Master's thesis

NTNU
Norwegian University of Science and Technology
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Optimal Placement of Offshore Refueling Facilities in Green Corridors

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2023

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Master Thesis in Marine Systems Design
Stud. techn. Jacob Maurud

“Optimal Placement of Offshore Refueling Facilities in Green Corridors”

Spring 2023

Background
As the maritime sector continues the green transition, there are several initiatives towards the development of green shipping corridors that will enable low or zero emission shipping. A difficult decision is how to make relevant fuels available in the corridor, using innovative and traditional solutions.

Overall aim and focus
The overall aim of the master thesis is to develop a model to find optimal refueling strategy across vessel fuel capacity and refueling points. The focus will be on the logistics and infrastructure aspects of offshore refueling, and the relevant fuels.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of the green corridor concept and related technology and support functions.*
2. *Present relevant optimization tools and principles.*
3. *Create a mathematical formulation for optimal placement of refueling facilities in a green corridor.*
4. *Describe and discuss relevant extensions to the model.*
5. *Further develop model with relevant extensions and apply the model to a relevant case.*
6. *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.

Stein Ove Erikstad
Professor/Responsible Advisor

Abstract

This thesis investigates the concept of green corridors and offshore refueling infrastructure, specifically examining the optimal placement of fixed and dynamic offshore refueling facilities for potential green corridors. The analysis takes the form of a mathematical optimization model, which is implemented and solved using Python solvers. Innovative offshore alternative fuel production and refueling facilities are discussed and proposed as potential components of future green corridor infrastructure.

The optimization process employed in this thesis follows an iterative approach, where each iteration introduces complexity to the model through relevant expansions. The finished model is then applied to a relevant case to assess the applicability of the model, and the feasibility of the proposed refueling infrastructure. In addition, a sensitivity analysis is performed by systematically varying key model parameters and reviewing their impact on the results and outputs.

Findings indicate the need for additional refueling points for longer green corridor routes when transitioning from traditional fuel to lower energy-density alternative fuels(e.g. ammonia) and viability for the proposed refueling infrastructure facilities.

Sammendrag

Denne avhandlingen undersøket konseptet grønne korridorer og offshore bunkeringsstruktur, og undersøker spesielt optimal plassering av faste og dynamiske offshore bunkeringsfasiliteter for potensielle grønne korridorer. Analysen tar form av en matematisk optimaliseringsmodell som er implementert og løst ved hjelp av Python-løsere. Innovative offshore alternative drivstoffproduksjons- og bunkeringsanlegg diskuteres of foreslås som potensielle komponenter i framtidig grønn korridor infrastruktur.

Optimaliseringsporsessen som er brukt i avhandlingen følger en iterativ tilnærming, der hver iterasjon introduserer kompleksitet til modellen gjennom relevante utvidelser. Den ferdige modellen blir deretter anvendt på en relevant case for å vurdere anvendeligheten av modellen og gjennomførbarheten til den foreslåtte infrastrukturen. I tilegg utføres en sensitivitetsanalyse ved å systematisk variere modellparametere og vurdere deres innvirkning på resultatene.

Resultatene indikerer behovet for ekstra bunkeringsfasiliteter offshore for lengre ruter i grønne korridorer ved overgangen fra tradisjonelt drivstoff til alternative drivstoff med lavere energitetthet(f.eks. ammoniakk), samt levedyktighet for de foreslåtte bunkeringsfasilitetene.

Preface

This master's thesis concludes my master's degree in Marine Systems Design at the Norwegian University of Science and Technology (NTNU). The thesis is written in the spring semester of 2023 and the work is carried out in its entirety by the author.

The master's thesis is a continuation of the project thesis written in the fall semester of 2022, and part of the background for the master's thesis is based on the project thesis.

I am grateful to my supervisor, Professor Stein Ove Erikstad from the Department of Marine Technology, for valuable guidance, support, and insight throughout the writing process. I would also like to thank my student peers for a fruitful work environment and interesting discussions throughout the semester.

Trondheim, June 11^{th}, 2023

Jacob Maurud

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Acronyms

IEA	International Energy Agency
IMO	International Maritime Organization
GHG	Greenhouse Gas
UN	United Nations
ICCT	International Council on Clean Transport
LNG	Liquefied natural gas
$\boldsymbol{CO_2}$	Carbon Dioxide
DNV	Det Norske Veritas
$\boldsymbol{NO_x}$	Nitrogen Oxides
$\boldsymbol{N_2O}$	Nitrous Oxide
DAC	Direct Air Capture
HFO	Heavy fuel oil
MGO	Marine Gas Oil
MSR	Molten Salt Reactor
CTV	Crew Transfer Vessel
RAS	Replenishment At Sea
UNREP	Underway Replenishment
LP	Linear Programming
FLP	Facility Location Problem

Chapter 1

Introduction

According to the International Energy Agency (IEA), international shipping is accountable for 3% of global CO_2 emissions, a number that can rise as high as 50% by 2050 if left unchecked as other sectors make progress towards net zero.[1] The International Maritime Organization (IMO) and other shipping sector regulators have in recent years put the green transition in shipping on the agenda. In 2018, IMO adopted an initial strategy to reduce the total annual greenhouse gas (GHG) emissions by at least 50% by 2050 compared to 2008 emissions, while still seeking to reach net zero shipping within the same time frame.[2] This initial strategy also has an interim goal of 40% reduction in carbon intensity from shipping by 2030. IMO's interim and end emission reduction goals have since been criticized by United Nations (UN) and the international council on clean transport (ICCT) for falling short of the Paris Agreement goals of reducing global warming by 1.5°C.[3][4]

Improving logistics and curtailing traffic volumes could reduce emissions from the shipping sector by 5%. In addition, improvements in engine efficiency, propulsion systems, and ship design can further the emission decline by between 15 and 55%.[5] Although these steps, if taken, can reduce emissions significantly they will not be sufficient to hit the targets set by IMO's initial strategy. The main step towards net zero shipping is to transition from traditional fossil fuels to alternative low or zero-emission fuels. Many alternative fuels are being considered as possible replacements, although each of them presents a trade-off in terms of efficiency and fuel capacity requirements. This transition will be time-consuming, even with the implementation of carbon taxation and subsidiary actions.

As a means to speed up the green transition in the shipping sector, green corridors have been proposed as a solution. This would see key stakeholders collaborate making net zero shipping feasible on specific trade routes between two or more ports. This collaboration would reduce the risk of monetary loss for all stakeholders involved, and open up opportunities to explore zero-emission solutions on smaller scales which later can be implemented on a worldwide scale. These solutions include refueling and value chain infrastructure, alternative fuels, and zero-emission vessel concepts.

