Master's thesis

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

Preben Kristen Olsen

# Decision support for renewal and retrofitting of the fleet of offshore supply vessels to guide the transition towards zero-emission logistics

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
Co-supervisor: Andreas Breivik Ormevik

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NTNU
Det skapende universitetet

# Master Thesis in Marine Systems Design
## Preben Olsen

## *«Decision support for renewal and retrofitting of the fleet of offshore supply vessels to guide the transition towards zero-emission logistics”*

## Spring 2023

### Background

The offshore supply sector is increasingly becoming a contributor to global emissions of greenhouse gases. As long as there is demand for oil and gas, the need for ships to transport goods and services to and from offshore locations is still there. The industry itself must succeed in reducing emissions to reach Norway’s climate goals for 2030 and 2050.

### Overall aim and focus

The main objective of this master thesis is to provide optimization-based decision support for fleet owners and key actors in Norway’s offshore industries to guide their transition toward more sustainable and low-emission logistics within its fleet.

### Scope and main activities

The candidate should presumably cover the following main points:

1. Describe the problem
2. Map the necessities of the offshore supply vessel fleet.
3. Present different fuel technologies for the future, and describe their potential for the platform supply fleet.
4. Present a literature review of similar problems and optimization models
5. Formulate a strategic “offshore vessel fleet renewal and retrofitting” optimization problem providing decision support on how to succeed in the transition towards zero-emission logistics.
6. Carry out a case study where the PSV fleet should meet new regulations with regard to $CO_2$ emission reduction.
7. Discuss and conclude

### Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. The work shall follow the guidelines given by NTNU for the MSc Project work.

# Abstract

This master's thesis introduces a mathematical model to address the maritime fleet renewal problem (MFRP) with a focus on emission control for platform supply vessels (PSVs). The model's primary objective is to guide ship owners on the optimal timing and selection of fuel technologies to incorporate into their fleet to comply with new regulations and achieve reductions in $CO_2$ emissions.

The literature review consists of an introduction to the PSV and its operations. Possible fuel options for the PSV fleet are showcased. Relevant literature regarding similar problems, modeling, and optimization is presented and used to construct a model.

To demonstrate the model's applicability, a computational study is conducted involving a fleet of three conventional-fuelled platform supply vessels operating in the North Sea. The study looks at potential different emission reduction strategies. One of them being IMO's 2030 and 2050 goals. The study results indicate that by 2030, the fleet would consist of three LNG-fuelled vessels and one retrofitted vessel utilizing MDO along with a carbon capture and storage system. Furthermore, by 2050, two of the LNG-fuelled vessels will be replaced with hydrogen-fuelled vessels, leading to a more sustainable fleet configuration and complying with IMO's goal.

Another key aspect of the computational study involves exploring various parameters to understand their impact and identify the optimal approach for modeling the MFRP with emission control.

The case study validates the effectiveness of the proposed model in generating strategic fleet renewal decisions based on the provided input. However, a notable concern arises regarding the accuracy of the input data concerning vessel design.

# Sammendrag

Denne masteroppgaven introduserer en matematisk model som løser det maritime flåte fornyelse problemet med et fokus på utslippskutt av $CO_2$ for forsyningsskip. Modellens primære mål er å veilede skipsredere om optimal timing og valg av hvilke drivstoffsteknologier som skal blir brukt av skipene i flåten for å oppfylle nye reguleringer med hensyn på $CO_2$ utslipp.

Litteraturstudie består av en introduksjon av forsyningsskip og deres operasjoner. Ulike drivstoffteknologier som forsyningsskip kan benyttes seg av er presentert. Tilslutt så er lignende problemer og modeller presentert og brukt til å lage en model.

For å demonstrer modellens anvendelighet, utføres en case-studie hvor en flåte på tre konvensjonelle forskyningsskip operer i Nordsjøen. Studien ser på ulike utslippreduksjons strategier, en av strategiene er IMO's 2030 og 2050 mål på å redusere utslippet $CO_2$ med henholdsvis 40 og 70 prosent. Med IMO's mål, blir resultatet at flåten fornyes i 2030 til å innholde tre LNG-drevene skip og et skip med karbonfangst og lagringssystemer ombord. I 2050 blir to av de LNG-drevene skipene erstattet med hydrogen-drevene skip, noe som resultere i en mer bærekraftig flåte som oppnår IMO's mål.

En annen viktig del av case-studien innebærer å utforske ulike parametere for å fortså deres påvirkning og finne den optimale måten å modellere det maritime flåte fornyelse problemet med et fokus på utslippskutt av $CO_2$.

Case-studien bekrefter effektiviteten til den foreslåtte modellen for å generere strategiske beslutninger om fornyelse av flåten basert på gitt inndata. Men det er en stor usikkerhet med tanke på nøyaktigheten til inndaten angående skipsdesignene.

# Preface

This thesis concludes my Master of Science in Marine Technology specializing in Marine Systems Design and Logistics at the Norwegian University of Science and Technology (NTNU). The thesis was written by Preben Kristen Olsen, spring 2023

I would like to thank my supervisors Professor Stein Ove Erikstad and Andreas Breivik Ormevik, for providing valuable guidance throughout the last year, with regard to the model, relevant literature, and good discussions. Further Elisabeth Lindstad for an interesting meeting about the future of the PSVs and fuel technology. A special thanks to Jose Jorge Agis from Ulstein for insights into the retrofitting and newbuilds of PSVs and technology evolutions. I would also like to thank André Risholm at Amon Maritime for knowledge about ongoing ammonia PSV projects and thoughts about the future. And lastly thanks to Endre Sandvik and Truls Flatberg for valuable insight in the industry.

A special thanks to my classmates for engaging discussions and creating a pleasant working environment.

Preben Kristen Olsen
Trondheim, June 2023

Preben Olsen

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# Abbreviations

| | |
|---|---|
| $AIRR$ | Average internal rate of return |
| $CAPEX$ | Capital expenditure |
| $CCS$ | Carbon capture and storage |
| $CO_2$ | Carbon dioxide |
| $ECA$ | Emission control areas |
| $GHG$ | Greenhouse gas |
| $kWh$ | Kilo watt hours |
| $LNG$ | Liquid natural gas |
| $LH_2$ | Liquid hydrogen |
| $LHV$ | Lower heating value |
| $MD\mathbf{O}$ | Marine diesel oil |
| $METS$ | Maritime emission trading system |
| $MFRP$ | Maritime fleet renewal problem |
| $MFSMP$ | Maritime fleet size and mixture problem |
| $NH_3$ | Ammonia |
| $NO_x$ | Nitrogen oxides |
| $SFC$ | Specific fuel consumption |
| $SO_x$ | Sulfur oxides |
| $TTW$ | Tank-to-wake |
| $VRP$ | Vehicle routing problem |

| | |
|---|---|
| $VOYEX$ | Voyage expenditure |
| $WWT$ | Well-to-wake |

# Chapter 1

# Introduction

Norway has for decades been one of the major exporters of oil and gas through high activity from drilling and production platforms across a large part of the North Sea. A crucial part of maintaining a reliable production is effective logistics planning. Every day, even in extreme weather conditions, voyages must be scheduled for a large fleet of platform supply vessels (PSVs) to service the installations with the required demands for technical equipment, chemicals, and consumable cargoes.

The activity on the Norwegian Continental Shelf faces several challenges over the next years: new climate action targets in the EU will shrink the demand for oil and gas products, and the industry itself must succeed in reducing emissions from production to reach Norway's climate goals for 2030 and 2050. Despite reductions in oil and gas demand, the activity level in the North Sea will remain high. The largest oil and gas fields will continue to produce towards 2060, while major efforts will be required in the tasks of plugging and abandoning wells in older fields.

Even though the ambitions and goals are well defined, there is a lack of knowledge on how to reach them. Furthermore, technology development is subject to a large degree of uncertainty. Lastly, the timing of the decisions to make is important. A large fleet of conventional vessels is still in operation, and many of them will continue to operate for several years. A more economically reasonable option than scrapping these vessels is to modify their fuel and propulsion system to more sustainable alternatives. We need a decision support tool to guide when the changes to the fleet should happen.

Efficient sailing is a stepping stone towards reaching the emission goal but there is a need for new fuel technologies combined with new vessel concepts to comply. Therefore the main objective of this project thesis is to provide optimization-based decision support for fleet owners and key actors in Norway's offshore industries to guide their transition towards more sustainable and low-emission logistics.

The objectives are highly ambitious, entailing a mandate to curtail carbon emissions by a minimum of 40% before 2030 (referred to as the ’2030 Goal’), while concurrently striving to achieve a 70% reduction by 2050, relative to the 2008 emissions level(IMO 2023).

The offshore supply sector is increasingly becoming a contributor to global emissions of air pollutants and greenhouse gases. As long as there is demand for oil and gas, the need for ships to transport goods and services to and from offshore locations is still there. These vessels are responsible for a portion of 1.2-1.4% of Norway’s $CO_2$ emissions(Risholm 2020), and the industry as a whole is working to reduce its impact on the environment. New industries will emerge in the future when the oil and gas stops, like offshore wind production, which will require many complex maritime operations.

When it comes to the domestic $CO_2$ emissions from the shipping and offshore industry, the offshore supply vessels are the second biggest contributor only beaten by the passenger ships. A good place to start to easily see results in the reduction of emissions.

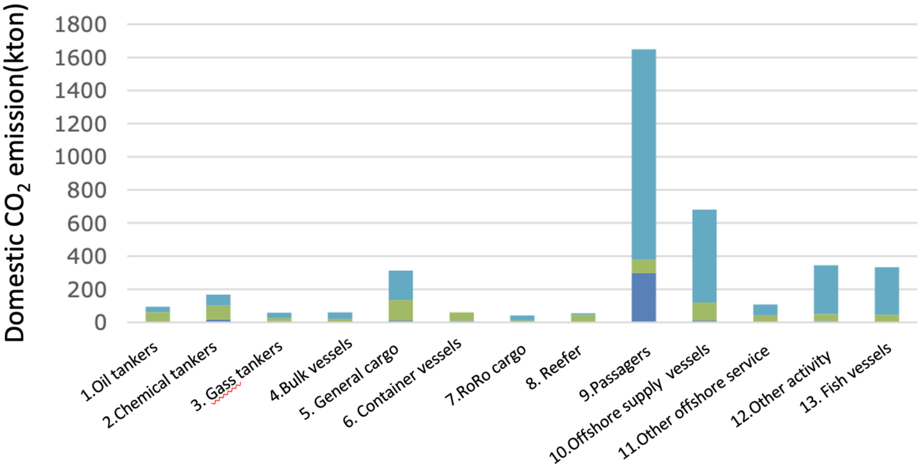


Figure 1.1: Domestic $CO_2$ emission in 2030, section in ship type and operational time in Norwegian water (DNV 2018).

## 1.1 Objective

The objective of this master’s thesis is to develop a strategic decision optimization model for fleet renewal. The model aims to assist in determining the optimal timing for fleet renewal and making informed choices regarding the most appropriate fuel technologies, including the evaluation of retrofitting options versus new builds. As the shipping industry is undergoing a transition toward zero-emission, this model will consider the landscape of different carbon-neutral fuel options and their impact on the fleet renewal decision. The model will be tested using a case study from the North Sea, to provide practical insights into the application of the model.

## 1.2 Structure of report

Chapter 2 provides a literature review on platform supply vessels. Chapter 3 explores and analyzes different fuel options for future use in platform supply vessels. Similar problems are investigated in chapter 4, where a thorough examination of relevant research is conducted. Chapter 5 outlines the problem statement, providing a clear description of the research problem addressed in the thesis. In chapter 6, the notation and mathematical formulation of the model utilized in the study are presented. Chapter 7 showcases the application of the model by solving two different cases, illustrating its practical implementation. A discussion of the thesis findings is presented in chapter 8, offering critical insights and interpretations. The conclusion of the thesis is summarized in chapter 9, highlighting the main outcomes and contributions of the research. Lastly, chapter 10 outlines future research directions and potential areas for further investigation.

# Chapter 2

# PSV

Platform supply vessels (PSVs) are commonly referred to as the workhorses of the offshore supply chain, playing a role similar to that of bulk carriers in the shipping industry. The primary function of a PSV is to facilitate the transportation of liquid or dry cargo from onshore supply bases to oil and gas platforms. Such cargo may include, but is not limited to, drilling mud, cement, potable water, pipes, spare parts, and various equipment.

PSVs are typically chartered by oil companies through either a time charter or a voyage charter. Under these arrangements, the oil company assumes full control over the vessel's operations and logistics throughout the charter period. However, vessel owners may specify certain requirements, such as allocating a few days in port for routine maintenance.

Figure 2.1: CBO ITAJAÍ (Ulstein 2023).

Several properties are crucial for a PSV in order to fulfill its operational requirements. First and foremost, ample deck space is essential to accommodate cargo efficiently. Additionally, a PSV needs sufficient tank storage capacity to transport various types of goods effectively.

To ensure safety, a PSV should possess a robust sailing capability that enables it to operate in diverse weather conditions. Moreover, the inclusion of a dynamic positioning system is essential as it facilitates safe unloading in close proximity to offshore platforms.

Efficient pumps are necessary for the transfer of liquid cargo, ensuring smooth and timely operations. Furthermore, a PSV should be equipped with firefighting equipment to address any fire-related incidents that may occur onboard. Adequate measures to prevent and manage oil contamination risks are also critical to ensure environmental safety and compliance.

These properties collectively contribute to the overall functionality and reliability of a Platform Supply Vessel, enabling it to effectively support offshore operations.

