guide the retrofitting decision-making process.

The data utilized in this thesis is provided by the shipping company Torvald Klaveness, where the author of the thesis had an internship during the summer of 2022. The student proposed a collaboration throughout the master's thesis writing, which was accepted. The data contains information about all 16 vessels in Klaveness' fleet, including annual fuel consumption, emissions, and specific vessel dimensions information.

To solve the optimization problem, the data provided by Klaveness was used in a binary integer problem, utilizing Python and the optimization library Xpress [3]. The model is mathematically presented on the right-hand side.

The model determines the optimal timeline for retrofitting each vessel in a fleet with the most suitable technology, with the goal of achieving the IMO and EU's emissions reduction targets. Its effectiveness is demonstrated through three case studies, each targeting a different annual fleet emissions reduction: 3%, 4%, and 5%, respectively.

By providing a methodical approach to evaluating retrofitting options, this thesis aims to help Klaveness and the shipping industry develop viable decarbonization strategies. Ultimately, the goal is to contribute to the shipping industry's sustainable future, balancing its role in global trade with the urgent need to reduce its environmental footprint.

Model

The objective function of the fleet model is to minimize the total cost of retrofitting and operating vessels in the fleet. It includes the installation cost ($C^{AI}{}_r$) for retrofitting a vessel with a certain retrofit option and the operation cost ($C^{AO}{}_r$) for operating a vessel (v) with a certain retrofit option (r). Both costs are discounted to the present using a discount factor for calculating the net present value (NPV_r).

Constraint (1) restricts the emissions of the fleet making sure it does not exceed its total annual allowed emissions in the given year. Constraint (2) and (3) ensures that a retrofit option may only be installed on a vessel in the fleet once, and if an option is installed, the vessel must be operated with it. Constraint (4), (5) and (6) ensures that if a vessel is operating with a retrofit option, it must have been installed with it as well as operating with that option for the remaining time periods. Constraints (7) and (9) reduce a vessel's annual emissions by 25% representing its replacement with an equal but more efficient vessel due to it turning 25 years old, while also ensuring that neither of the vessels may be retrofitted after turning that age. Constraint (8) ensures that a vessel may only be retrofitted while in dry-dock, which is every 2.5 years. Constraint (10) presents binary variables.

Objective function

$$\min \mathrm{Z} = \min \sum_{v\in V}\sum_{r\in R}\sum_{t\in T}\frac{(C_r^{AI}x_{vrt} + C_r^{AO}y_{vrt})}{(1+NPV_r)^t} \tag{0}$$

Constraints

$$\sum_{v\in V}(E_v^V - \sum_{r\in R}\gamma_a E_v^V y_{vrt}) \leq E_y^{TOT}, \qquad \forall t\in T \tag{1}$$

$$\sum_{t\in T} x_{vrt} + I_{vr} \leq 1, \qquad \forall v\in V, \forall r\in R \tag{2}$$

$$M\sum_{t\in T} x_{vrt} + I_{vr} \geq \sum_{t\in T}, \qquad \forall v\in V, \forall r\in R \tag{3}$$

$$y_{vrt} \geq x_{vrt}, \qquad \forall v\in V, \forall r\in R, \forall t\in T \tag{4}$$

$$y_{vrt} \geq y_{vr(t-1)}, \qquad \forall v\in V, \forall r\in R, \forall t\in T/\{0\} \tag{5}$$

$$y_{vrt} - y_{vr(t-1)} = x_{vrt}, \qquad \forall v\in V, \forall r\in R, \forall t\in T/\{0\} \tag{6}$$

$$y_{vr1} - I_{vr} = x_{vr1}, \qquad \forall v\in V, \forall r\in R \mid Age_{vt} \;\&\; r\neq R/\{-1\} \tag{7}$$

$$x_{vrt} = 0, \qquad \forall v\in V, \forall r\in R, \forall t\in T \mid (Age_{vt} - Y_{vt}) \mod 5 \neq 0 \tag{8}$$

$$x_{vrt} = 1, \qquad \forall r\in R/\{-1\}, \forall v\in V, \forall t\in T \mid Age_{vt} > 25 \tag{9}$$

$$x_{vrt}, y_{vrt} \in \{0,1\}, \qquad \forall v\in V, \forall r\in R, \forall t\in T \tag{10}$$

Case studies

The three case studies take upon the optimization model developed using Python and the model described above. For each case, the annual allowed fleet emissions are increased by one percent relative to its total emissions in 2022.