1.1 Background

Currently, there are many initiatives toward establishing green corridors. A difficult challenge that arises is how to build a robust fuel infrastructure in order to make relevant alternative fuels available for vessels in and between ports in the corridor. This challenge encompasses various aspects, such as the placement and size of production facilities, fueling stations, and distribution networks. In addition, the fuel infrastructure would need to be tailored to the preferred fuel of the corridor, given that each fuel has distinct storage and handling properties. It would also have to be able to cater to different types of vessels of different sizes and fuel capacities. The energy density of most of the proposed alternative fuels is lower than that of traditional fuel, which put extra emphasis on fuel infrastructure.

In order to design a complete fuel infrastructure to service a green corridor, there are traditional and innovative solutions to be considered. These include utilizing the current fuel infrastructure found in most ports, where traditional fossil fuels are replaced with alternative fuels, and incorporating offshore bunkering facilities. The major investment into offshore wind may open doors for green alternative fuel production facilities offshore, which can in turn supply ships with fuel between ports.

1.2 Thesis objective

The main objective of the thesis is to create a mathematical optimization model to determine the optimal placement of refueling infrastructure facilities in a proposed green corridor.

The specific tasks that will be undertaken in this thesis are:

- Provide an overview of the green corridor concept as well as related technology, innovations, and support functions.
- Create a mathematical formulation for optimal placement of innovative offshore bunker production and supply facilities as a part of green corridor refueling infrastructure.
- Implement and expand the mathematical model and apply it to a case
- Discuss the results and conclude.
- Discuss further work that can be undertaken.

1.3 Scope and limitations

The proposed offshore bunkering facilities that are discussed in the thesis and are implemented in the mathematical model have varying levels of feasibility and are heavily reliant on the optimal placement of offshore wind farms. As the placement of wind farms is not part of the thesis, it is assumed that the placement of offshore alternative fuel production facilities coincides with the placement of wind farms. Other technologies and alternative fuels used are also presumed feasible.

1.4 Thesis Structure

The thesis is divided into seven chapters. Chapter 1 serves as a brief introduction to the thesis, providing background and explaining the objectives and structure of the thesis. Chapter 2 contains background on the green corridor concept, initiatives, alternative fuels, bunkering concepts, and stakeholders. Chapter 3 presents the relevant optimization theory background and the mathematical optimization model step-by-step. In Chapter 4 the model made in Chapter 3 is applied to a case where dry bulk shipping in the North Sea is examined. The case is solved for different parameter variations, and the results are presented. Chapter 5 discussed the results of the case study and model limitations and relevant expansions. Chapter 6, and Chapter 7 provide the conclusion and recommendations for further work respectively.

Chapter 2

Green Corridors

Parts of this chapter are from the project thesis *"Sustainable Refueling Options for Green Corridors"* by Maurud.[6]

2.1 The Challenge

Transport of goods and people is the second biggest polluter by industry with yearly greenhouse gas (GHG) emissions of 8.43 billion tons.[7] These emissions come primarily from road transport (74%), but ambitions to shift freight from road to sea are putting increased pressure on the shipping industry to change its emission trajectory.[8][9] According to the International Maritime Organization (IMO), the share of shipping emissions in global GHG emissions is approximately 3%, proving the important role the industry will play to reduce climate change and reaching the goals set by the Paris Agreement and maritime legislators.

There are several agreements and industry strategies that have set clear end- and interim goals for the maritime industry and the world as a whole. The aforementioned Paris Agreement sets out a global framework to limit global warming to below 2°C to avoid the dangerous effects of climate change. Even though the temperature goal is set to 2°C, the signatories of the Paris Agreement are obliged to pursue efforts to limit global warming to 1.5°C.[10] Despite this, data from the International Council on Clean Transport (ICCT) shows that the current emissions trajectory of the maritime industry is way off what trajectory is needed. Figure 2.1 shows the rising discrepancy between the current trajectory and the trajectories that align with the Paris Agreement and IMO's initial strategy.

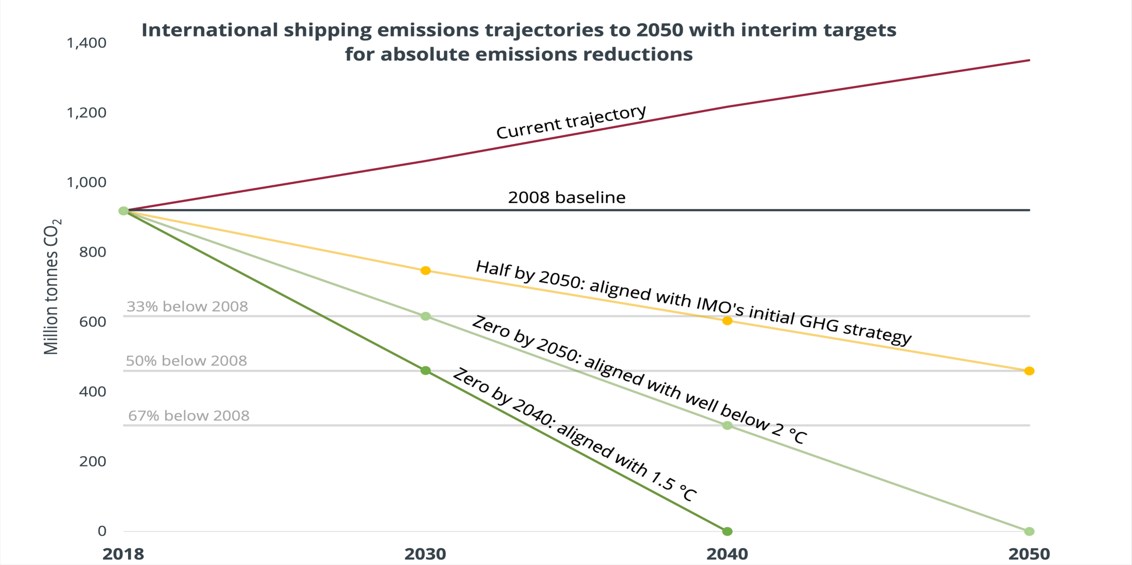


Figure 2.1: International shipping emission pathways consistent with the Paris Agreement temperature goals.[4]

There are continuous efforts to reduce the GHG emissions of the shipping industry, there are however key characteristics of the industry that makes a swift green transition challenging. These characteristics include the long average lifespan of merchant ships, the complexity of global shipping supply chains, and the industry's continuous dependency on fossil fuels. As shown in Figure 2.2 the number of ships, here represented by dead weight, in the global fleet has been on a steep incline since the start of the millennium. Since the average lifespan of merchant ships is 25-30 years many of these ships will still be sailing when IMOs interim goal of 40% deduction in shipping emissions should be reached in 2030.[11]