To accommodate all the mentioned properties, typical PSV often possess the characteristics outlined in Table 2.1.

| | | |
|---|---|---|
| Installed power | 4000-8000 | kW |
| Fuel tank | 200-300 | m3 |
| Average fuel consummation | 7-10 | days |
| Autonomy | 30 | days |
| Dwt | 3000-5000 | tonn |
| Length | 70-95 | m |
| Average transit speed | 8-12 | knots |

Table 2.1: Typical values for a PSV from talks with representatives from Amon Maritime.

## 2.1 Supply chain for upstream logistics

The logistics of the offshore can be split into up and downstream logistics(Aas et al. 2009). Downstream logistics is related to bringing oil and gas to customers onshore. Upstream logistics is related to supplying offshore production and drilling platforms with needed supplies. Its in the upstream logistics the platform supply vessels play a vital part. The expenses incurred due to disruptions and idle periods during the operation of offshore production facilities are considerable. Therefore, the provision of supplies to these platforms holds significant importance for their proprietors.

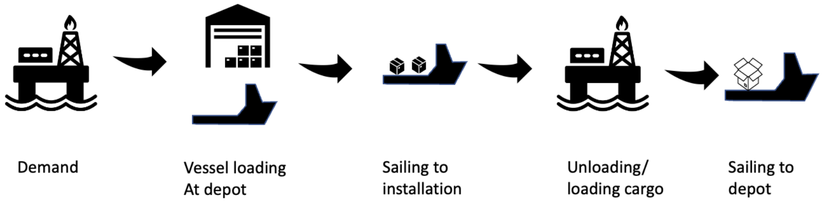


Figure 2.2: Supply chain of PSV based on Aas et al. (2009).

Figure 2.2 illustrates the supply chain for upstream logistics in the offshore industry. Offshore installations have a continuous demand for supplies when operating. These supplies are provided by PSVs, the cargo may vary from liquid cargoes to deck cargo. Generally, the cargo demand for the installations typically follows a schedule with regulatory visits. However, there are instances where installations may unexpectedly require additional cargo. This need is more common for drilling installation then production installations, as operations tend to be more demanding and uncertain (Aas et al. 2009).

At the onshore depot the vessels are loaded with the desired cargo requested by the offshore installations. Important aspects to consider before departure include cargo stowage, deck utilization, stability and weight distribution to ensure a safe voyage.

Upon reaching the installations, the unloading process begins, which is the most critical operation in the supply chain(E. Halvorsen-Weare and Fagerholt 2017). To ensure the vessel remains stationary during this process, dynamic positioning (DP) systems play a crucial role. Additionally, once the cargo has been unloaded, the installations can dispose of any redundant products they may have, bringing it back to shore.

## 2.2 Offshore installations

Oil and gas have been extracted from a cumulative of 120 fields on the Norwegian continental shelf since production commenced in 1971. As of the end of 2022, 93 fields were operational, with 70 located in the North Sea, 21 in the Norwegian Sea, and two in the Barents Sea(NPD 2023).

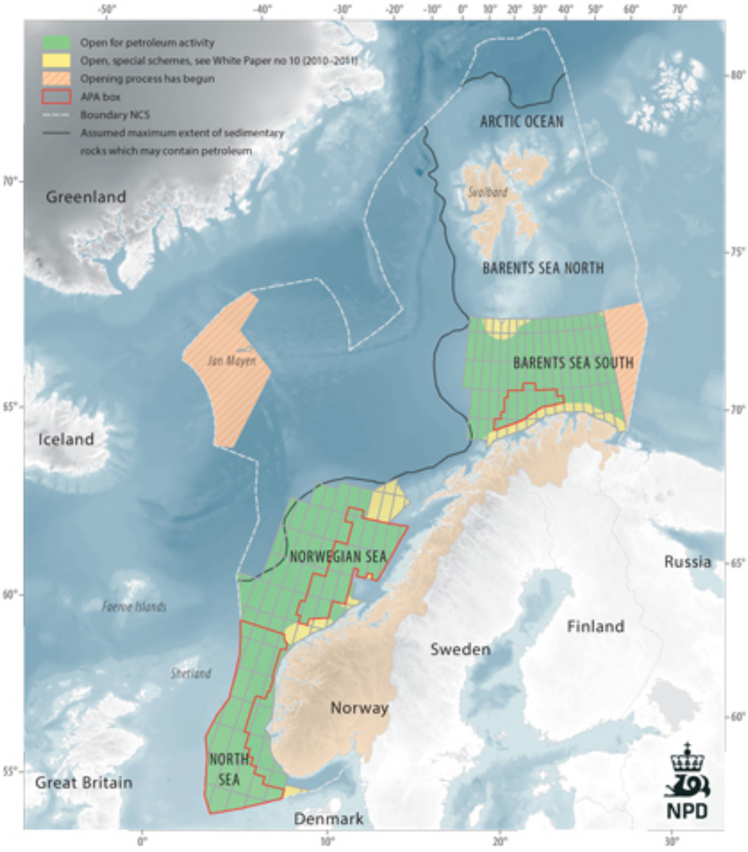


Figure 2.3: Norwegian continental shelf (NPD 2023).

Offshore installations are man-made structures located beyond the coastal zone.

Designed for operation in hash marine environments. These installations vary from wind turbines, oil and gas platforms, and aquaculture farms. In this thesis, the focus is on oil and gas platforms and drilling units, which will be referred to as offshore installations.

Figure 2.4: PSV operating at offshore installation(Rotex 2023).

# Chapter 3

# Possible fuel options

This chapter will examine different fuel options for the PSV fleet. It will outline the characteristics of each fuel, assess their level of readiness for implementation, and analyze their emission profiles.

## 3.1 Ammonia

The interest in utilizing ammonia($NH_3$) as a fuel for the shipping industry has increased with the pressure to reduce $CO_2$ emissions. Ammonia serves as a hydrogen carrier, offering several advantages over liquid hydrogen($LH_2$). Notably, ammonia has a higher volumetric energy density, resulting in smaller fuel tanks to keep operational properties more or less intact. Ammonia, with its boiling temperature of -33.4 degrees, offers advantages in terms of cost and ease of cooling compared to other hydrogen carriers. The lower boiling point of ammonia simplifies the cooling process, making it a more affordable and manageable option for utilizing hydrogen.

Ammonia can be classified into three categories: green, blue, or grey, depending on the production process and its carbon emission. Green ammonia has been produced using electricity from renewable energy sources. This ensures a minimal carbon footprint for the production. Grey ammonia uses fossil fuels to produce the ammonia. Blue ammonia includes carbon capture and storage in the production of ammonia using fossil fuels.

Some challenges with ammonia are toxicity and low flammability. However, when looking at the potential zero-carbon fuels for use in the maritime sector Amon Maritime has concluded that ammonia is the fuel to pursue(Risholm 2020). It's easier to handle than $CH_2$ and $LH_2$, bunkering offshore is safer. Hydrogen is highly explosive and a huge safety hazard when the PSV is working on oil fields.

Azane Fuel Solutions has initiated a project aimed at establishing ammonia fuel stations. They provide two options: floating and onshore fuel stations. During the initial stages of fleet transition, the preference is given to floating fuel stations due to their ease of relocation. The transition process has already commenced, as evidenced by Yara International's order for 15 floating fuel stations in 2022. Figure 3.1 illustrates the supply chain for providing the vessels with fuel.

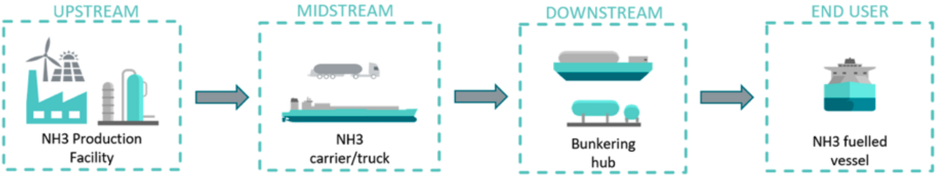


Figure 3.1: $NH_3$ supply chain obtained from Azane (2023).

## 3.2 Hydrogen

Hydrogen can be produced from different energy sources, from fossil fuels or electrolysis of renewable energy sources. However today about 95% of the hydrogen is produced from natural gas, oil, and coal. This results in grey hydrogen, if the $CO_2$ emission from the production stage is captured and stored, it would be called blue hydrogen.

To be able to store the hydrogen as fuel onboard a vessel it can either be stored as a cryogenic liquid, compressed gas, or chemically bound. The boiling point for hydrogen is -253 degrees at 1 bar. Liquid hydrogen has an energy density of 120 MJ/kg and a volumetric density of 71kg/$m^3$. This translates into needing five times more volume to store the liquid hydrogen when compared to HFO. Thus, transitioning from conventional vessels to those powered by hydrogen fuel would need modifications in their operational attributes. Specifically, in order to sustain a comparable range of navigation, the dimensions of the vessel would need to be augmented or there would be a substantial decrease in cargo capacity.

According to DNV (2019), the capital expenditure(CAPEX) for hydrogen-fueled vessels is anticipated to be higher compared to LNG-fueled vessels. Despite similarities in certain equipment such as piping, heat exchangers, and ventilation, the cost of fuel tanks for $LH_2$ is expected to be more expensive due to the requirements of extremely low temperatures. The operational expenditure(OPEX) is projected to be similar to an oil-fueled system. This suggests that while the initial investment in hydrogen-fueled vessels may be higher, the ongoing operational costs are expected to remain comparable to traditional oil-based systems.

## 3.3 LNG

Liquid natural gas(LNG) serves as the cleanest fossil fuel available on the market today(DNV 2019). Due to its boiling point of -162 degrees Celsius, LNG requires insulated tanks for storage. In terms of volumetric density, LNG is approximately 43% of HFO, necessitating nearly double the tank capacity to store an equivalent amount of energy.

LNG offers notable emission reductions compared to HFO. It emits no sulfur oxides ($SO_x$) and considerably fewer nitrogen oxides ($NO_x$). Switching to LNG results in a 23% reduction in carbon dioxide ($CO_2$) emissions, as reported by Thinkstep 2019. For a 4-stroke engine utilizing LNG, the emission rate is approximately 155.8 grams per kilowatt-hour ($g/kWh$).

According to DNV (2019), the initial capital expenditure (CAPEX) for LNG-fueled vessels is currently higher compared to similar vessels powered by HFO. However, it is predicted that as more stakeholders enter the market, the CAPEX for LNG-fueled vessels will decrease over time. LNG systems on board vessels have a similar OPEX to MDO system and roughly the same efficiency as a conventional fuelled system.

## 3.4 Onboard carbon capture and storage

There is an increasing interest among companies worldwide in implementing Carbon Capture and Storage (CCS) technology onboard vessels. The ambition of engine manufacturers is to capture up to 70 - 100 % of the CO2 from the exhaust gas from the combustion engines onboard. A vast amount of additional energy is used in this process, but “heat-recovery” onboard technology can reduce the amount of extra energy used for CCS. The solution also requires a large storage capacity on board, which in some cases is not possible for some vessels.

As there will be a limited amount of “carbon-neutral energy” going forward, a good option is to also utilize existing types of fuel and clean the exhaust for long haul / deep sea trading. To reach the zero-emission target, it will be far too costly and almost practically impossible to procure sufficient “carbon-neutral energy”. The production of “carbon-neutral energy” also causes a vast loss of energy.

Going forward, CCS onboard can become an economically exciting solution to an almost unsolvable problem due to fuel availability and infrastructure to tackle the shift to “carbon-neutral energy”. Handling of accumulated CO2 on land is under development in several locations around the world, and with a high focus on “green corridors” it will make the use of this solution more competitive than other energy sources.

This solution with the right technology might be the cheapest way to reach official targets for cuts in greenhouse gas emissions in a world with a major shortage of renewable energy and is hence included as a feasible fuel technology option for the fleet renewal problem for PSVs.

## 3.5 Well to wake or tank to wake

There are three different perspectives to consider when evaluating emissions from various fuels: well-to-tank (WTT), tank-to-wake (TTW), and well-to-wake (WTW). Although some fuels, such as hydrogen, may have low emissions during the tank-to-wake stage, the overall emissions may be much higher when taking into account the production process. Figure 3.6 displace the supply chain for fuels utilized by vessels.

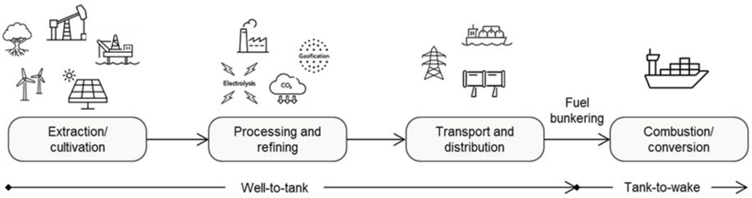


Figure 3.2: Well-to-wake supply chain from IMO (2021).

Switching from fossil fuels to alternative fuels will only be effective if the alternative fuels are produced from renewable energy sources. In a study by Lindstad et al. (2021), the potential for GHG reduction in the maritime sector was researched. The study concluded with the reduction potential of electrofuels depends on the abundance of renewable electricity. However, at present, the well-to-wake emission from potential zero-emission fuels, are significantly higher than those of fossil fuels.

One important aspect to consider when deciding whether to switch to more carbon-neutral fuels is the required energy required to produce one kWh onboard the vessel. Figure 3.3 shows how much kWh is needed for different fuel technologies to provide one kWh onboard the vessel. In a world where renewable energy is limited, it raises the question of whether renewable energy could be better utilized. If E-fuels were fully deployed in the shipping industry, the industry might double or triple its energy consumption (Lindstad et al. 2021). DNV anticipates that by 2050 more the half of the world's energy demand will be supplied by renewable energy.