In **case 1**, the annual CAPEX due to retrofit options installations, peaks at 4 million USD, and average on about 1.5 million until the year 2040. During the last 10 years of the time period, several new-builds will be introduced in the fleet, with each being 25% more efficient than the vessel it is replacing, eliminating the need for more retrofit installations. The annual requirement of a 3% emissions reduction for the fleet is respected, reducing the fleet's total emissions with about 56% within 2050. The annual OPEX increases proportionally with installations done to the fleet.

In **case 2**, the annual CAPEX peaks at 7 million USD, due to installations of retrofit options, while averaging on about 3 million. The lack of need for additional installations in the last third of the time horizon is caused by the same reason as for case 1. Likewise, the OPEX reflects the CAPEX increase. The fleet respects the requirement of an annual emissions reduction of 4%, projecting a reduction of 67% by 2050.

As for **case 3**, the annual CAPEX peaks on about 14 million USD, while averaging on about 5 million. The need for retrofit installations until 2043 is necessary, but dabbers off thereafter due to new-builds. The OPEX follows with installations to the fleet (CAPEX). Additionally, the fleet respects the requirement of reducing its total annual emissions by 5% due to the installations, aiming for a reduction of 75% by 2050.

Setting the annual required emissions reduction to 6%, the model is not able to find a feasible solution. Should Klaveness wish to reduce the fleet's emissions at this rate, other decarbonization measures should be considered, such as alternative fuel or electrifying the fleet.

References

[1] IMO, HYPERLINK, author: IMO, last visited: 29.05.23
[2] EU, HYPERLINK , author: the EU, last visited: 29.05.23
[3] Fico Xpress, HYPERLINK , author: Fico, last visited: 29.05.23

Acknowledgments

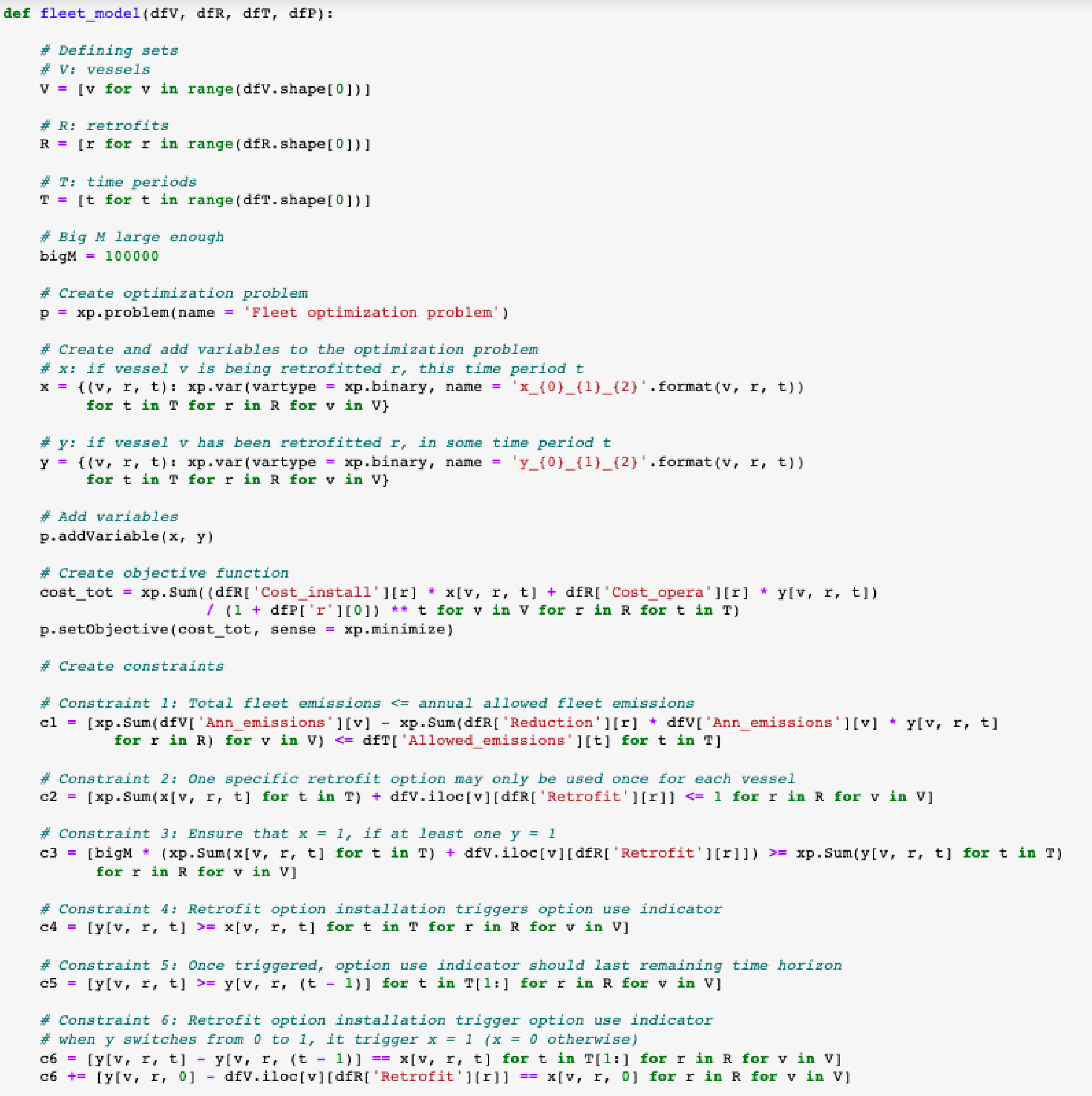
This work is submitted to The Norwegian University of Technology and Science (NTNU) in cooperation with the shipping company Torvald Klaveness as finishing requirements for the degree of Master of Science (MSc) in Marine Technology, written during the spring of 2023.