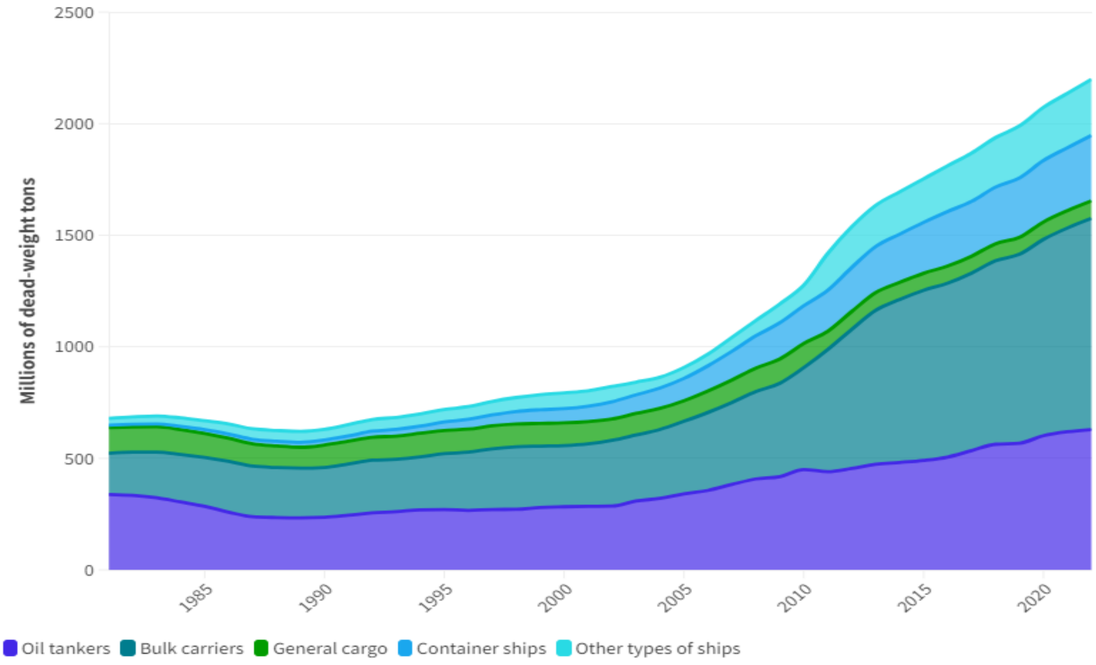


Figure 2.2: World fleet by principal vessel type.[12]

2.2 Concept

Creating green corridors makes it possible to scale down the challenges mentioned earlier to a manageable size, whilst still creating an impact on the overall CO_2 emissions of the sector. Green corridors are defined as ’specific trade routes between major port hubs where zero-emission solutions have been demonstrated and supported.[5] The ultimate goal of creating green corridors is to test the feasibility of fuel and infrastructure options in order to eventually deploy them on a worldwide scale.

In the face of climate challenges, green corridors are meant to speed up development with collaboration between the main stakeholders, who are described in Section 2.5. A challenge the stakeholders have is the classic chicken-and-egg scenario where investments in new technology are risky in a transition phase where no one wants to push the envelope. A green corridor makes it possible for stakeholders to make investments on a smaller scale, with the certainty that others in the value chain will make supporting investments and decisions. There is a widespread understanding that the changes will not be overnight, but a series of steps that in time will cover all parts of the value chain for a specific route. In the startup phase, it’s important for stakeholders to outline a timeline with interim goals that everyone can agree upon. There are also some key decisions that have to be taken in terms of what fuel to choose and other logistical aspects of the green corridor.

There is a growing number of major sector players, such as governments and private sector actors, that are focusing on green shipping corridors. Even though there is a set definition of what a green corridor is and should be, there is yet to be a shared understanding of what the prefix green should entail.[13] This ranges from net-zero emissions in the entire value chain, from the production of fuel and cargo and the shipment itself to only the vessel itself using fuel that emits less than traditional fuel. These distinctions can be important when discussing green corridors, in order for all actors to have a common base. Regardless of how the definition of a green corridor is interpreted, a green corridor would still see an impact on overall emissions.

2.3 Green Corridor Initiatives

2.3.1 Getting to Zero Coalition

The Getting to Zero Coalition is a global partnership of governments, businesses, and organizations working to accelerate the development and deployment of zero-emission, commercially viable ships. The coalition’s goal is to have a fully operational fleet of zero-emission ships carrying international trade by 2030[14].

The Getting to Zero Coalition was launched in 2018 at the United Nations Climate Change Conference in Katowice, Poland. Since then, the coalition has grown to include over 100 members, including major shipping companies, shipyards, fuel providers, and other stakeholders.

The coalition's work is focused on three main areas: developing zero-emission technologies, promoting regulatory frameworks that support the deployment of these technologies, and mobilizing investment in green corridors. This includes supporting the development of technologies such as hydrogen fuel cells, batteries, and ammonia, as well as working with governments and international organizations to create the necessary regulations and incentives for the deployment of these technologies.

By reducing emissions from the shipping industry, the Getting to Zero Coalition aims to help limit global warming and protect the environment. The coalition believes that transitioning to zero-emission ships is not only necessary for the environment but also presents a significant business opportunity for its members.

They have a strong belief in the green corridor concept and have done extensive studies on their feasibility for certain trade routes[5]. They have also created a roadmap to 2030 with interim goals for the shipping sector in order to reach IMO's 2030 emission goals, as seen in Figure 2.3.

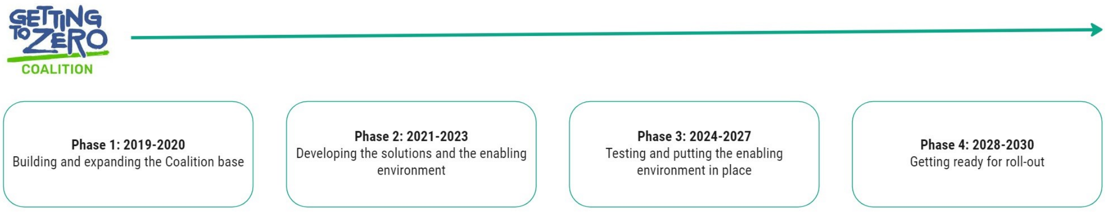


Figure 2.3: Getting to Zero Coalition Roadmap.[14]

2.3.2 Clydebank Declaration

The Clydebank Declaration is a statement that was issued by a group of shipbuilders and maritime industry leaders at a conference in Clydebank, Scotland in 2018. The declaration calls for urgent action to address the environmental challenges facing the shipping industry, and outlines a series of principles and commitments for achieving a sustainable and low-carbon future for shipping.

As described in the Clydebank declaration mission statement, the signatories of the Declaration, table 2.1, are to support the establishment of green shipping corridors[15]. Their aim is to establish at least 6 green shipping corridors by 2025, and in doing so lay a foundation for reaching zero-emission shipping. The Clydebank Declaration recognizes the significant contributions of the shipping industry to global trade and economic development but also notes the industry's significant environmental impacts. The declaration calls for urgent action to reduce emissions and improve the sustainability of shipping operations, and outlines a number of key principles and commitments for achieving this goal.

Some of the key principles outlined in the Clydebank Declaration include:

- The need for an ambitious global decarbonization strategy for shipping, with the goal of achieving zero emissions as soon as possible.