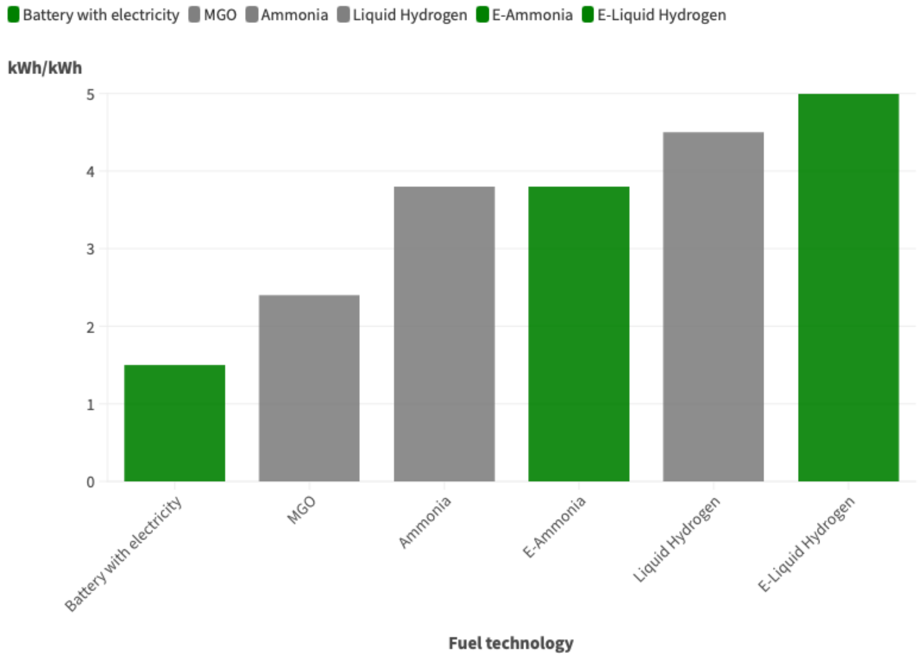


Figure 3.3: WTW - the energy required as a function of fuel per kWh delivered at the propeller. Values taken from Lindstad et al. (2021).

## 3.6 Comparative Evaluation of Fuels

The values and data presented in this section will serve as crucial inputs for the model used to solve the problem presented in this thesis. These inputs will enable the model to incorporate accurate and relevant information, facilitating the analysis, optimization, and decision-making processes within the problem domain

The availability of fuel technologies changes as technologies and solutions evolve. Today both hydrogen and ammonia are not available at a large commercial scale(DNV 2021). There are a few concepts utilizing these fuels today but they require new infrastructure to supply the vessels with fuel as it's not been developed enough at present time. According to DNV's forecast, hydrogen and ammonia are projected to become commercially available by 2030 for use in both internal combustion engines and fuel cells.

In 2020, Equinor entered into a contract with Eidesvik Offshore to retrofit the Viking Energy supply vessel and convert its fuel source to ammonia(Equinor 2023). The vessel is scheduled to start operations in 2024, with the goal of deriving 70% of its power requirements from ammonia. Furthermore, Amon Maritime has outlined plans to develop and deliver fully ammonia-fueled vessels by 2050(Bræin 2023).

Among the alternative fuels investigated in this thesis, LNG is the only one that is currently fully commercially applicable. As of 2019, there were 500 LNG carriers utilizing LNG as fuel(DNV 2019). Furthermore, LNG has also been adopted in the PSV fleet, with Siem Offshore operating three large-sized PSVs powered by LNG. This indicates the successful integration of LNG as a fuel option within the maritime industry, demonstrating its feasibility and potential for wider adoption.

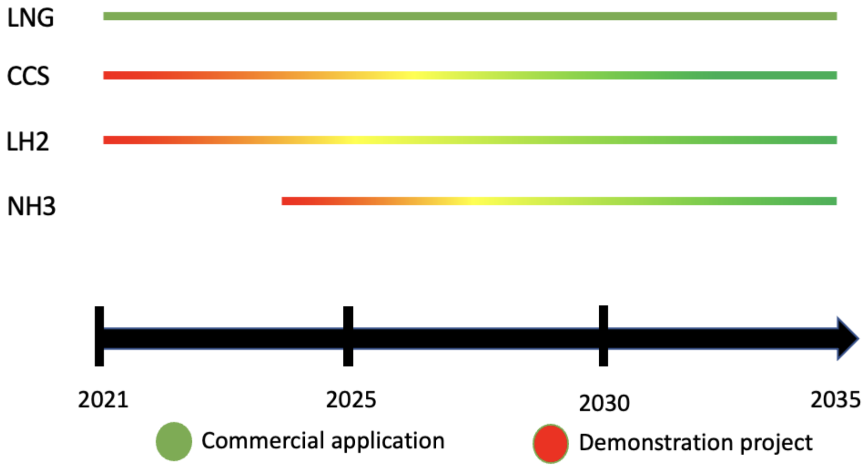


Figure 3.4: Expected timeline for availability of alternative fuel technologies. Based on DNV (2021).

As previously described, each fuel exhibits distinct properties and characteristics, consequently necessitating varying fuel tank volumes and supporting equipment to maintain the fuels at their desired temperature and pressure. Figure 3.5 illustrates the required volume for the various fuels with MDO as the reference.

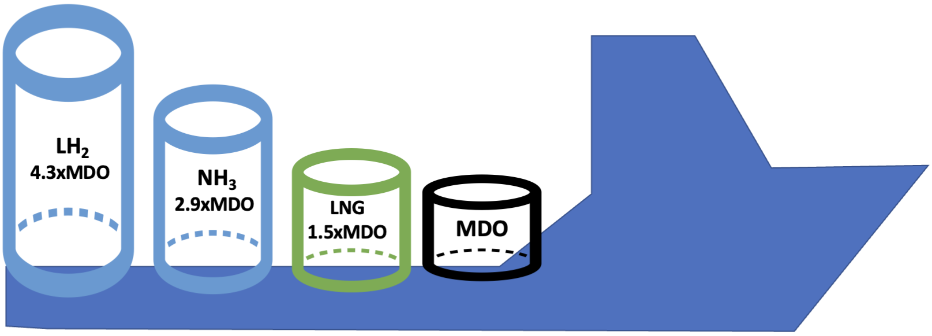


Figure 3.5: Relative volume per unit of energy.

Figure 3.6 showcases the WTW emission for the various fuels. Notably, liquid hydrogen possesses the highest emission factor, primarily due to the significant amount of energy required during the production of the fuel. However, its counterpart, E-liquid hydrogen, is emission-free as it is solely produced using renewable electricity. The same applies to ammonia and E-ammonia, which are also produced solely with renewable electricity, resulting in zero emissions throughout their life cycle.

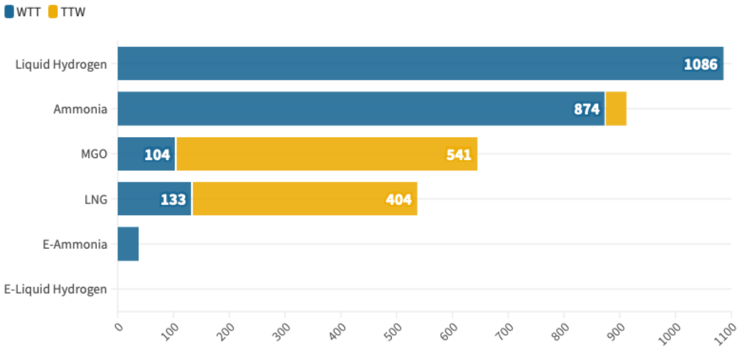


Figure 3.6: WTW emission in gram $CO_2$ per kWh for different fuels based on Lindstad et al. (2021).

## 3.7 Carbon tax

To advance decarbonization efforts, it is essential to implement a carbon tax that incentivizes ship owners to choose for more environmentally friendly fuels in the future. Figure 3.7 illustrates the expected carbon price in the future.

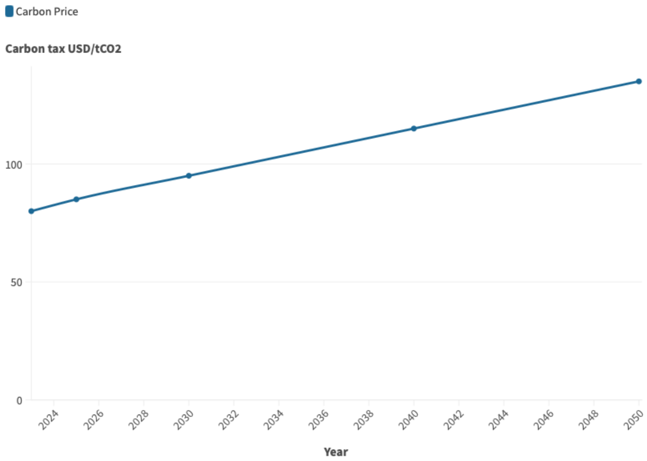


Figure 3.7: Expected carbon price for Europe inspired by (DNV 2021).

Chapter 4

# Literature review

The main focus of this thesis is to solve the maritime fleet renewal problem(MFRP) with emission constraints. In this chapter, a review of relevant literature for solving the MFRP is presented. The literature review focuses on maritime fleet size and mixture problem(MFSMP) and MFRP. By investigating existing literature, the aim is to identify key methodologies and approaches used to handle similar problems.

## 4.1 Vehicle routing problem

Vehicle routing problems are problems regarding the distribution of products between depots and customers. The problems can include time schedules when products need to be delivered. A vehicle routing problem can be formulated as a set partitioning problem(Balinski and Quandt (1964)). In this formulation, the distance of a specific route is denoted as $d_r$, where $r$ represents the route index. The binary variable $z_r$ indicates whether a route is used or not. Parameter $a_{ir}$ represents the value 1 if installation i is included in route r, otherwise 0. Lastly, $m$ represents the total number of vehicles available for the routing problem.

$$\min \sum_{r \epsilon R} d_r z_r \tag{4.1}$$

subject to:

$$\sum_{r \epsilon R} a_{ir} z_r = 1 \qquad i \epsilon V \backslash \{0\} \tag{4.2}$$

$$\sum_{r \epsilon R} z_r = m \tag{4.3}$$

$$z_r = \{1, 0\} \qquad r \epsilon R \tag{4.4}$$

The objective function 4.1 minimizes the total distance traveled. Constrain 4.2 guarantees that each installation is visited once. Constrain 4.3 secures that a total of m vessels are utilized. Constrain 4.4 determines whether a route is included or excluded in the solution.

Formulating the Vehicle Routing Problem (VRP) as a set partitioning problem offers advantages in terms of ease of solution and modeling. By considering the routes as feasible routes included in the model, it simplifies the problem and reduces the number of constraints within the model.

## 4.2 Maritime fleet size and mix problem

The MFSMP is a significant challenge in the maritime industry that involves determining the optimal fleet size and composition to efficiently meet demand while minimizing costs. The MFSMP is of great importance to shipping companies, as it directly affects their operational efficiency and profitability.

In general, the MFSMP involves deciding what types and how many vessels are required to transport goods or passengers between different locations, while taking into account factors such as demand patterns, distance, vessel availability, fuel consumption, crew costs, and cargo handling requirements. The goal is to find a cost-effective fleet configuration that meets demand while minimizing total operating costs.

Pantuso et al. (2014) provides a concise illustration of the MFSMP, by a basic formulation of the problem. The author formulates a simple example that can be used to demonstrate the main aspects of the MFSMP.

$$Min \sum_{v \epsilon V} C_v^F y_y + \sum_{v \epsilon V} \sum_{r \epsilon R_v} C_{vr}^V x_{vr} \tag{4.5}$$

**s.t.**

$$\sum_{r \epsilon R_v} Z_{vr} x_{vr} - Z y_v \leq 0, v \epsilon V \tag{4.6}$$

$$\sum_{v \epsilon V} \sum_{r \epsilon R_v} A_{ir} x_{vr} \leq D_i, i \epsilon N \tag{4.7}$$

In objective function(4.5), the set of available ship types is denoted by $V$, and for each ship type $v$, the set of routes that the ship can sail is denoted by $R_v$. The fixed term of the objective function is expressed as $C_v^F$ times the number of ships of type $v$, denoted by variable $y_v$, representing the cost of including a ship of type $v$ in the fleet. The variable term of the objective function is expressed as $C_{vr}^V$ times the number of times route $r$ is sailed by ships of type $v$, denoted by variable $x_{vr}$, representing the cost of sailing route $r$ with ships of type $v$.

Constrain 4.6 ensures that the time $Z_{vr}$, which represents the duration that vessel $v$ spends on sailing route $r$, remains within the total allocated time for each vessel within the planning horizon. Constrain 4.7 makes sure the required port calls $D_i$ for each port are satisfied. The parameter $A_{ir}$ takes a value of 1 if route $r$ includes port $i$ and 0 otherwise.

Alvarez et al. (2011) proposed a mixed integer robust fleet sizing and deployment model for the bulk shipping marked. It will help ship owners with decisions like sale, purchasing, chartering, lay-ups, and scrapping of vessels with a certain degree of risk.

E. E. Halvorsen-Weare et al. (2012) presented a model for the optimal offshore supply vessel fleet size and corresponding weekly voyages together with the schedules. The model has a voyage-based approach, where all the possible voyages are made in advance before being put into the model for optimal fleet size. Further research should be done when it comes to the robustness of the schedules.

E. Halvorsen-Weare and Fagerholt (2017) addresses the offshore supply vessel planning problem. This problem aims to determine the optimal fleet size and mix of OSVs, along with their optimal routes for servicing oil and gas installations with one depot. The study proposes both an arc flow and voyage-based model. The research reveals that the voyage-based model outperforms the arc flow model. When considering multiple depots in the model, likely, the model would not be sufficient. This paper analyzes the robustness of schedules, as mentioned in E. E. Halvorsen-Weare et al. (2012). Specifically, it examines the influence of weather conditions on schedule execution and presents robust approaches to obtain solutions that effectively handle delays caused by harsh weather.