Conclusion

The graphical comparison compares the total costs including installation and operation costs of the fleet revealing a trend of increasing cost reductions with higher emissions reduction targets. At the beginning of the time horizon, the total costs of the fleet due to mainly fuel consumption and emissions taxes, average on about 80 million USD. With retrofit options installed throughout the respective timeline, the annual fuel consumption of the fleet reduces due to the rise in energy efficiency per vessel, and hence emissions decrease with respect to the required annual reduction, as depicted in the figure to the right. With lower fuel consumption and emissions, voyage expenses and taxes decrease proportionally.

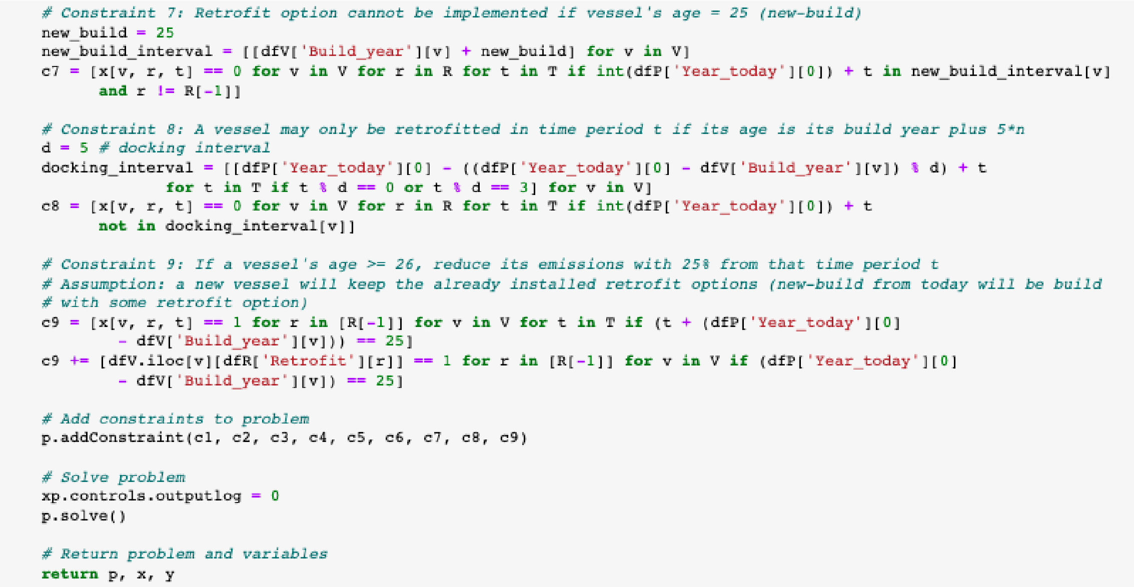
The downward-sloping trend for the total costs reveals that investments in retrofit options installations have an economic benefit for Klaveness' combination carrier fleet for all three narratives. The reduction in operational costs outweighs the installation costs for the retrofit options. Additional to being economically beneficial, Klaveness obtains the possibility of keeping up with IMO's and the EU's emissions targets within the coming ten years. However, by reaching net-zero within 2050, Klaveness will be required to implement heavier decarbonization measures, such as carbon-neutral fuel or integration of electricity into the fleet.