- The importance of research and innovation in developing sustainable and low-carbon technologies for the shipping industry.
- The need for collaboration and partnership between different stakeholders, including shipbuilders, operators, regulators, and academics.
- The importance of supporting the development of necessary infrastructure and support systems, such as LNG bunkering facilities, charging stations for electric ships, and waste management systems.
- The need for clear and consistent regulatory frameworks to support the transition to a sustainable and low-carbon future for shipping.

The Clydebank Declaration has been widely endorsed by the shipping industry and other stakeholders, and the number of signatories to the declaration, and their current impact on the maritime industry gives reasons to believe that the Clydebank declaration can be a turning point for the shipping industry.

Australia	Belgium	Canada	Chile	Costa Rica	Denmark
Fiji	Finland	France	Germany	Ireland	Italy
Japan	Marshall Islands	Morocco	Netherlands	New Zealand	Norway
Palau	Singapore	Spain	Sweden	UK & Northern Ireland	USA

Table 2.1: Signatories of the Clydebank Declaration.

2.3.3 Cargo Owners for Zero Emission Vessels

Cargo Owners for Zero Emission Vessels (COZEV), is a collaboration between cargo owners who wants to use their brand power and influence to accelerate maritime decarbonization[16]. They understand their importance to the creation of green shipping corridors and have developed a green corridor advisory board for enabling fluent 'across-value-chain' communications for future green corridor projects[17]. Through this board, they hope to be able to provide important input and stay updated on project progress. They want to provide this help not only for trans-oceanic routes but also for smaller projects where there is feasible scalability.

2.4 Alternative Fuels and Refueling Infrastructure for Green Corridors

The creation of green corridors will require a transition away from fossil fuels to alternative fuels with lower GHG emissions and greater sustainability. Alternative fuels are crucial in order for the shipping industry to reduce its environmental impact and reach emission targets. Choosing the right alternative fuel is an important initial step, it will however be difficult, as it involves considering several factors such as availability, fuel properties, compatibility, and technology readiness level. The fuel selection will have an impact on refueling infrastructure and vessel properties.

2.4.1 Alternative Fuels

As the shipping industry is exploring both long- and short-term future alternative fuels, some have surfaced as more eligible than others. The most prominent short-term transition fuel that has been presented is Liquified Natural Gas (LNG) for its worldwide availability and low carbon emissions, it will however only reduce emissions not erase them. In this section, alternative fuels that can be both produced and used carbon neutral will be presented. These include ammonia, hydrogen, methanol, and battery electric. They have in common that they can be produced green and will emit no CO_2 when used as propulsion.

When discussing alternative fuels, there is often a large emphasis on how it is produced and a set of prefixes have been made to distinguish the production by its energy source. These sources are described in Figure 2.4.

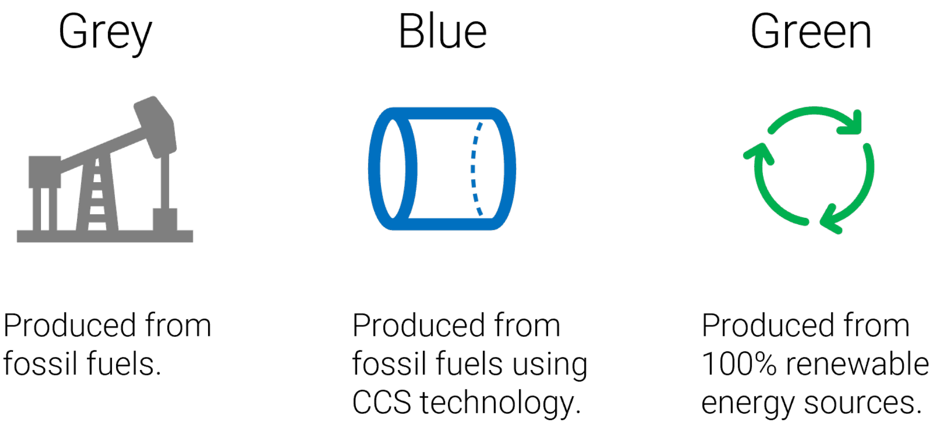


Figure 2.4: Description of alternative fuel production and resulting prefix.

Ammonia

Ammonia is an alternative fuel, that if produced from renewable sources like solar or wind, is carbon-free. According to the maritime forecast to 2050 by DNV from 2022, ammonia onboard fuel technology will be available in three to eight years.[18] Ammonia as a marine fuel is possible using both an internal combustion engine as well as fuel cell technology. One of the downsides of ammonia combustion is NOx and N2O emissions, as well as the potential danger of ammonia spills. Such spills will have local environmental impacts as it is both highly toxic and corrosive.[19] As with many of the proposed alternative fuels, ammonia has a lower energy density than traditional fuel. This will have an impact on the cargo-carrying capacity of ammonia-fueled vessels, as more fuel would have to be brought on voyages. A detailed table of fuel properties are shown in Table 2.2.

Ammonia is relatively easily stored and transported. It is stored as a liquid either under pressure at atmospheric temperature or fully refrigerated at -33°C at atmospheric pressure.[20] Today, 80% of the annual ammonia production of 289 million metric tons is used as fertilizer and is produced using non-renewable sources.[21][22] Although there are advantages to ammonia being a widely used and produced chemical, production would still need expanding and tweaking in order for it to supply a world fleet, and be considered green.

Hydrogen

As with ammonia, DNVs Maritime Forecast to 2050 predicts that onboard fuel technology for hydrogen will be available in three to eight years. Hydrogen can also be produced using renewable sources, and when used in a fuel cell hydrogen only emits water.[23] Similarly to ammonia, hydrogen has a lower energy density compared to traditional fuel. Hydrogen storage as a liquid requires cryogenic temperatures due to its boiling point of -252.8°C at one-atmosphere pressure. The energy density and handling of hydrogen are seen as the biggest obstacles for use as a fuel, and scientists say the lack of data on possible leaks and the damage it may cause is a worrying blind spot.[24]

The main portion of hydrogen being produced today is used for oil refining, ammonia and methanol production, and steel production. Roughly 95% of all hydrogen that is produced today is grey, using fossil fuels.[25] Over the last 50 years, there has been a growing demand for hydrogen as an energy source, and there have been made major strides in hydrogen fuel cell technology in recent years. High hydrogen demand may impact the willingness to expedite the green transition in hydrogen production. Figure 2.5 Shows global demand for pure hydrogen and ammonia between 1975 and 2018.