## 4.3 Maritime fleet renewal problem

The maritime fleet renewal problem has the purpose of deciding the optimal number of vessels and types in the fleet to be able to supply the demand. It includes the time aspect, and when should the different vessels be added to the fleet or removed. The demand from the customer may go up and one would need more vessels, on the contrary, it may go down and the current fleet is too big.

Giovanni Pantuso (2016) looks at the fleet renewal problem with a focus on the uncertainty of the maritime sector. The fleet includes new builds, second-hand and chartered vessels. Resulting in the optimal fleet size throughout the time window with different scenarios. Scenarios for vessel prices, charter rate, and demand in the market. It shows that the stochastic model results are noticeably better than a deterministic model with average data.

Bakkehaug et al. (2014) proposed a new multi-stage stochastic model for strategic fleet renewal for the shipping sector. The model looks at uncertainty in demand, vessel prices, and rates. The outcome shows that using uncertainties gives a better result compared to using expected values.

The paper from Zhu et al. (2018) investigates the impact of an open maritime emission trading system(METS) for the shipowner with regards to fleet size and $CO_2$ emissions levels. The stochastic fleet size model includes different scenarios where the $CO_2$ price changes. The inclusion of METS in the fleet renewal problem results in more energy-efficient vessels in the fleet and vessels with high $CO_2$ emissions being put in lay-up status.

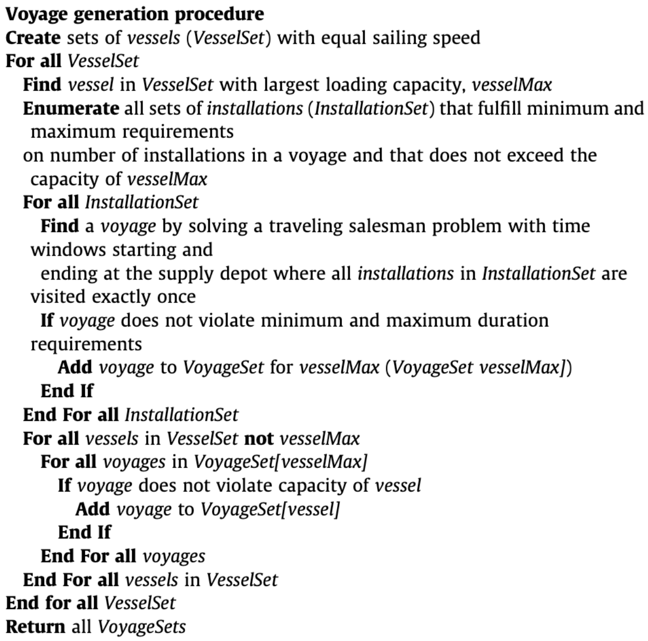
Patricksson et al. (2015) expanded upon the MFRP by incorporating regional limitations in the form of emission control areas. The study's findings demonstrate substantial savings with the inclusion of regional emission limitations. The traditional fleet renewal problems may result in sub-optimal fleet renewal decisions, due to higher operational costs in ECA zones.

In their work, Mørch et al. (2017) presents a mathematical model, building upon the model proposed by Pantuso et al. (2014). Their new model aims to maximize the Average Internal Rate of Return(AIRR). The results show an aggressive expansion of the fleet, resulting in a more balanced renewal strategy which may be preferable for many ship owners.

Skålnes et al. (2020) observed a prevailing gap in MRFP literature, of the limited emphasis on negative cash flows arising from the fleet renewal decisions. In response, they introduced two models based on the AIRR model proposed by Mørch et al. (2017). These models aim to limit the risk of insolvency resulting from negative cash flows associated with fleet renewal decisions.

## 4.4 Voyage generation

E. E. Halvorsen-Weare et al. (2012) introduced a voyage generation procedure to solve the MFSMP for offshore supply vessels. Their method enables the problem to be solved as a set partitioning problem, enabling its effective solution. Figure 4.1 illustrates the algorithm created by E. E. Halvorsen-Weare et al. (2012).



```
Voyage generation procedure
Create sets of vessels (VesselSet) with equal sailing speed
For all VesselSet
  Find vessel in VesselSet with largest loading capacity, vesselMax
  Enumerate all sets of installations (InstallationSet) that fulfill minimum and maximum requirements on number of installations in a voyage and that does not exceed the capacity of vesselMax
  For all InstallationSet
    Find a voyage by solving a traveling salesman problem with time windows starting and ending at the supply depot where all installations in InstallationSet are visited exactly once
    If voyage does not violate minimum and maximum duration requirements
      Add voyage to VoyageSet for vesselMax (VoyageSet vesselMax])
    End If
  End For all InstallationSet
  For all vessels in VesselSet not vesselMax
    For all voyages in VoyageSet[vesselMax]
      If voyage does not violate capacity of vessel
        Add voyage to VoyageSet[vessel]
      End If
    End For all voyages
  End For all vessels in VesselSet
End for all VesselSet
Return all VoyageSets
```

Figure 4.1: Voyage generation procedure from E. E. Halvorsen-Weare et al. (2012).

Chapter 5

# Problem description

In this chapter, the MFRP with emission control is described in detail.

The primary objective of the model is to support decision-making for ship owners by determining the optimal time to renew the fleet in order to reduce $CO_2$ emissions by choosing fuel technology and newbuild or retrofit. The model considers factors such as fuel technology selection, as well as the choice between newbuild and retrofit options. The model serves as a strategic planning tool for ship owners, ensuring that contracts to installations are fulfilled whilst transitioning the fleet to become more environmentally friendly.

Vessels are typically paid for in three installments to the shipyard (Stopford 2008). Nonetheless, vessels are often financed by equity or debt. Here, the cost for a newbuild or retrofit vessel is shared over the expected lifetime of the vessel, set to 30 years.

In order to meet the demand of offshore installations, the fleet must supply each installation with supplies from the onshore base. Vessels in the fleet have specific cargo capacities and ranges, which are utilized to determine feasible preset routes for each vessel.

Even though the model does not directly handle route planning, it considers different routes generated prior for each vessel, handling the problem as a set partitioning problem.

For each preset route and vessel, there is a corresponding investment cost, voyage cost, and $CO_2$ emission. The goal is to minimize the total cost of owning and operating a fleet of vessels over the total time horizon while achieving set emission reduction goals for each time period. To accomplish this objective, ship owners have five alternatives for vessel types: a conventional vessel fueled by MDO, a vessel fueled by LNG, a vessel fueled by liquid hydrogen, a vessel fueled by ammonia, and a conventional MDO-fueled vessel equipped with carbon capture and storage systems onboard. It can either be newbuild or retrofit of MDO-fuelled vessels. However, the only option to obtain a vessel with CCS systems is to retrofit an MDO-fuelled vessel.

The model uses discrete time periods, in years. Within each time period, a 30-day operation of the fleet is analyzed. During the operational time, $CO_2$ emissions, VOYEX, and CAPEX are analyzed.

By employing this model, ship owners can make informed decisions with regard to fleet composition throughout different time periods, with new regulations for emissions on the way. The outcome of the model is depicted in Figure 5.1. It suggests that by 2030, one of the vessels powered by MDO fuel should be substituted with an NH3-fueled vessel, while in 2050, a retrofit from an MDO-fueled vessel to an LH2 vessel is recommended

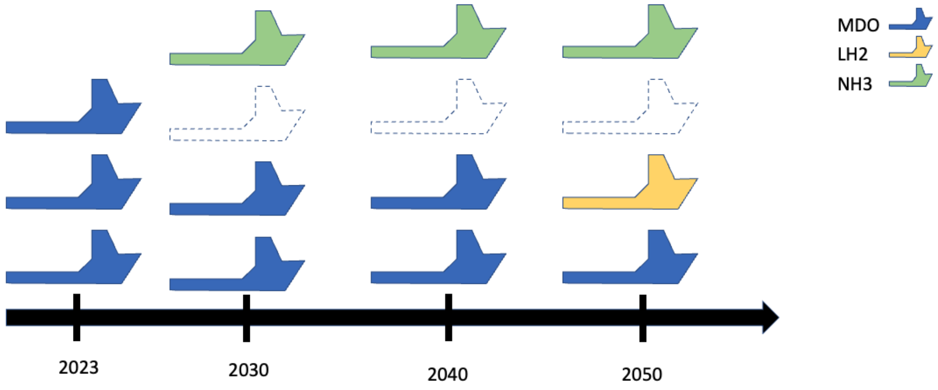


Figure 5.1: Fleet composition for four time periods.

Chapter 6

# Model

## 6.1 Assumptions

**Time periods**

The time periods are intervals of time where a decision will take place. In this model, a time period is set as a year. In each time period, an operational 30 days month is inspected.

**Costs**

We assume the costs for owning and operating the vessels are limited to capital expenditure cost and fuel costs. Other costs like crew salary, insurance, and maintenance are neglected.

**Acquisition**

The model should advise when and what kind of vessel to be added to the fleet. So building and retrofit time in a shipyard is not introduced.

## 6.2 Mathematically notation

**Sets:**

| | |
|---|---|
| $\mathcal{V}$ | Set of vessels |
| $\mathcal{V}^{\mathcal{C}} \subset \mathcal{V}$ | Subset of current vessels in fleet |
| $\mathcal{V}^{\mathcal{R}} \subset \mathcal{V}$ | Subset of retrofitted vessels |

| | |
|---|---|
| $\mathcal{V}^{\mathcal{N}} \subset \mathcal{V}$ | Subset of newbuild vessels |
| $\mathcal{I}$ | Set of installations to visit from the base |
| $\mathcal{R}_v$ | Set of routes that can be sailed by vessel $v$, $r \in \mathcal{R}_v$ |
| $\mathcal{T}$ | Set of discrete time periods in years |

**Parameters:**

| | |
|---|---|
| $C^S_{vrt}$ | Fuel cost for vessel v sailing route $r$ in time period $t$ |
| $C^{TC}_{vt}$ | Time charter cost for new build or retrofit for vessel $v$ in time period $t$ |
| $D_{it}$ | Monthly cargo demand for installation $i$ in period $t$ |
| $T_{vr}$ | Time duration for route $r$ using vessel $v$ |
| $E_{vrt}$ | Emission for vessel v sailing route $r$ in time period $t$ |
| $G_t$ | Emission reduction goal in time period $t$ |
| $Q_{ir}$ | Number of cargo taken to installation $i$ in route $r$ |

**Decision variables:**

| | |
|---|---|
| $x_{vrt}$ | Integer variable vessel v sails route r, in time period t |
| $y_{vt}$ | 1 if vessel v is used in time period t, otherwise 0 |
| $z_{vv't}$ | 1 if retrofit of vessel $v$ to vessel $v'$ in time period $t$, otherwise 0 |

**objective function:**

$$min \sum_{v \epsilon \mathcal{V}} \sum_{r \epsilon \mathcal{R}_v} \sum_{t \epsilon \mathcal{T}} C^S_{vrt} x_{vrt} + \sum_{v \epsilon \mathcal{V}} \sum_{t \epsilon \mathcal{T}} C^{TC}_{vt} y_{vt}, \tag{6.1}$$

**s.t.**

$$\sum_{v \epsilon \mathcal{V}} \sum_{r \epsilon \mathcal{R}_v} x_{vrt} E_{vrt} \leq G_{vt}, \quad t \epsilon \mathcal{T}, \tag{6.2}$$

$$\sum_{v \epsilon \mathcal{V}} \sum_{r \epsilon \mathcal{R}_v} Q_{ir} x_{vrt} \geq D_{it}, \quad i \epsilon \mathcal{I}, t \epsilon \mathcal{T}, \tag{6.3}$$

$$\sum_{r \epsilon \mathcal{R}_v} T_{vr} x_{vrt} \leq T^{max}, \quad v \epsilon \mathcal{V}, t \epsilon \mathcal{T}, \tag{6.4}$$

$$x_{vrt} \quad integer \quad v \epsilon \mathcal{V}, r \epsilon \mathcal{R}_v, t \epsilon \mathcal{T}, \tag{6.5}$$

$$y_{vt} \epsilon \{0, 1\}, \quad v \epsilon \mathcal{V}, t \epsilon \mathcal{T}, \tag{6.6}$$

$$\sum_{v' \epsilon V^C_v \cup V^R_v} y_{v't} \leq 1 \quad v \epsilon V^C, t \epsilon T, \tag{6.7}$$

$$\sum_{r \epsilon \mathcal{R}_v} x_{vrt} \leq M y_{vt}, \quad v \epsilon \mathcal{V}, t \epsilon \mathcal{T}, \tag{6.8}$$

$$y_{v't'} \geq z_{vv't}, \quad v \epsilon V^C, v' \epsilon V^R, t \epsilon T, t' \epsilon T | t' \geq t, \tag{6.9}$$

$$\sum_{v' \epsilon V^R} \sum_{t \epsilon T} z_{vv't} \leq 1, \quad v \epsilon V^C, \tag{6.10}$$

$$y_{v't} \leq \sum_{t'=1}^{t} z_{vv't'}, \quad t \epsilon T, v \epsilon V^C, v' \epsilon V^R, \tag{6.11}$$

The objective function in (6.1) minimizes the overall costs related to investments in fleet renewal and retrofitting, as well as the deployment of the fleet in each time period over the planning horizon.

Constraint 6.2 ensures that for each time period, the total amount of $CO_2$ emission for all sailing vessels is less or equal to the emission reduction goal.

Constraint 6.3 ensures the monthly demand for each installation is supplied by all sailing vessels in all time periods.

Constraint 6.4 enforces a maximum time limit for each vessel, ensuring that they do not exceed their maximum allowed sailing time. Constraints 6.5 ensure that $x_{vrt}$ is a positive integer and constraint 6.6 secures that $y_{vt}$ is a binary number.