J Python code



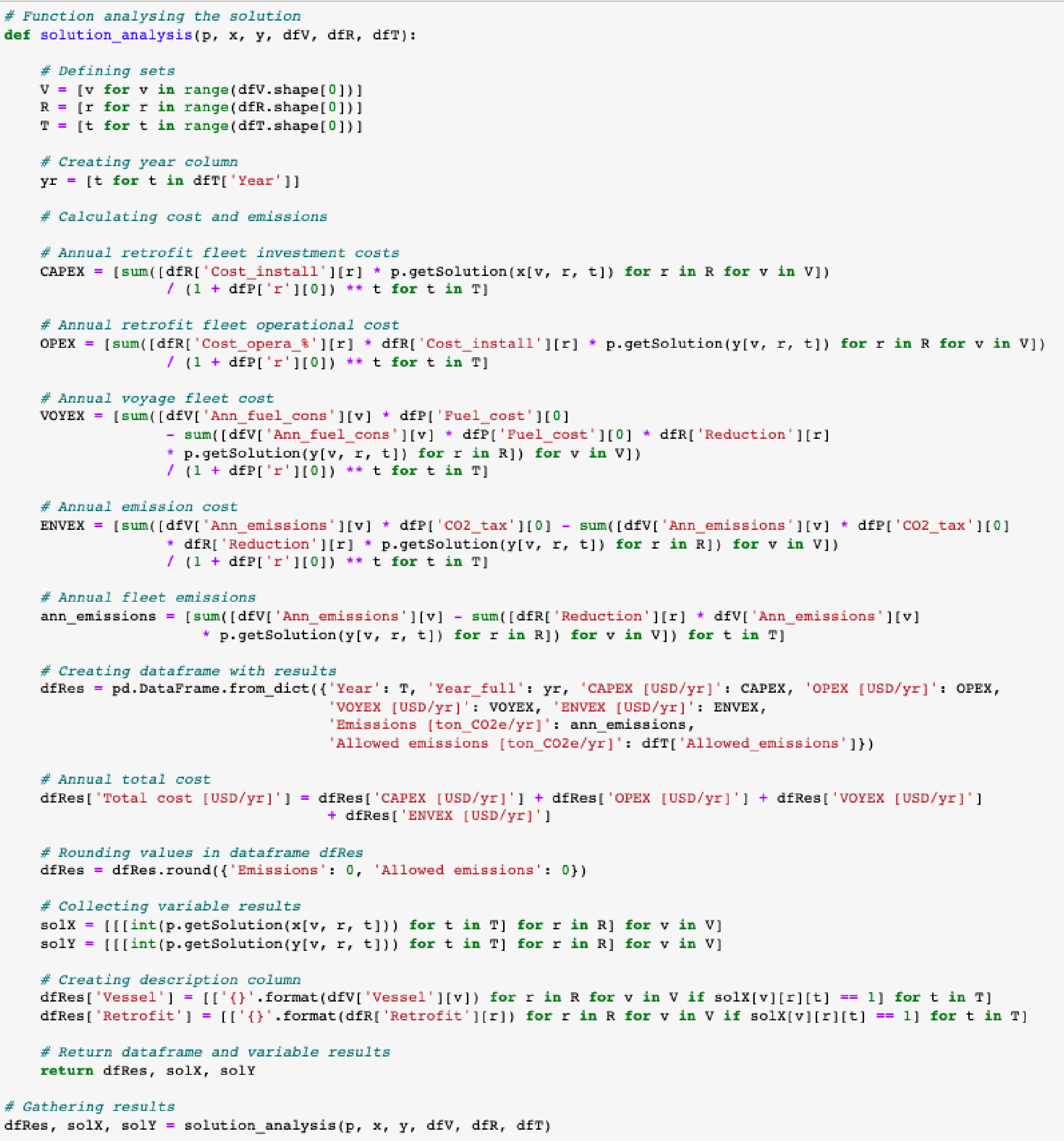
```
def fleet_model(dfV, dfR, dfT, dfP):

    # Defining sets
    # V: vessels
    V = [v for v in range(dfV.shape[0])]

    # R: retrofits
    R = [r for r in range(dfR.shape[0])]

    # T: time periods
    T = [t for t in range(dfT.shape[0])]

    # Big M large enough
    bigM = 100000

    # Create optimization problem
    p = xp.problem(name = 'Fleet optimization problem')

    # Create and add variables to the optimization problem
    # x: if vessel v is being retrofitted r, this time period t
    x = {(v, r, t): xp.var(vartype = xp.binary, name = 'x_{0}_{1}_{2}'.format(v, r, t))
         for t in T for r in R for v in V}

    # y: if vessel v has been retrofitted r, in some time period t
    y = {(v, r, t): xp.var(vartype = xp.binary, name = 'y_{0}_{1}_{2}'.format(v, r, t))
         for t in T for r in R for v in V}

    # Add variables
    p.addVariable(x, y)

    # Create objective function
    cost_tot = xp.Sum((dfR['Cost_install'][r] * x[v, r, t] + dfR['Cost_opera'][r] * y[v, r, t])
                      / (1 + dfP['r'][0]) ** t for v in V for r in R for t in T)
    p.setObjective(cost_tot, sense = xp.minimize)

    # Create constraints

    # Constraint 1: Total fleet emissions <= annual allowed fleet emissions
    c1 = [xp.Sum(dfV['Ann_emissions'][v] - xp.Sum(dfR['Reduction'][r] * dfV['Ann_emissions'][v] * y[v, r, t]
            for r in R) for v in V) <= dfT['Allowed_emissions'][t] for t in T]

    # Constraint 2: One specific retrofit option may only be used once for each vessel
    c2 = [xp.Sum(x[v, r, t] for t in T) + dfV.iloc[v][dfR['Retrofit'][r]] <= 1 for r in R for v in V]

    # Constraint 3: Ensure that x = 1, if at least one y = 1
    c3 = [bigM * (xp.Sum(x[v, r, t] for t in T) + dfV.iloc[v][dfR['Retrofit'][r]]) >= xp.Sum(y[v, r, t] for t in T)
          for r in R for v in V]

    # Constraint 4: Retrofit option installation triggers option use indicator
    c4 = [y[v, r, t] >= x[v, r, t] for t in T for r in R for v in V]

    # Constraint 5: Once triggered, option use indicator should last remaining time horizon
    c5 = [y[v, r, t] >= y[v, r, (t - 1)] for t in T[1:] for r in R for v in V]

    # Constraint 6: Retrofit option installation trigger option use indicator
    # when y switches from 0 to 1, it trigger x = 1 (x = 0 otherwise)
    c6 = [y[v, r, t] - y[v, r, (t - 1)] == x[v, r, t] for t in T[1:] for r in R for v in V]
    c6 += [y[v, r, 0] - dfV.iloc[v][dfR['Retrofit'][r]] == x[v, r, 0] for r in R for v in V]
```