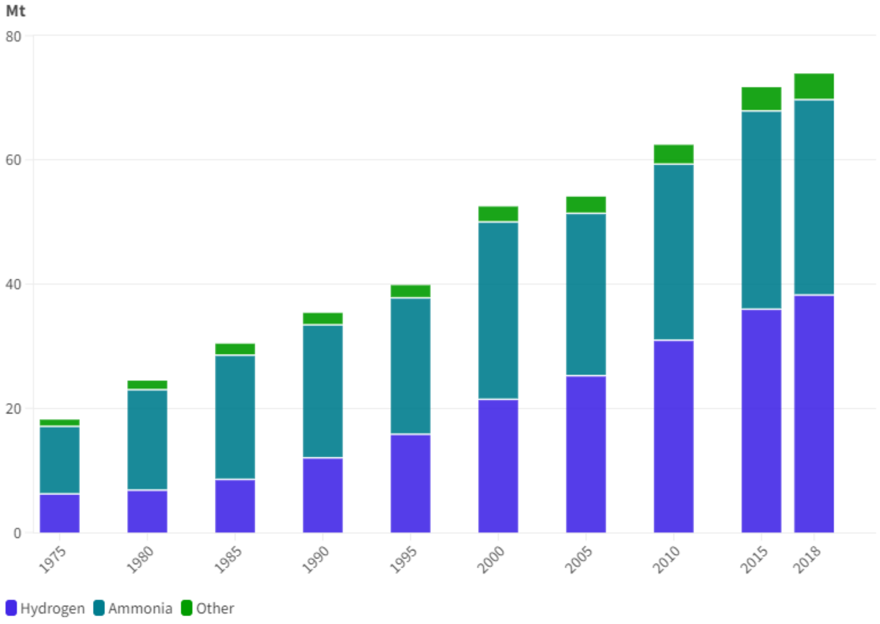


Figure 2.5: Global demand for pure hydrogen and ammonia, 1975-2018.[25]

Methanol

Methanol is a liquid fuel that is derived from natural gas, coal, hydrogen, or biomass. It shows promise as an alternative fuel due to its low emission profile, in addition, methanol can be easily produced from a variety of feedstock, making it a potentially abundant and inexpensive fuel source.[26]

An advantage methanol holds over other alternative fuels is that it is already in operation as a marine fuel.[27] It is also in a liquid state under normal conditions and is easily handled. Methanol has a higher energy density compared to both ammonia and hydrogen, despite being lower than that of traditional fuel.

Battery electric

The concept of electric propulsion of seagoing vessels has been around since the first electric ship in 1839.[28] Currently, fully electric ships are mainly small ferries and passenger ships that sail short distances on inland waterways and dock often, allowing them to recharge often and quickly. Electric propulsion holds the advantage over other alternative fuels in that it emits no noise or pollutants during use. This makes them great for their current use in fjords and rivers where the local environment is more at risk than on the open sea.

The biggest disadvantages related to the use of electric propulsion are short ranges, lack of recharging infrastructure, and slow speeds.[29] This was for a long time also true for electric cars. In 2012 fewer than 10,000 electric vehicles were registered in Norway, in 2021 that number had increased to 647,000, and in 2022 79.3% of all new cars sold were fully electric.[29][30] This rapid shift to electric cars is a worldwide trend, and the increased demand has also streamlined the development of more efficient and long-lasting batteries as well as the development of rapid charging station infrastructure. This displays the effects of economic incentives and high demand, and this knowledge can be transferred to electric seagoing vessels.

Cars had a natural and gradual transition from hybrids to fully electric. This is a feasible path for ships as well. This will allow bigger ships to sail on fully electric when close to shore where the local environmental impact is worse and sail on other fuel for the remainder of the voyage. This concept has been utilized by Color Line on their Sandefjord-Strømstad line where they have built the world's largest plug-in diesel-electric hybrid.

Although electric batteries emit no green house gases, electricity production still heavily relies on coal-fired power plants. World Coal Association predicts that electricity from coal will be reduced from today's 37% to 22% in 2040 globally, and not less than 39% in South East Asia, which is a major hub for large container vessels.[31] A consequence of this is that even if battery technology reaches a point where it can be used for large vessels, the electricity used may not be carbon neutral. There is however a positive trend in total renewable electricity production, although it is far to go before total global demand can be supplied by renewable electricity, as shown in Figure 2.6. This figure also present projected renewable electricity production in

2030.

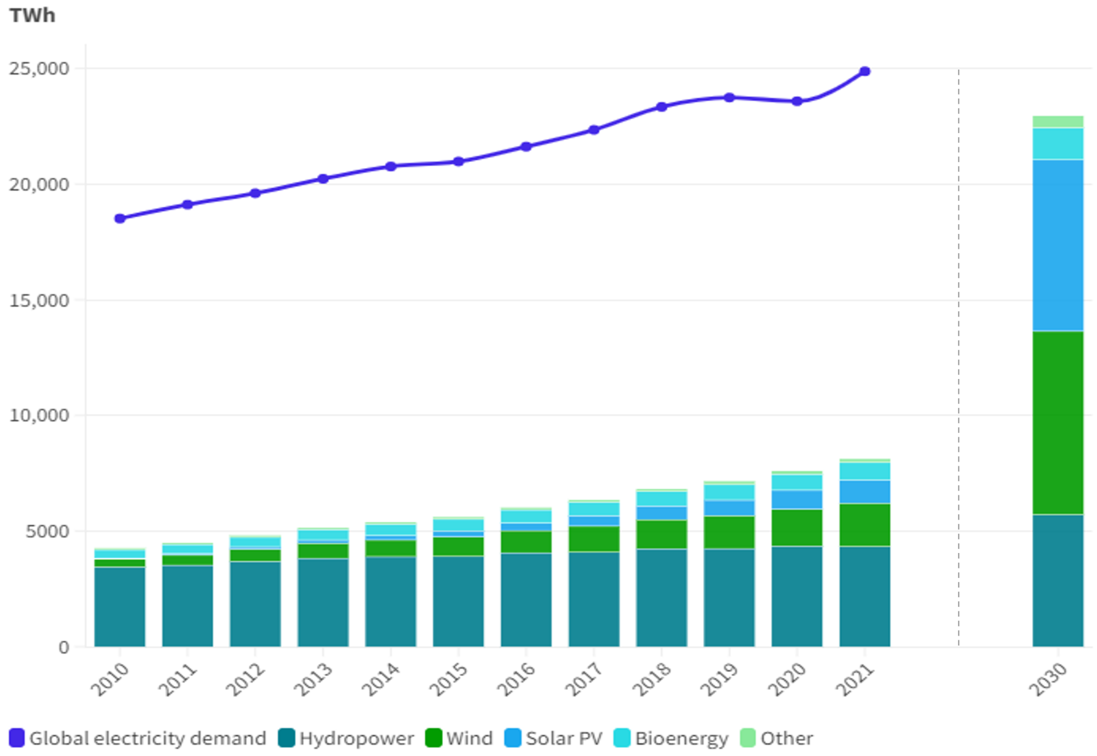


Figure 2.6: Global electricity demand compared to renewable energy production, 2010-2021.[32][33]

Key properties and technology readiness level of alternative fuels

The concept of green corridors relies on swiftness in decision-making so that a green corridor becomes a platform from which one can make global and long-lasting decisions with greater supporting data. When initially choosing an alternative fuel for a green corridor, looking at handling complexity and technology readiness level will be important decision factors. Table 2.2 displays the energy density and storage properties of alternative and traditional fuels. As can be observed from the table, all alternative fuels have a lower energy density than diesel as previously described. Ammonia and hydrogen also require either pressure or cryogenic temperatures respectively to be stored and transported in liquid form. Out of the three alternative fuels in the table, methanol is the easiest to handle as it is a liquid in ambient conditions.