To enforce the irreversible nature of the retrofitting process and prevent the reversion to the former fuel technology, constraint 6.7 is incorporated into the model.

Constraint 6.8 guarantees that if a vessel $v$ is deployed on route $r$ during time period $t$, it must be an active vessel during that specific time period $t$. Constraint 6.9 ensures that if a vessel $v$ undergoes a retrofitting process and becomes vessel $v'$, it must be utilized in the fleet. Constraint 6.10 limits the retrofitting of a vessel to occur only once, preventing multiple retrofitting instances for the same vessel.

Constraint 6.11 guarantees that if a vessel is active during a particular time period, it must have undergone retrofitting either in that time period or in a preceding time period.

Chapter 7

# Computational study

The model, showcased in chapter 6 is implemented in the optimization software FICO Xpress. The software utilizes the programming language Mosel, specifically designed for efficient modeling and solving of complex optimization problems. Python 3.9 was used for route generation. The software is run on a MacOS Ventura 13.2, with an Apple M1 chip and 8 GB of memory.

## 7.1 Case info

In this case study, we analyze the evolution of an initial fleet of three MDO-fuelled platform supply vessels in response to new regulations requiring a reduction in emission levels. The study highlights five emission strategies and proposes corresponding fleet renewal strategies to meet the emission reduction goals. These emission reduction goals are expressed as percentages of the reduction desired relative to a 30-day period of operation with three MDO-fueled vessels in 2030. These strategies are evaluated based on their associated costs, and a trade-off curve is developed to illustrate the cost implications of each strategy. Section 4.3 presented various fuel technologies, which represent the possible fuel options for the fleet renewal process.

The fleet of PSVs is responsible for supplying ten installations outside Bergen, with their operational base located in Mongstad. Mongstad serves as the hub where these vessels are supplied with the demands of the installations. Figure 7.1 shows the location of the installations and the supply depot.

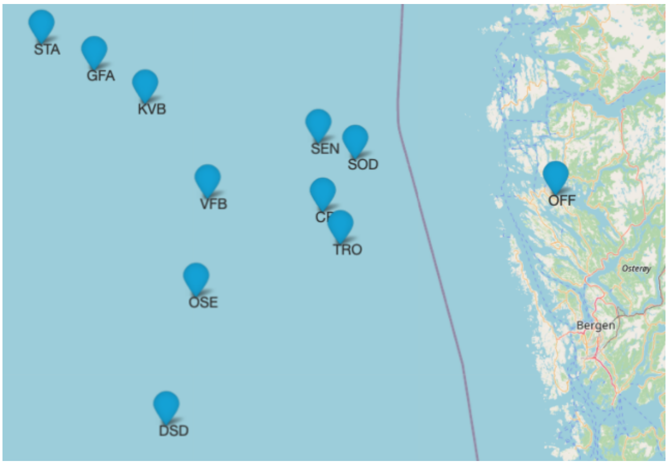


Figure 7.1: The installations and depot.

## 7.2 Model Structure

In order to solve the proposed MFRP, the model requires input. A Python script is utilized to generate all possible candidate routes for each vessel type. The script shares similarities with the voyage generation procedure showcased in Section 4.4. The script considers factors such as vessel speed, capacity, installation locations, and operational time for cargo loading and unloading. By considering these variables, the Python script generates feasible sailing routes along with the corresponding distance, time consumption, and cargo allocation plans.

The values generated by the Python script are uploaded into Xpress as a txt file. In conjunction with other inputs such as installation demand, investment cost, vessel design details, and emission goals, the Xpress model works to minimize the total cost over the defined planning horizon. The model aims to find the most cost-effective solution that satisfies the given constraints and achieves the specified emission goals.

Figure 7.2 illustrates the structure of the model and demonstrates how its components work together.

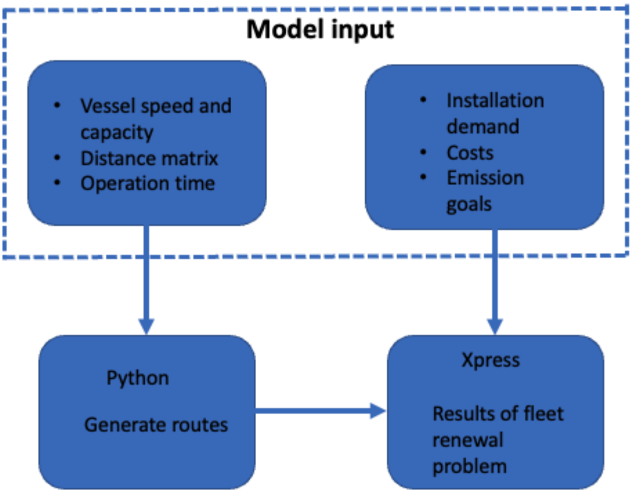


Figure 7.2: Structure of model.

## 7.3 Input parameters

To enable the model to solve the fleet renewal problem, various input parameters are required. These input parameters are presented in the following subsections.

### 7.3.1 Capital expenditure cost

When deciding to renew the fleet, an investment cost occurs. This investment cost needs to be distributed into monthly costs since the model considers a month of operations in the time period. To calculate the equivalent monthly cost of investing in a newbuild or retrofitted vessel, Equation 7.1 is applied. Here, the $C^I$ is the investment cost for the vessel, and $r$ denotes the discount rate set to 5% in this case. Here, $n$ is the projected lifetime of the vessel assumed to be 25 years.

$$EMC = \frac{1}{12} \cdot \left(\frac{C^I}{1-(1+r)^{-n}}\right) r \tag{7.1}$$

### 7.3.2 Voyage expenditure cost

As previously stated the only VOYEX cost utilized in this analysis is fuel costs. The fuel cost for various routes utilizing different fuel technologies can be determined through the following equations. The specific fuel consumption (SFC) is computed using the lower heating value (LHV) and the energy converter service efficiency ($\eta$) for each respective fuel technology.

$$SFC = \frac{1}{LHV \cdot \eta}, [\frac{kg}{kWh}] \tag{7.2}$$

Here, $LHV$ denotes the lower heating value for the fuel in $kWh/kg$, and $\eta$ signifies the energy converter service efficiency. The equation results in $SFC$ given by $kg/kWh$. The set fuel properties and the fuel systems efficiency are outlined in Table 7.1

| Fuel technology | $\eta$ | LHV[kWh/kg] | SFC[kg/kWh] |
|---|---|---|---|
| MDO | 0.48 | 11.89 | 0.186 |
| $LH_2$ | 0.5 | 33.33 | 0.06 |
| $NH_3$ | 0.48 | 5.17 | 0.403 |
| LNG | 0.5 | 13.08 | 0.153 |
| CCS | 0.42 | 11.89 | 0.208 |

Table 7.1: SFC for each fuel type. Fuel systems efficiency(Kim et al. 2020,Shakeri et al. 2020).

To determine the fuel consumption per route, the calculated SFC from Table 7.1 is employed in Equation 7.3. This equation quantifies the fuel consumption in metric tons.

$$FuelConsumption = \frac{SFC \cdot EnergyConsumption \cdot distance}{1000}, [t] \tag{7.3}$$

Here, $EnergyConsumption$ denotes the energy consumption per nautical mile and $Distance$ corresponds to the route's total distance. Resulting in a fuel consumption expressed in tons.

### 7.3.3 Energy consumption

It is assumed that the vessels follow Figure 7.3 energy consumption when sailing. In this case, the vessels sails with a speed of 10 knots and a significant wave height of 3 meters.

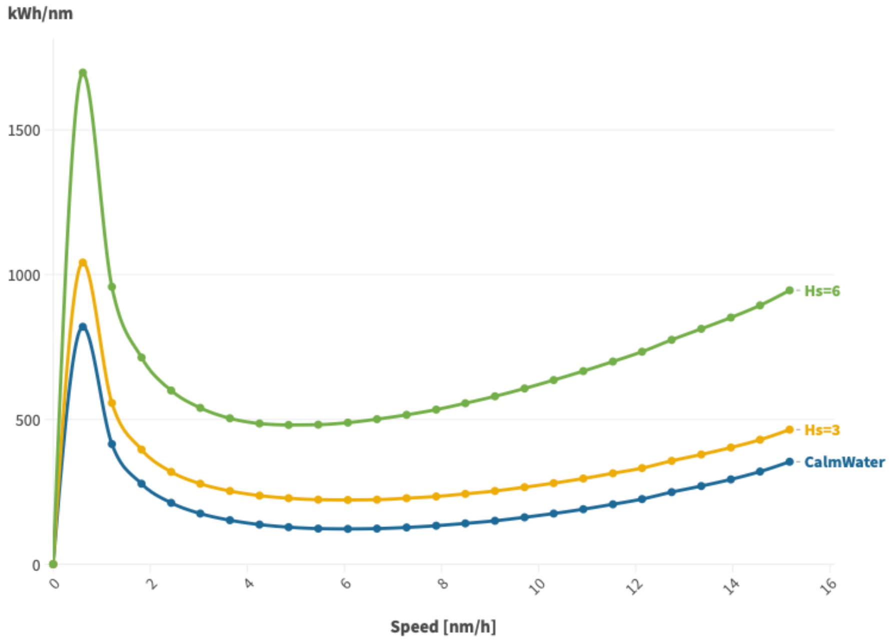


Figure 7.3: Energy consumption (kWh/nm) for different sea states as a function of speed.

During operations at the installations, the vessel requires dynamic positioning to supply the installations without any difficulties. A power requirement of 800 kW is set for the dynamic positioning system to facilitate this. This ensures the vessels, are capable of effectively maneuvering and maintaining their position while supplying the installations. The required time with DP is governed by the demand for units by the installation, as well as the vessel's unloading rate. In this case, the load and unloading rate has been set to 10 units per hour.

### 7.3.4 Demand

For this case, realistic demands for actual installations in the North Sea are considered. The demands are assumed to be unchanged during the different time periods. By assuming unchanged demands, a more focused analysis can be conducted to examine the impact of variables such as emissions and costs on fleet composition decision-making.

| Installation | Weekly demand[Unit] | Monthly demand[Unit] |
|---|---|---|
| TRO | 190 | 855 |
| CPR | 70 | 315 |
| SEN | 75 | 335 |
| OSE | 330 | 1485 |
| DSD | 50 | 225 |
| KVB | 220 | 990 |
| VFB | 210 | 945 |
| STA | 200 | 900 |
| GFA | 220 | 990 |
| SOD | 70 | 315 |

Table 7.2: Demand by installations.

### 7.3.5 Vessel types

The vessel design used in the case study is an average PSV based on Skandi Aukra.

| Dimension | Value | Unit |
|---|---|---|
| Loa | 90 | m |
| B | 18 | m |
| D | 8 | m |
| Dwt | 4500 | ton |
| Deck area | 1000 | $m^3$ |
| Power installed | 4500 | kW |
| AUX power | 500 | kW |
| Drill/Ballast water tank | 3000 | $m^3$ |
| Fuel Tank | 1000 | $m^3$ |

Table 7.3: Vessel design conventional fuelled PSV.

The vessels fueled by different fuels, including the MDO-fueled vessels, will have identical designs in terms of their dimensions. The hull size of the vessels remains the same, regardless of the type of fuel used. However, when new fuel systems are installed, the cargo capacity and range of the vessels may vary. Retrofitted vessels will generally have lower capacity and range compared to their respective newly built counterparts. This is because newbuild vessels have greater flexibility in designing the layout of components inside the hull, allowing for optimized cargo capacity and range. In contrast, retrofitting involves modifying existing vessels, which may limit the extent of changes that can be made to the internal layout and overall design, resulting in reduced capacity and range compared to newbuild vessels.

| Vessel Design | Cargo capacity[units] | Range[nm] | Monthly investment cost[$] |
|---|---|---|---|
| Current MDO | 120 | 1000 | 186250 |
| Newbuild MDO | 120 | 1000 | 266072 |
| Newbuild LNG | 110 | 1000 | 328066 |
| Retrofit LNG | 100 | 1000 | 307579 |
| Newbuild $NH_3$ | 90 | 300 | 353875 |
| Retrofit $NH_3$ | 90 | 300 | 319286 |
| Newbuild $LH_2$ | 80 | 200 | 399108 |
| Retrofit $LH_2$ | 100 | 300 | 359197 |
| Retrofit CCS | 80 | 100 | 337113 |

Table 7.4: Vessel types capacities.

According to McKinlay et al. (2021) paper on the route to zero-emission shipping, a majority of vessels carry an excess of fuel onboard compared to what is required for a single voyage. They observed that zero-emission fuelled vessels effectively can operate on routes with less fuel stored onboard.

When determining the capacities for various vessel designs as depicted in Table 7.4, the capacities are selected using MDO vessels as the reference point, assuming they possess full cargo capacity and sufficient range to navigate all routes. Figure 3.5 illustrates the required tank volume for different fuels, relative to that of an MDO-fuelled vessel, in order to maintain equivalent sailing capabilities. Consequently, alternative ship designs are established by finding a balance between range and cargo capacities, considering the trade-off associated with larger fuel systems.

Based on discussions held with representatives from Ulstein, it has been determined that the current estimated cost to build a conventional fuelled PSV in Norway stands at approximately 45 million dollar. To determine the prices for alternative designs, the study by Lagemann et al. (2022) provides valuable insight. The prices are derived by considering the ratio of newbuild prices associated with different fuel systems. Based on discussions with representatives from AMON, the cost estimation for constructing an $NH_3$-fuelled vessel is consistent with the estimates derived in this case.

### 7.3.6 Route generation

A vessel can sail numerous routes to supply the installations with the required amount of cargo. When constructing the different routes there are some restrictions. Each route start and ends at the depot, however, it can include all possible combinations of installations up to the set amount of stops in a route. The distances between the different installations are presented in Table 7.5. In this case, the maximum amount of stops on a single route is four. If two or more routes visit the same installations, only the shortest route is added to the feasible routes. When evaluating routes for ten installations the total number of feasible routes results in 637 different routes.