Figure A29: Fleet model python code part 1



```
    # Constraint 7: Retrofit option cannot be implemented if vessel's age = 25 (new-build)
    new_build = 25
    new_build_interval = [[dfV['Build_year'][v] + new_build] for v in V]
    c7 = [x[v, r, t] == 0 for v in V for r in R for t in T if int(dfP['Year_today'][0]) + t in new_build_interval[v]
          and r != R[-1]]

    # Constraint 8: A vessel may only be retrofitted in time period t if its age is its build year plus 5*n
    d = 5 # docking interval
    docking_interval = [[dfP['Year_today'][0] - ((dfP['Year_today'][0] - dfV['Build_year'][v]) % d) + t
                 for t in T if t % d == 0 or t % d == 3] for v in V]
    c8 = [x[v, r, t] == 0 for v in V for r in R for t in T if int(dfP['Year_today'][0]) + t
          not in docking_interval[v]]

    # Constraint 9: If a vessel's age >= 26, reduce its emissions with 25% from that time period t
    # Assumption: a new vessel will keep the already installed retrofit options (new-build from today will be build
    # with some retrofit option)
    c9 = [x[v, r, t] == 1 for r in [R[-1]] for v in V for t in T if (t + (dfP['Year_today'][0]
            - dfV['Build_year'][v])) == 25]
    c9 += [dfV.iloc[v][dfR['Retrofit'][r]] == 1 for r in [R[-1]] for v in V if (dfP['Year_today'][0]
            - dfV['Build_year'][v]) == 25]

    # Add constraints to problem
    p.addConstraint(c1, c2, c3, c4, c5, c6, c7, c8, c9)

    # Solve problem
    xp.controls.outputlog = 0
    p.solve()

    # Return problem and variables
    return p, x, y
```