McKinsey Sustainability has done a study using direct air capture (DAC) technology and other quantitative data as well as qualitative data to describe the technology readiness level of the possible alternative fuels.[36] It is important to note that both green ammonia and green methanol are derived from green hydrogen and that the hydrogen was assumed liquid in the study. The results of the study are shown in Figure 2.7, where 9 means ready and 0 means not ready at all. In their study, green methanol was proven the most technically advanced as methanol engines are

Table 2.2: Properties of alternative fuels.[34][35]

Properties	**Ammonia**	**Hydrogen**	**Methanol**	**Diesel**	**Units**
Energy density	11.3	8.5	15	36.4	MJ/m^3
Storage method	Compressed liquid	Cooled liquid/Compressed gas	Liquid	Liquid	-
Storage temperature	298	20.3/298	298	298	K
Storage pressure	10.2	1.0/690.8	1.0	1.0	atm

already commercially available and methanol is relatively easy to handle. However, for methanol to be considered green, the CO_2 used in production must originate from biogenic sources, which makes it both hard to upscale and costly.

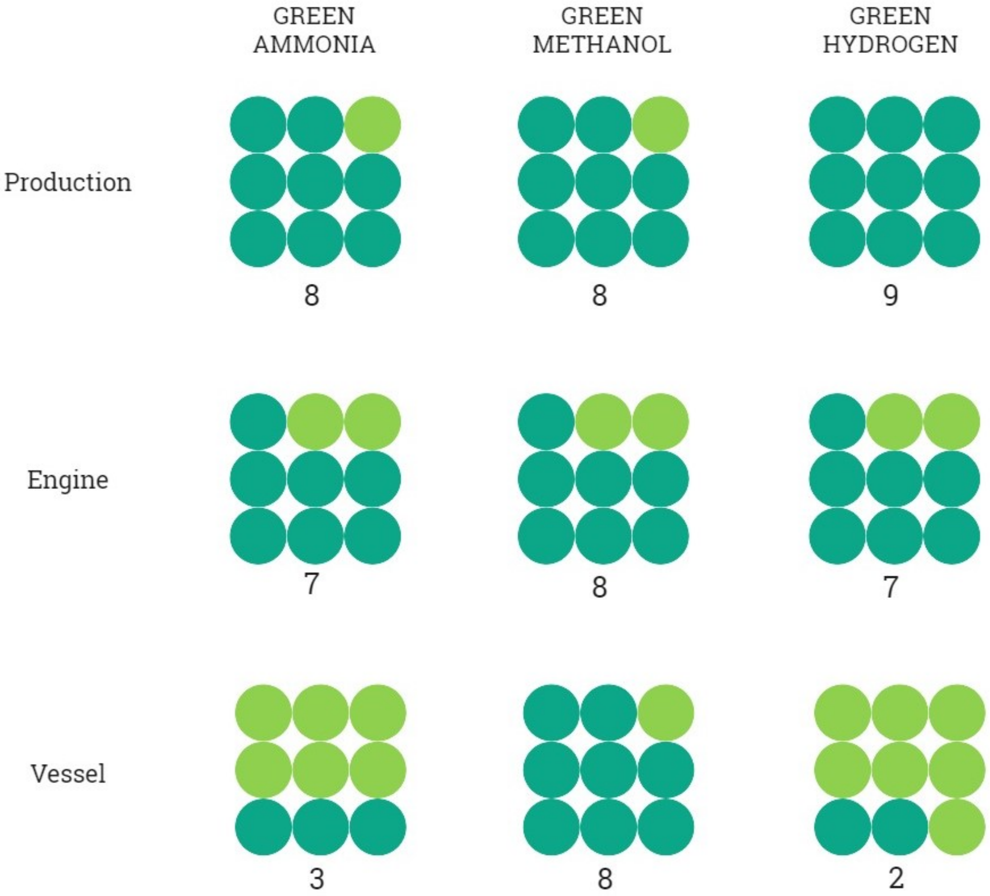


Figure 2.7: Technology readiness level of alternative fuels.[36]

Cost

Before ammonia, methanol, and hydrogen can be produced using renewable sources, their price will rely on fluctuating natural gas prices as well as the cost of carbon capture and storage solutions. Future costs will also heavily rely on demand, availability, and cost of renewable energy sources and is therefore difficult to predict.

Figure 2.8 shows the indicative costs of alternative and traditional fuels, and it can be observed that the alternative fuels are both more expensive and have a wider cost range than traditional fuels. The high costs are mostly due to expensive technology and low availability, the range is a result of different production methods and fluctuating resource costs. The bottom of the cost range for alternative fuels requires a renewable electricity cost of around $25 USD/MWh$. The current cost of renewable energy from different sources is approximately double depending on the source, as shown in Table 2.3.

Table 2.3: Levelized cost of electricity from renewable sources, 2021.[37]

Rewnewable source	**USD/MWh**
Offshore wind	64
Solar PV	61
Onshore Wind	43

One of the ways governments and maritime organizations are suggesting to close the cost gap is to implement a carbon tax. According to the International Transport Forum, there are 68 generic carbon pricing schemes worldwide. Norway's national carbon tax is the only one of them that encompasses emissions from maritime shipping.[38] The implementation of a carbon tax will not only make alternative fuels more competitive, but it will also generate revenue that can, in turn, be invested in zero-emission technology and infrastructure.