For each route, the vessels are filled up to their maximum capacity with supplies. The supplies by each vessel are evenly distributed between the number of installations visited on the selected route.

| | **OFF** | **TRO** | **CPR** | **SEN** | **OSE** | **DSD** | **KVB** | **VFB** | **STA** | **GFA** | **SOD** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **OFF** | 0 | 32.9 | 33.0 | 33.4 | 60.1 | 77.3 | 65.6 | 53.5 | 86.3 | 75.9 | 26.4 |
| **TRO** | | 0 | 6.8 | 19.1 | 28.2 | 46.7 | 44.0 | 25.8 | 65.7 | 55.1 | 15.8 |
| **CPR** | | | 0 | 12.6 | 28.0 | 49.1 | 38.0 | 21.3 | 59.7 | 49.0 | 11.2 |
| **SEN** | | | | 0 | 36.0 | 59.3 | 18.1 | 22.6 | 53.3 | 42.8 | 7.4 |
| **OSE** | | | | | 0 | 24.7 | 36.6 | 18.1 | 54.2 | 45.5 | 38.5 |
| **DSD** | | | | | | 0 | 59.6 | 42.7 | 73.9 | 66.8 | 60.3 |
| **KVB** | | | | | | | 0 | 20.8 | 21.7 | 11.1 | 39.5 |
| **VFB** | | | | | | | | 0 | 41.4 | 31.2 | 27.9 |
| **STA** | | | | | | | | | 0 | 10.7 | 60.7 |
| **GFA** | | | | | | | | | | 0 | 50.1 |
| **SOD** | | | | | | | | | | | 0 |

Table 7.5: Distance matrix in nm.

### 7.3.7 Fuel development towards 2050

The future outlook of the fuel market remains uncertain, particularly regarding the changes in emissions associated with various fuels over time. Notably, the transition from conventional to greener fuels is expected to occur as renewable energy sources gain prominence. Liquid hydrogen, and ammonia, are anticipated to play a pivotal role in the transformation.

According to a report by (PWC 2023), the cost of green hydrogen is projected to be 2$ per kilogram by 2050. Remarkably, this cost is comparable to the current price of grey hydrogen. Consequently, it is assumed that the price of hydrogen will remain the same across different time periods. However, the crucial change lies in the increasing sustainability of the fuel over time, as it gradually shifts from a grey to a greener variant.

Due to similarities between hydrogen and ammonia, the development is assumed to follow the same pattern.The carbon capture and storage system has been configured to achieve an 80% capture rate. Both MDO and LNG fuels will maintain the same emission rate across different time periods. The progression of the five different fuel technologies employed in this study is illustrated in Figure 7.4

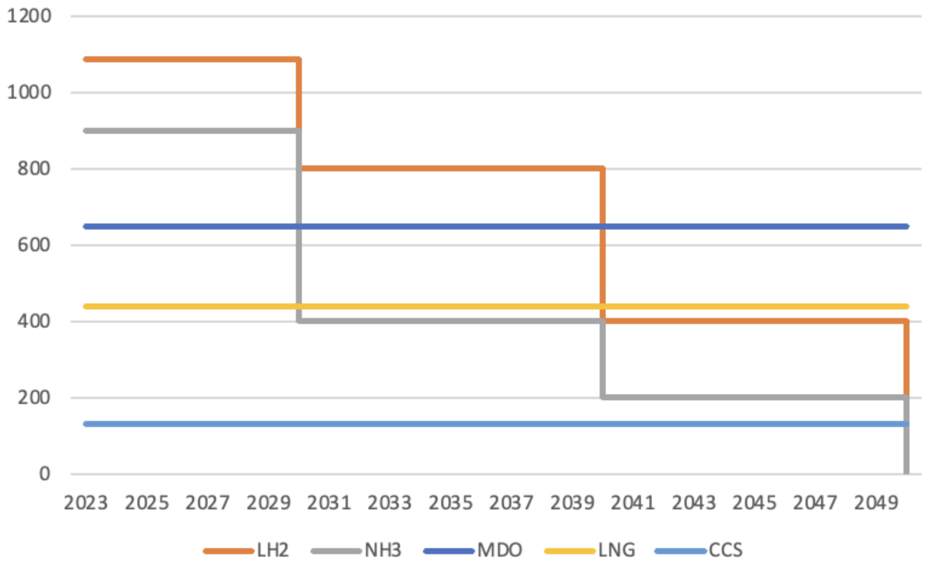


Figure 7.4: CO2 emission [g/kWh] for the different time periods.

The fuel prices for the different fuels used in this case are highlighted in Figure 7.5. The development for MDO and LNG is based on the ratio between fuel production prices in the selected time periods from Solakivi et al. 2022

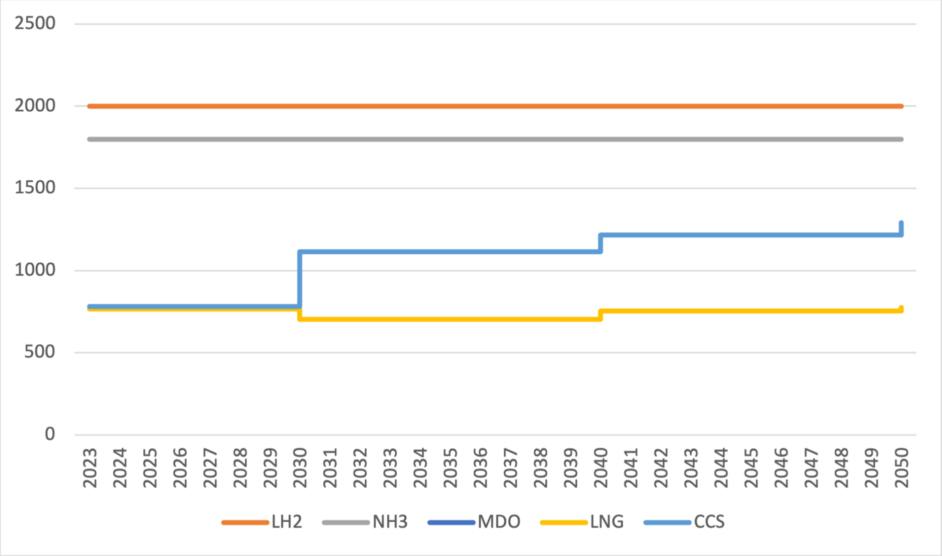


Figure 7.5: Fuel price per ton for the different fuels through time periods.

## 7.4 Model solutions

In this section, the proposed model will be solved using various emission strategies, which are outlined in Table 7.6. These strategies are then compared to each other based on the price per ton of CO2 reduced. The objective is to evaluate and assess the relative effectiveness and cost-efficiency of each emission strategy in reducing $CO_2$ emissions.

| Emission strategic | Reduction by 2030 | Reduction by 2050 |
|---|---|---|
| 1 | 0% | 0% |
| 2 | 10% | 40% |
| 3 | 20% | 50% |
| 4 | 40% | 70% |
| 5 | 50% | 100% |

Table 7.6: Emission strategies.

### 7.4.1 Emission strategy 1

In the absence of regulatory measures and other incentives to reduce emission, the optimal fleet composition, cost, and $CO_2$ emission are presented in table 7.7.

| Time period | Fleet | Newbuild | Retrofit | Voyex[$] | Capex[$] | Total cost[$] | $CO_2$[t] |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 382446 | 558751 | 939392 | 1705 |
| 2030 | 3xMDO | - | - | 547805 | 558751 | 1106560 | 1325 |
| 2040 | 3xMDO | - | - | 598999 | 558751 | 1157750 | 1325 |
| 2050 | 3xLNG | 2xLNG | 1xLNG | 340542 | 963713 | 1304255 | 1270 |

Table 7.7: Solution for emission strategy 1.

| | |
|---|---|
| Run time | 1800[s] |
| Solutions found | 52 |
| Nodes explored | 561106 |
| The gap between found solution and lower bound | 1.83% |

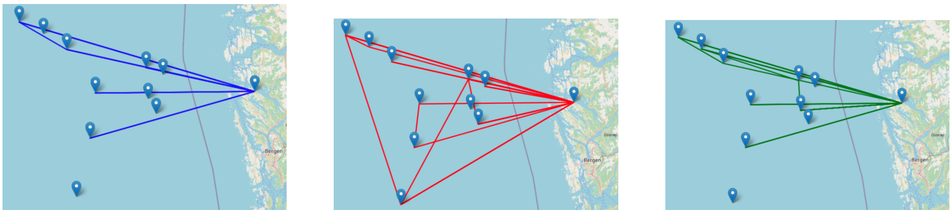
Table 7.8: Computational details.

Despite an absence of emission restriction in the model, it still advises the addition of three LNG-fuelled vessels in 2050. By 2050 the initial fleet needs replacing since the vessel's age exceeds its lifetime.

While both the newbuild and retrofit prices for an LNG-fuelled vessel are higher compared to a newbuild MDO-fuelled vessel, the price of MDO is assumed to rise significantly by 2050. Consequently, the reduction in VOYEX by opting for an

LNG-fuelled vessel instead of MDO outweighs the increased CAPEX. Additionally, this option results in an emission reduction of 25% in 2050 compared to 2023.

In time period 2023 the underlying deployment problem of which routes each vessel should sail is solved and illustrated in Figure 7.6



(a) Routes sailed by MDO-fuelled vessel number 1

(b) Routes sailed by MDO-fuelled vessel number 2

(c) Routes sailed by MDO-fuelled vessel number 3

Figure 7.6: Routes sailed by each vessel in time period 2023.

### 7.4.2 Emission strategy 2

To meet the relatively low reduction goals of emission strategy 2, the solution is presented in Table 7.9

| Time period | Fleet | Newbuild | Retrofit | Voyex[\$] | Capex[\$] | Total cost[\$] | $CO_2$[t] |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 382446 | 558751 | 939392 | 1705 |
| 2030 | 2xMDO<br>1xLNG | - | - | 455582 | 700568 | 1156150 | 1540 |
| 2040 | 2xMDO<br>1xLNG | - | - | 700568 | 506424 | 1206990 | 1540 |
| 2050 | 4xLNG | - | 3xLNG | 340542 | 1302400 | 1676290 | 1015 |

Table 7.9: Solution for emission strategy 2.

| | |
|---|---|
| Run time | 1800[s] |
| Solutions found | 52 |
| Nodes explored | 435331 |
| The gap between found solution and lower bound | 3.49% |

Table 7.10: Computational details.

### 7.4.3 Emission strategy 3

To meet the targets for 2030 of 20% and for 2050 of 50% emission reduction. The solution is presented in Table 7.11.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 379978 | 558751 | 938729 | 1705 |
| 2030 | 1xMDO<br>2xLNG | 2xLNG | - | 366568 | 842384 | 1208950 | 1360 |
| 2040 | 1xMDO<br>2xLNG | - | - | 397633 | 842384 | 1250020 | 1360 |
| 2050 | 2x$LH_2$<br>2xLNG | 1x$LH_2$ | 1x$LH_2$ | 373438 | 1767390 | 1767390 | 850 |

Table 7.11: Solution for emission strategy 3.

To achieve a reduction of 20% in emissions, the most cost-effective option is to incorporate LNG-fueled vessels into the fleet. Although retrofitting the existing MDO-fueled vessels would be a more economical choice, it would result in a reduction in cargo capacity, requiring the addition of an extra vessel. Therefore, the model selects the newbuild LNG vessels as the preferred option to maintain cargo capacity while achieving the desired emission reduction.

In order to achieve a 50% reduction in emissions by 2050, the model recommends the inclusion of two LH2-fueled vessels. However, due to the decrease in cargo capacity associated with LH2 fuel, an additional vessel is required to meet the cargo demands. This additional vessel is necessary to compensate for the reduced capacity of the LH2-fueled vessels and ensure efficient and timely transportation of goods.

| | |
|---|---|
| Run time | 1800[s] |
| Solutions found | 54 |
| Nodes explored | 380873 |
| The gap between found solution and lower bound | 9.77% |

Table 7.12: Computational details for emission strategy 3.

### 7.4.4 Emission strategy 4

To meet IMO targets for 2030 of 40% and for 2050 of 70% $CO_2$ emission reduction. The solution is presented in Table 7.13 and an illustration of the fleet development in Figure 7.7.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 380894 | 558751 | 939645 | 1705 |
| 2030 | 1xCCS<br>3xLNG | 3xLNG | 1xCCS | 432951 | 1321310 | 1754270 | 1020 |
| 2040 | 2xCCS<br>2xLNG | - | - | 488194 | 1321310 | 1809510 | 1020 |
| 2050 | 2x$LH_2$<br>1xCCS<br>1xLNG | 2x$LH_2$ | - | 484756 | 1463400 | 1984815 | 468 |

Table 7.13: Solution for emission strategy 4.

| | |
|---|---|
| Run time | 1800[s] |
| Solutions found | 34 |
| Nodes explored | 464501 |
| The gap between found solution and lower bound | 13.87% |

Table 7.14: Computational details emission strategy 4.

| | |
|---|---|
| Run time | 28800[s] |
| Solutions found | 34 |
| Nodes explored | 3463998 |
| The gap between found solution and lower bound | 13.54% |

Table 7.15: Computational details 8 hours.

When the model is solved for a duration of thirty minutes, the optimal solution obtained is identical to the optimal solution obtained after running the model for eight hours. Moreover, during this execution comparison, the discrepancy between the lower bound and the best solution found diminishes by only 0.33%.