Figure A30: Fleet model python code part 2



```
# Function analysing the solution
def solution_analysis(p, x, y, dfV, dfR, dfT):

    # Defining sets
    V = [v for v in range(dfV.shape[0])]
    R = [r for r in range(dfR.shape[0])]
    T = [t for t in range(dfT.shape[0])]

    # Creating year column
    yr = [t for t in dfT['Year']]

    # Calculating cost and emissions

    # Annual retrofit fleet investment costs
    CAPEX = [sum([dfR['Cost_install'][r] * p.getSolution(x[v, r, t]) for r in R for v in V])
                  / (1 + dfP['r'][0]) ** t for t in T]

    # Annual retrofit fleet operational cost
    OPEX = [sum([dfR['Cost_opera_%'][r] * dfR['Cost_install'][r] * p.getSolution(y[v, r, t]) for r in R for v in V])
                  / (1 + dfP['r'][0]) ** t for t in T]

    # Annual voyage fleet cost
    VOYEX = [sum([dfV['Ann_fuel_cons'][v] * dfP['Fuel_cost'][0]
                  - sum([dfV['Ann_fuel_cons'][v] * dfP['Fuel_cost'][0] * dfR['Reduction'][r]
                  * p.getSolution(y[v, r, t]) for r in R]) for v in V])
                  / (1 + dfP['r'][0]) ** t for t in T]

    # Annual emission cost
    ENVEX = [sum([dfV['Ann_emissions'][v] * dfP['CO2_tax'][0] - sum([dfV['Ann_emissions'][v] * dfP['CO2_tax'][0]
                  * dfR['Reduction'][r] * p.getSolution(y[v, r, t]) for r in R]) for v in V])
                  / (1 + dfP['r'][0]) ** t for t in T]

    # Annual fleet emissions
    ann_emissions = [sum([dfV['Ann_emissions'][v] - sum([dfR['Reduction'][r] * dfV['Ann_emissions'][v]
                      * p.getSolution(y[v, r, t]) for r in R]) for v in V]) for t in T]

    # Creating dataframe with results
    dfRes = pd.DataFrame.from_dict({'Year': T, 'Year_full': yr, 'CAPEX [USD/yr]': CAPEX, 'OPEX [USD/yr]': OPEX,
                                    'VOYEX [USD/yr]': VOYEX, 'ENVEX [USD/yr]': ENVEX,
                                    'Emissions [ton_CO2e/yr]': ann_emissions,
                                    'Allowed emissions [ton_CO2e/yr]': dfT['Allowed_emissions']})

    # Annual total cost
    dfRes['Total cost [USD/yr]'] = dfRes['CAPEX [USD/yr]'] + dfRes['OPEX [USD/yr]'] + dfRes['VOYEX [USD/yr]']
                                    + dfRes['ENVEX [USD/yr]']

    # Rounding values in dataframe dfRes
    dfRes = dfRes.round({'Emissions': 0, 'Allowed emissions': 0})

    # Collecting variable results
    solX = [[[int(p.getSolution(x[v, r, t])) for t in T] for r in R] for v in V]
    solY = [[[int(p.getSolution(y[v, r, t])) for t in T] for r in R] for v in V]

    # Creating description column
    dfRes['Vessel'] = [['{}'.format(dfV['Vessel'][v]) for r in R for v in V if solX[v][r][t] == 1] for t in T]
    dfRes['Retrofit'] = [['{}'.format(dfR['Retrofit'][r]) for r in R for v in V if solX[v][r][t] == 1] for t in T]

    # Return dataframe and variable results
    return dfRes, solX, solY

# Gathering results
dfRes, solX, solY = solution_analysis(p, x, y, dfV, dfR, dfT)
```

Figure A31: Fleet model python code part 3

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