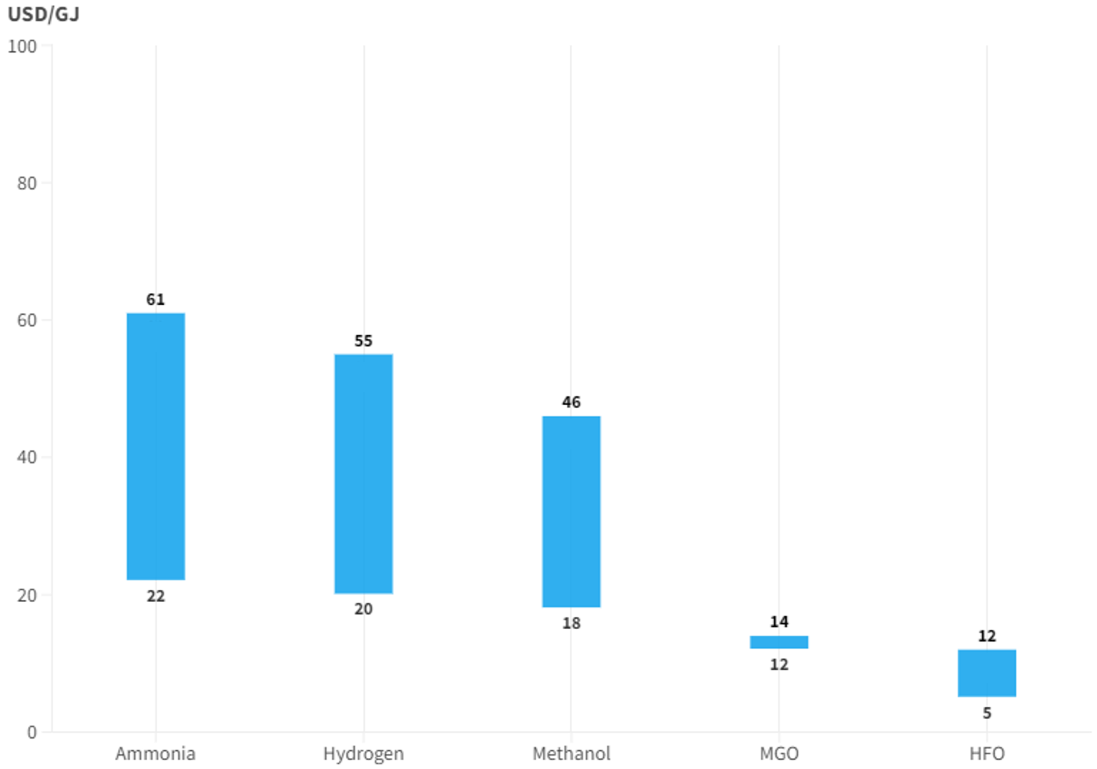


Figure 2.8: Indicative shipping fuel cost ranges.[39][40]

Although it is difficult to say what the future cost of alternative fuels will be, McKinsey Sustainability has made a projection for the total cost of ownership of a bulk iron-ore carrier running on green- ammonia, methanol, and hydrogen respectively. Their results, as seen in Figure 2.9, show that the total cost of ownership will decrease between 2030 and 2050 and that green ammonia will be the most cost-effective solution.

Figure 2.9: Total cost of ownership $ million.[36]

2.4.2 Current bunkering practices

Bunkering today is predominantly achieved in ports either onshore using trucks, pipelines, and tankers or offshore using barges. The bunkering method is determined by the type of fuel that is being supplied. When supplying marine fuel oil, such as heavy fuel oil (HFO), a barge can be used to transfer the bunker to the docked or anchored vessel. If the quantity of oil is less, as with Marine Gas Oil(MGO) and Liquefied Natural Gas(LNG), shore-to-ship bunkering methods such as trucks can be used.[41] It is often routine for the chief engineer to calculate the bunker requirements for the voyage and add a 5-day safety margin so that they do not run out on the open sea where there are no bunkering facilities.[42] This port-only bunkering infrastructure is convenient, cheap, and works when the fuels that are predominantly used have a high energy density.

Refueling infrastructure innovation will be important when creating a green corridor, and the choice of alternative fuel and its properties will have a direct impact on innovation efforts. When the energy density is lowered and inherently making vessel range shorter, stakeholders are left with choices of how to improve the refueling infrastructure of a green corridor, and the vessels sailing the particular route. One of the choices is to take the loss in cargo carrying capacity and expand the fuel tanks on vessels so that they are able to undertake similar-length voyages. This will affect profit-making for both cargo- and shipowners and could entail altering onshore cargo handling infrastructure in ports as there will be a slower throughput of cargo. This would also be contrary to trends in the global seaborne trade, which grew from 8.7 billion tons in 2011 to 11 billion tons in 2021.[12]

A second alternative is to build bigger ships that can undertake the same length of voyages and carry the same amount of cargo as before. This would in many cases also have an impact on port and channel infrastructure as the largest ships today are as large as can be to fit certain ports and channels. There is also the option of exploring possibilities to develop more efficient engines and propulsion systems and improve hull designs and speed calculations to get the most out of limited bunker capacity. With ammonia having a third of the energy density compared to diesel, and hydrogen only having a fourth these developments would have to be groundbreaking in order for the bunker capacity to not affect cargo carrying capacity.

There is also the possibility to expand bunker infrastructure to include offshore bunkering facilities, either fixed installations or dynamic ones in the form of bunkering vessels. This approach would offer the possibility for vessels to maintain their existing dimensions and cargo capacity. However, its implementation would require significant economic investments and the active involvement of key stakeholders.

2.4.3 Offshore bunkering concepts

There have emerged many new concepts for offshore fuel production and bunkering facilities, often related to the big investments and progress being done in offshore wind. If the full potential of offshore wind is utilized, there will be excess renewable energy that can be used to produce green alternative fuels, as Figure 2.10 shows.

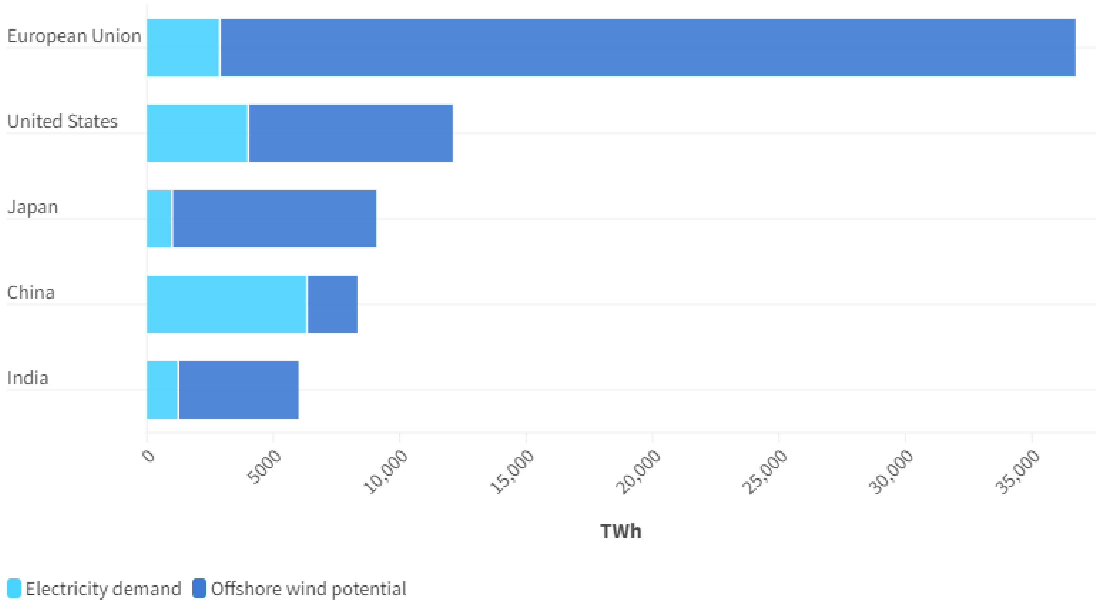


Figure 2.10: Offshore wind technical potential and electricity demand, 2018.[43]

In this section, some of the technologies and innovations that can be used as offshore refueling stations for a green corridor will be discussed.