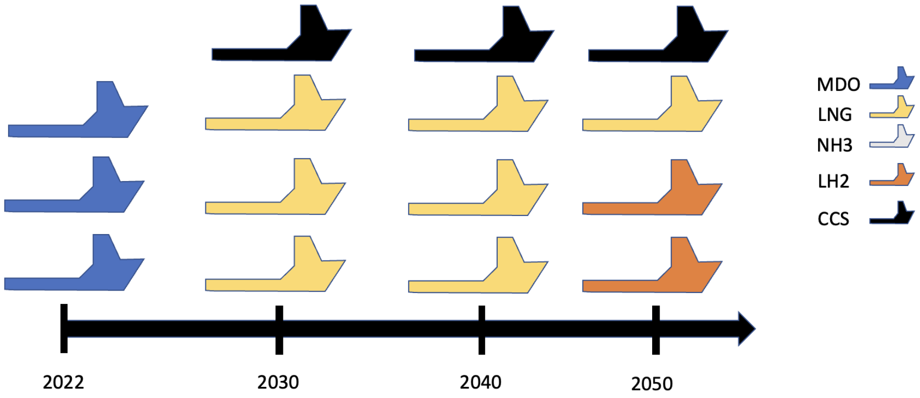


Figure 7.7: Optimal fleet development through time periods for emission strategy 4.

### 7.4.5 Emission strategy 5

In pursuit of the objective to achieve complete carbon neutrality within the fleet, the model has four viable options, retrofitting existing vessels or constructing new vessels fueled by either ammonia or hydrogen. However, these alternative fuel options entail a lower cargo capacity compared to MDO-fueled vessels. Consequently, to maintain the required cargo transport volume, additional sailings would be necessary when utilizing ammonia or hydrogen-fueled vessels, as opposed to MDO-fueled vessels. The model's solution to the problem is presented in Table 7.16.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 383051 | 558751 | 941802 | 1716 |
| 2030 | 2xCCS<br>2xLNG | 2xLNG | 2xCCS | 542641 | 1330360 | 1873000 | 852 |
| 2040 | 2xCCS<br>2xLNG | - | - | 584038 | 1330360 | 1914400 | 852 |
| 2050 | 4x$LH_2$ | 3x$LH_2$ | 1x$LH_2$ | 438082 | 2230750 | 2668830 | 0 |

Table 7.16: Solution for emission strategy 5.

In order to achieve a 50% emission reduction in 2030, the initial fleet is renewed to include two LNG and two CCS vessels. This results in a total of four vessels, compared to the three vessels required in 2023. However, this fleet composition adjustment drives the total cost in 2030 up by 69% when compared to using three MDO vessels. The increase in cost is solely attributed to the CAPEX of the fleet, while the VOYEX experience a slight decrease due to the anticipated rise in MDO prices in 2030.

By 2050, the fleet achieves full carbon neutrality by exclusively utilizing $LH_2$-

fuelled vessels. This transition involves the construction of three new $LH_2$-fuelled vessels and the retrofitting of one existing vessel. Notably, the VOYEX experience a decrease in this scenario, primarily attributed to $LH_2$ being the most cost-effective fuel per kWh in 2050. Further details regarding the cost analysis and considerations related to $LH_2$ as the preferred fuel option can be found in Section 8.3.

| | |
|---|---|
| Run time | 1800[s] |
| Solutions found | 23 |
| Nodes explored | 706 217 |
| The gap between found solution and lower bound | 2.88% |

Table 7.17: Computational details emission strategy 5.

By limiting the options in 2050 to just two fuel options, the difference between the found solution and the lower bound drastically diminishes in comparison to emission strategies 2,3, and 4. This suggests that the range of feasible solutions becomes narrower and more aligned with the lower bound as there are fewer options to consider.

### 7.4.6 Comparison of emission strategies

Over the four time periods, resulting in four months of operations in four unique years. The cumulative cost, relative to strategy 1 as the baseline, and the corresponding $CO_2$ emissions are presented in Figure 7.8.

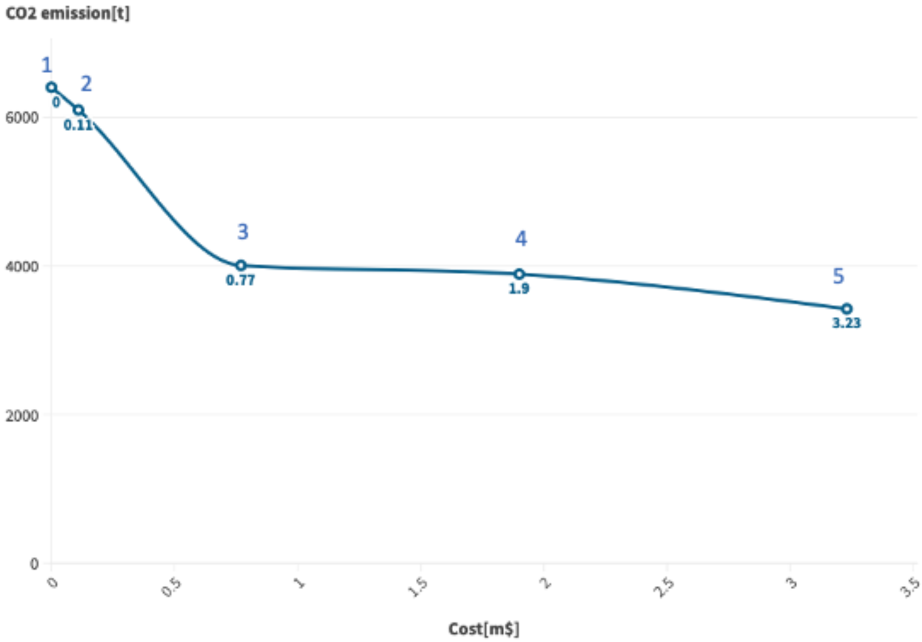


Figure 7.8: Comparison of the different emission strategies with strategy 1 as baseline.

Further investigation of the cost from time period 2050, one can analyze the cost per tonne $CO_2$ reduced with the different emission strategies. The analysis reveals that strategies 2,3 and 4 have a similar cost for tonne $CO_2$ reduced, with a marginal difference ranging from three to six percent. However, in the case of strategy 5, which achieves zero $CO_2$ emission, the cost per tonne is significantly higher at 780$, representing a 55% increase compared to strategy 2.

| Emission strategy | Emission[t] | Total cost[$] | $\$/tCO_2$ saved |
|---|---|---|---|
| 2 | 1015 | 376265 | 511 |
| 3 | 870 | 468005 | 531 |
| 4 | 215 | 841445 | 548 |
| 5 | 0 | 1364575 | 780 |

Table 7.18: Emission strategy comparison $\$/tCO_2$.

The implementation of carbon taxes will play a crucial role in transitioning from fossil fuels to greener alternatives, making the transition more economically feasible. Figure 3.7 displays the projected carbon tax, expected to reach 130[$/t$CO_2$] in 2050.

Despite the implementation of a 130$ per tonne of $CO_2$ tax, the cost difference for reducing emissions remains significantly higher. By adopting strategy 4, the cost still amounts to 418$ per tonne of $CO_2$ reduced. However, strategy 4 appears to be a more viable option compared to strategies 2 and 3, as the reduction in emissions is considerably lower in those cases. This suggests that although the cost is higher, strategy 4 offers a more effective approach to reducing emissions in a cost-efficient manner. Figure 7.9 illustrates the cost dynamics associated with the emission strategies. This pattern demonstrates that the cost initially rises, then stabilizes to a more moderate increase for strategies 3 and 4, before witnessing a substantial cost escalation for strategy 5, which focuses on achieving zero emissions.

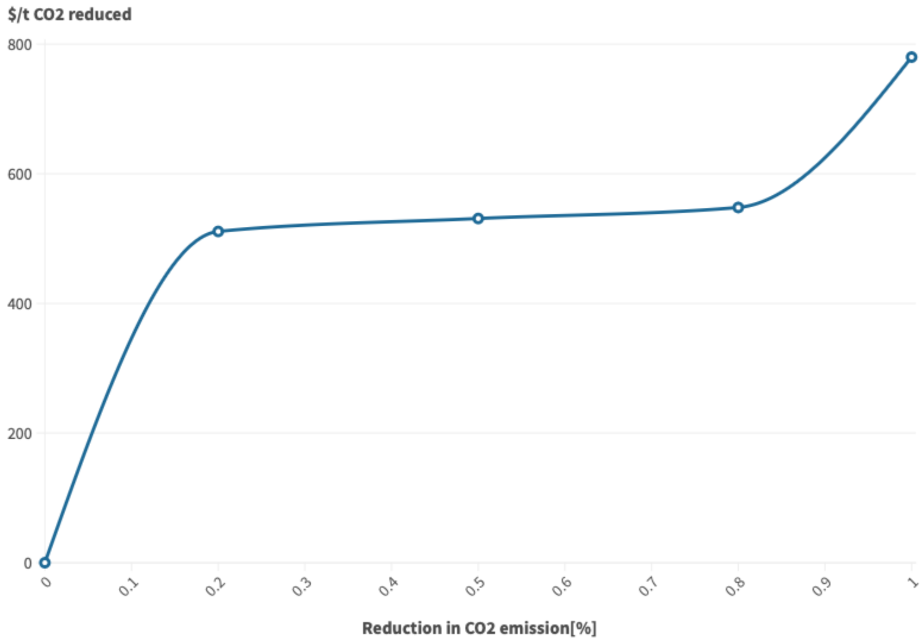


Figure 7.9: Comparison of the different emission strategies, dollar per tonne $CO_2$. The initial point corresponds to strategy 1, and each subsequent point to the right represents the next strategy.

Figure 7.10 displaces the added cost of choosing different emissions strategies.

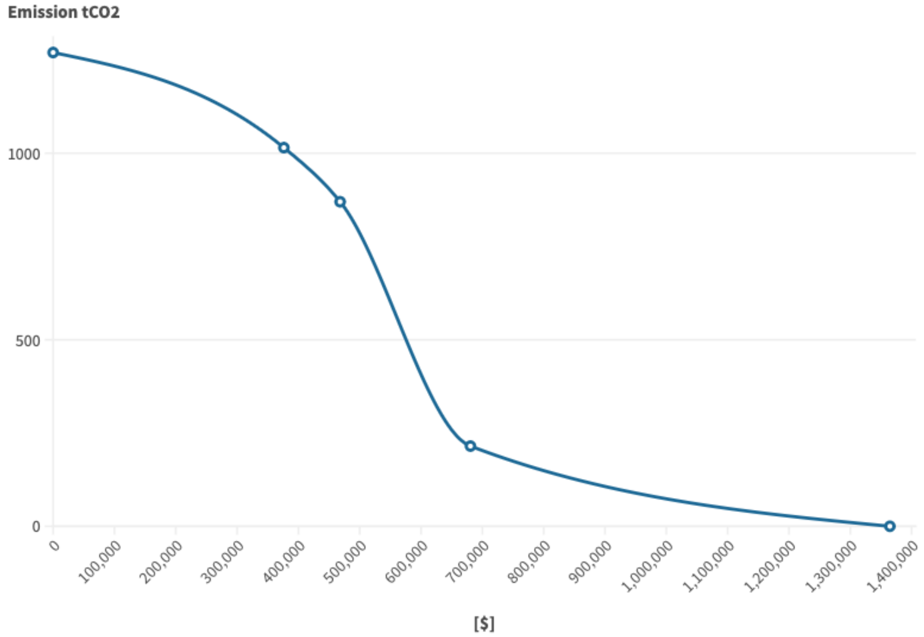


Figure 7.10: Comparison of the different emission strategies in 2050. The initial point corresponds to strategy 1, and each subsequent point to the right represents the next strategy.

## 7.5 Sensitivity analysis

These subsections aim to investigate the behavior of the model when specific input variables are altered. By analyzing the model's response to changes in these variables, further insights and information are gathered. This analysis helps in understanding how the model behaves under different scenarios, providing a more comprehensive understanding of its functioning.

These analysis utilizes emission strategy 4, which aligns with IMO goals for 2030 and 2050.

### 7.5.1 Constant fuel price

Estimating fuel prices and their development from 2023 to 2050 is associated with significant uncertainty. While established companies and research publications may provide some estimates, the actual development can only be determined with time. In this analysis, a conservative assumption is made that fuel prices will remain constant. The fuel prices utilized in the analysis are presented in Table 7.19.

| Fuel | Price[$/t] |
|---|---|
| MDO | 780 |
| LNG | 766 |
| $LH_2$ | 2000 |
| $NH_3$ | 1500 |

Table 7.19: Fuel prices.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 380231 | 558751 | 938983 | 1710 |
| 2030 | 1xMDO<br>2xCCS<br>1xLNG | 1xLNG | 2xCCS | 434102 | 1188549 | 1622650 | 1050 |
| 2040 | 1xMDO<br>2xCCS<br>1xLNG | - | - | 434102 | 1188549 | 1622650 | 1050 |
| 2050 | 2xCCS<br>2x$LH_2$ | 2x$LH_2$ | - | 494400 | 1472440 | 1966840 | 215 |

Table 7.20: Solution for emission strategy 4 with constant fuel prices.

When comparing the current analysis to the results in Table 7.13, notable differences arise in the fleet composition. In contrast to the previous results, it is now observed that retaining one MDO-fuelled vessel in 2030 proves to be a more cost-effective approach than having two LNG-fuelled vessels. Similarly, in 2050, the revised fleet configuration involves utilizing two CCS vessels instead of one LNG-fuelled vessel and one CCS vessel, reflecting a distinct deviation from the earlier findings. As a consequence of these modifications in the fleet composition, there is a saving of approximately 5% in the objective function.

### 7.5.2 Cargo capacity

Through talks with representatives from Amon Maritime, it has become evident that the design of the PSV should not deviate significantly from the conventional PSV design. The PSV market values the service as a premium product, and therefore, the vessel design should not impose limitations on its ability to perform assignments effectively. Consequently, in this case, the cargo capacity of each vessel design is set to 120 units, matching that of the MDO-fueled vessel. The results are presented in Table 7.21.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 380894 | 558751 | 939645 | 1705 |
| 2030 | 1xCCS<br>2xLNG | 1xLNG | 1xCCS,1xLNG | 372476 | 972759 | 1345230 | 946 |
| 2040 | 1xCCS<br>2xLNG | - | - | 408461 | 972759 | 1381220 | 946 |
| 2050 | 1x$LH_2$<br>1xCCS<br>1xLNG | - | 1x$LH_2$ | 417673 | 1003890 | 1421560 | 512 |

Table 7.21: Solution for emission strategy 4 with full capacity.

As expected, the fleet configuration consists of three vessels across all time periods, in contrast to the requirement for four vessels when the capacity of the alternative designs decreases. This reduction in vessel count has a significant impact on the total cost, primarily driven by the CAPEX. By maintaining a fleet of three vessels, the total cost is drastically reduced due to the decreased investment in additional vessels. In total the cost decreases by 21% compared to the solution found in Table 7.13

### 7.5.3 Tank to wake

As previously mentioned, there is an ongoing debate regarding the appropriate metrics to use when calculating emissions. Initially, we assumed well-to-wake emissions, anticipating an increase in renewable energy usage in the future, resulting in a higher proportion of fuel being derived from renewable sources. However, in this analysis, we will evaluate the disparity using tank-to-wake emissions.

To expedite the advancement of green fuel technologies, it is advantageous to emphasize the tank-to-wake perspective. This approach facilitates the transition towards greener vessels, ensuring that when an abundance of renewable energy is available, and the well-to-wake emissions of hydrogen and ammonia reach zero, the fleets will be well-prepared to operate in a carbon-neutral manner.

| Time period | Fleet | Newbuild | Retrofit | Voyex | Capex | Total cost | Emission |
|---|---|---|---|---|---|---|---|
| 2023 | 3xMDO | - | - | 380894 | 558751 | 939645 | 1705 |
| 2030 | 1xMDO<br>1x$LH_2$<br>2xLNG | 2xLNG, 1$LH_2$ |  | 352572 | 1241900 | 1594060 | 1020 |
| 2040 | 1xMDO<br>1x$LH_2$<br>2xLNG | - | - | 386654 | 1241900 | 1628150 | 1020 |
| 2050 | 3x$LH_2$<br>1xLNG | - | 1x$LH_2$ | 408264 | 1485480 | 1893700 | 380 |

Table 7.22: Solution for emission strategy 4 with TTW emission.

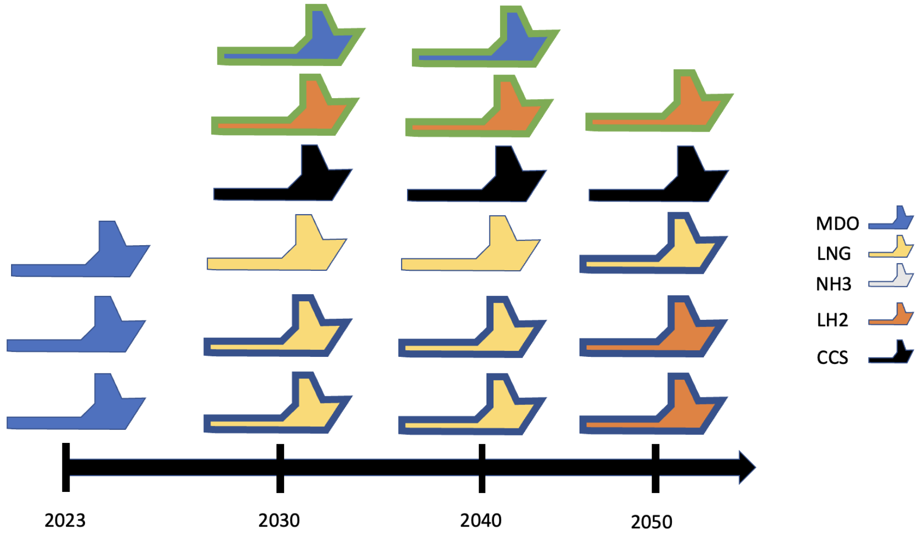


Figure 7.11: Comparison of the optimal solutions obtained using TTW and WTW emission considerations. Green outlines represent the different vessel choices exclusively identified through TTW analysis, while blue outlines indicate the common ship selections for both TTW and WTW. Solutions obtained solely through WTW analysis are represented without any outlines.

The difference between using TTW and WTW emission is illustrated in Figure 7.11. Notably, the difference arises from the incorporation of an $LH_2$ fuelled vessel when it becomes commercially applicable in 2030. This allows for the inclusion of the most cost-effective and polluting vessel, the MDO-fueled vessel, in the fleet. As the $LH_2$ fueled vessel does not emit any $CO_2$, it significantly reduces the fleet's overall emissions. However, the vessel equipped with a CCS system is not included in the fleet due to its higher fuel consumption and cost. Despite its previously preferred status due to its low CO2 emission, the model opts for $LH_2$ instead.

Incorporating the TTW perspective instead of the WTW perspective leads to a reduction in the total cost by approximately 6%. However, the noteworthy finding is that adopting TTW results in four fleet renewal decisions, whereas WTW requires six renewal decisions. This reduction in the number of fleet renewal decisions is advantageous for ship owners as it reduces risks and reduces costs associated with newbuild projects.

Utilizing the TTW parameter emerges as the most cost-effective approach for shipowners. By employing TTW, the capital risk is reduced, and it places greater emphasis on the energy sector to integrate more green energy sources into the market. This approach promotes a fair distribution of responsibilities, preventing ship owners from facing significant disadvantages in the transition towards zero-emission operations.

Chapter 8

# Discussion

The main objective of this thesis is the development of an optimization model for decision support for the fleet renewal with a focus on emission reduction. This chapter focuses on the optimization model

## 8.1 Model execution

In the model restriction 6.2 plays a decisive role in choosing the fleet compositions. Without this restriction, the model functions as a route planner, and an optimal solution is found quickly. However, the main objective of the problem is to reduce the emission. Achieving this objective requires additional computational time, resulting in longer runtime. With certain values for the emission goals, running the model for 12 hours, results in a gap between the best obtained solution and the lower bound of approximately 8%. The study findings indicate that for different emission strategies that the gap between the best obtained solution and the lower bound increases for each strategy until reaching strategy 5, where it decreases to 2.88%.

## 8.2 Underlying deployment problem

Since the model does not account for the time required for shipbuilding or retrofitting in a shipyard, certain solutions may encounter deployment issues during specific time periods. For example, in emission strategy 4(7.13), it is necessary to retrofit one of the MDO-fueled vessels into a CCS vessel by 2030. However, in order to comply with this plan, the vessel should have already undergone conversion in the preceding months, leading to a shortfall in supplies to the installations.

This shortage arises because only two vessels would be available for delivery during those months. To meet the demand, an additional vessel would need to be chartered, a cost that is not considered in the model. Consequently, this may result in a deviation from the optimal solution found.

Despite this limitation, the model provides detailed routes for each vessel currently in the fleet, effectively solving the underlying deployment problem.

## 8.3 Input parameter

### 8.3.1 Fuel

The fuel prices and emission rates per fuel in the shipping industry are subject to significant uncertainty. As the decarbonization process unfolds, it becomes challenging to determine the preferred fuel type in the future. Several factors must be considered, including the state of the world economy, fuel production methods, and the maturity of propulsion and fuel systems. These variables play crucial roles in shaping the future landscape of fuel preferences within the shipping industry.

In the computational study conducted, liquid hydrogen consistently emerged as the favored potential carbon-neutral fuel over ammonia. This preference can be attributed to the significantly lower specific fuel consumption value of liquid hydrogen at 0.06 kg/kWh compared to ammonia at 0.40 kg/kWh. Considering a price difference of only $500 per tonne, it becomes evident that opting for ammonia over hydrogen would result in a five times increase in cost per kWh.

Looking at Table 7.1, $LH_2$ would be the cheapest fuel option from 2030-2050, when it is assumed that it becomes commercially available at full scale when just considering the fuel costs. However, it is important to note that the construction and retrofitting of vessels to accommodate $LH_2$ is anticipated to be the most expensive compared to other fuel options.

### 8.3.2 Vessel design

In the specific case examined here, the distances between the depot and installations are relatively short, as indicated in Table 7.5. The maximum distance from the depot to an installation amounts to 86.3 nautical miles, resulting in a round trip of 172.6 nautical miles. This distance is considerably lower compared to deep-sea shipping routes. However, they share the same objective of reducing emissions.

The transition to more environmentally friendly fuels is expected to be comparatively easier for PSVs than for container or bulk vessels. This is primarily due to the shorter sailing distances involved. With shorter distances, PSVs have increased flexibility and can leverage the proximity to available refueling infrastructure. As a result, PSVs are well-positioned to adopt greener fuel options and contribute to emissions reduction efforts.

Determining the appropriate capacities for various fuel technologies poses challenges. A conventional fuelled PSV has fuel enough for sailing 30 days at service speed. For this case, the maximum duration of routes is calculated to be a little over three days. A vessel designed with an autonomy of 5 days would be able to keep the same deck area, and tank storage to support both liquid hydrogen and ammonia. But due to regulations and versatility of the vessel, this is not wanted by ship owners(Risholm 2020).

As things stand right now the there would be difficulties with bunkering of the alternative fuels and unloading of the captured $CO_2$. The infrastructure needed for these operations are not yet in place. Its assumed that by the time these alternatives become commercial applicable the infrastructure at the port should be in place. This may be optimistic.

## 8.4 Value of model

Despite the uncertainty associated with input values to the model, the model described in Chapter 6 offers valuable insights and information for ship owners with regard to fleet renewal plans. By considering various factors, such as fuel options, emissions, costs, and demands for installations, the model serves as a valuable decision-making tool. It aids ship owners in evaluating different scenarios, assessing trade-offs, and making informed choices regarding fleet composition and renewal strategies.

While the objective function value does not provide a comprehensive understanding of the actual operating cost of the fleet throughout the planning horizon, as it only assesses a 30-day period within each time period, its primary purpose is to minimize the overall cost. However, to obtain valuable insights into the cost dynamics, it is necessary to analyze the cost for each individual time period separately. This allows for a more detailed examination of the cost implications and provides a deeper understanding of the fleet's financial performance over time. Furthermore, by comparing the costs associated with different emission strategies, it is possible to assess their respective impacts on the fleets economic viability and make informed decisions regarding the adoption of specific strategies.

The initial plan for the model was to target the ship owners, it turns out the model can be an excellent tool for ship operators that charter vessels. Utilized by chartering companies the limitation regarding the underlying deployment discussed previously would not be a problem anymore. Operators would have the flexibility to simply charter the desired vessel at the desired time. However, a significant problem arises due to the fact that the vessels considered in this thesis are fueled by alternative fuels that are not currently utilized by PSVs. Consequently, it becomes difficult to charter vessels that have not yet been constructed or implemented with alternative fuel systems.

## 8.5 Retrofit

The model does not account for the sale or scrapping of vessels, which can lead to unusual decisions. For example, in emission strategy 5 (7.4.5), the model suggests removing three MDO-fueled vessels in 2030, and retrofitting one of these removed vessels to $LH_2$ in 2050. In reality, it would be uncommon to have a vessel in lay-up for 20 years, as ship owners would typically opt to sell or scrap the vessel rather than keeping it idle.

# Chapter 9

# Conclusion

The objective of the thesis was to develop an optimization tool that could provide guidance for the transition of the platform supply vessel fleet toward zero-emission logistics. To achieve this, a mathematical model was constructed and applied to a fictional case study to gather insights into the functionality of the model. The results demonstrate the effectiveness of the model in selecting the most optimal fleet composition to achieve the desired emission goals.

The primary objective of the computational study was to validate the model; therefore, the results should be interpreted with caution. The outcomes generated by the model are highly reliant on the input data provided. However, due to the limited development of alternative ship designs incorporating fully hydrogen and ammonia-fueled vessels, as well as vessels equipped with CCS systems, it becomes challenging to obtain accurate and complete input data. This limitation poses a significant challenge in obtaining precise and reliable results from the model. Therefore, it is essential to acknowledge the potential uncertainties and limitations associated with the input data when interpreting the findings of the study.

The primary emission strategy of focus in this study is aligned with the IMO's goals for 2030 and 2050, which aim to reduce $CO_2$ emissions by 40% and 70% respectively. The study findings reveal that by 2030, the fleet composition would include three LNG-fuelled vessels and one retrofitted vessel utilizing MDO with a carbon capture and storage system. Furthermore, by 2050, two of the LNG-fuelled vessels would be replaced with hydrogen-fuelled vessels.

Through the analysis of various emission strategies, it becomes evident that three distinct cost thresholds exist. The initial transition towards zero-emission involves a substantial increase in costs. However, the cost difference between achieving a 20% reduction and an 80% reduction in emissions is relatively small when considering the price per tonne of $CO_2$ reduced. Finally, transitioning to full zero-emission incurs higher costs compared to the 80% reduction target.

# Chapter 10

# Further work

Based on the current model, the removal of vessels from the fleet does not result in positive cash flow. For ship owners, the options are either to sell the vessel on the second-hand market or scrap it. This is something the model do not include, but could include in the future.

To increase accuracy in the model, designing working vessel concepts for the different fuel technologies is beneficial. In this thesis, the vessel's capacities were determined by assuming how these vessels would differ from a conventional MDO design. With working ship designs, the model would be more realistic to the proposed problem.

The inclusion of $SO_x$ and $NO_x$ emission goal could also be included in the model, with the same procedure as for the $CO_2$ emission goals. This would increase the run time and gap between optimal and lower bound, but a strategy would be found with capable computers.

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