Offshore hydrogen production from offshore wind

The availability of renewable energy and water at offshore wind farms gives way to the production of green hydrogen using electrolysis. This would entail using renewable energy from the wind turbines to distill sea water and then splitting the water molecules to produce hydrogen and oxygen.[44] This process could either be done using hydrogen production vessels or building hydrogen production plants near the wind farms as shown in Figure 2.11 and 2.12.

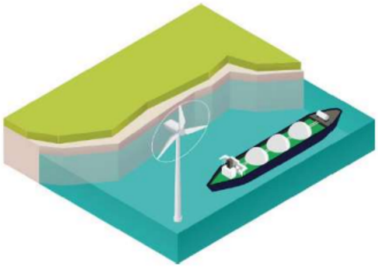


Figure 2.11: Small-scale green hydrogen production from offshore wind.[45]

Figure 2.12: Commercial scale offshore hydrogen production coupled with offshore wind farm.[45]

ERM Dolphyn has created a concept where the wind turbines platforms double as hydrogen production plants, as shown in Figure 2.13. This would eliminate the need to build new vessels and plants in order to produce hydrogen offshore.

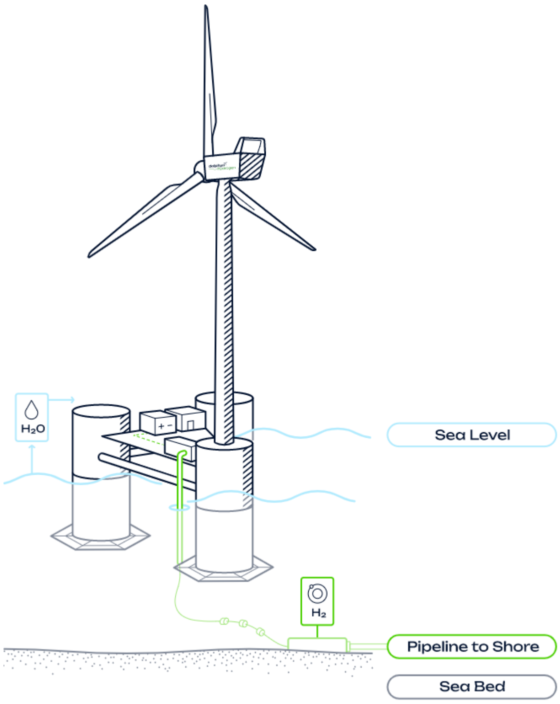


Figure 2.13: Dolphyn hydrogen production concept.[44]

These solutions have in common that they aim to produce green hydrogen that is then transported to shore either by ship or pipelines. In time these solutions can also be incorporated into green corridor bunkering infrastructure, where they can act as offshore refueling stations for vessels sailing with alternative fuels. The electricity generated from offshore wind farms could also be charging stations for electric vessels.

Energy Islands

The Danish government is building two energy islands in the North- and Baltic Seas that will serve as energy hubs for their offshore wind production. The primary reasoning behind this project is to be able to move offshore wind farms further from shore, and still efficiently supply both the Danish electricity grid as well as other countries in Europe. Whereas before, offshore wind farms directly supplied the Danish electricity grid, these new hubs - or green power plants - will gather the electricity and distribute it.[46]

These hubs will produce more green energy than Denmark will need, which opens up energy trade with neighboring countries as well as converting the green energy surplus to produce other forms of green energy such as alternative fuels for ships. As shown in Figure 2.14 and Figure 2.15, the geographical placement of the energy islands shows potential for them to be used also as refueling stations for ships. If the alternative fuels were produced using only electricity from the wind farm, this would also ensure that the alternative fuel produced is green.

The locations as shown below are in the North Sea and the Baltic Sea respectively. In the Baltic Sea, the existing Island of Bornholm will be used as the energy island, whereas the plan for the North Sea is to build an artificial island approximately 100 km off the coast of western Denmark.

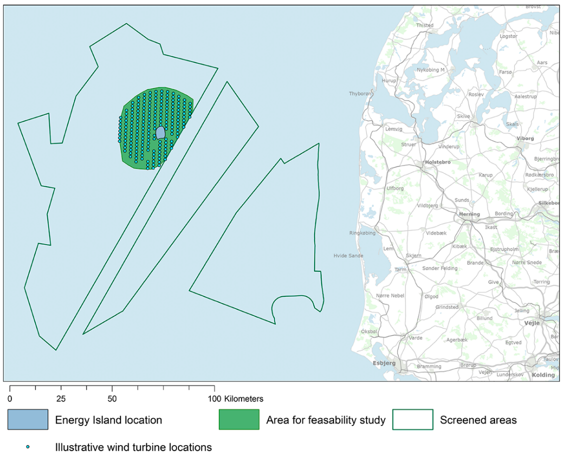


Figure 2.14: The energy island in the North Sea.[46]

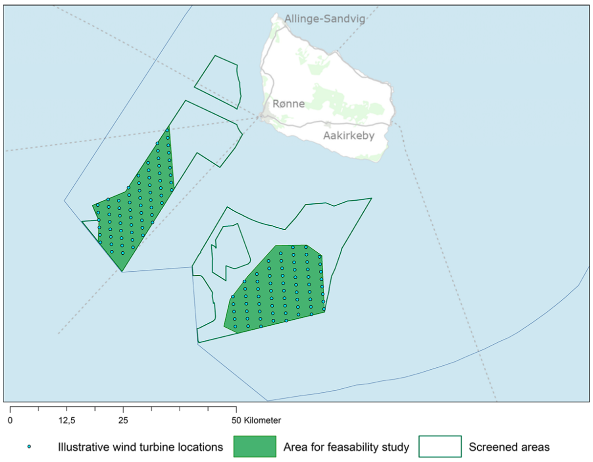


Figure 2.15: The energy island in the Baltic Sea.[46]

Bunker Vessel Concepts

Bunker vessels that are used to refuel ships both in ports and offshore have been utilized for a long time with traditional fuel. Innovative bunker vessels that can generate and supply vessels with clean energy can also be utilized in green corridor refueling infrastructure. These can increase fuel availability along a corridor, are dynamic, and can meet other vessels on their specific routes. Traditionally these bunker vessels gather fuel in onshore facilities before they refuel another vessel, there are however concepts that will allow for energy production on the bunker ships themselves.

One of the ongoing projects exploring this is the Ulstein Thor concept vessel, by the Norwegian company Ulstein. Ulstein Thor is a replenishment, researcc, and rescue vessel featuring a Thorium Molten Salt Reactor (MSR) for generating electricity[47]. This in order to be used as a mobile charging station for battery-driven cruise ships. However, the concept can also be extended to also supply other alternative fuels.

Figure 2.15: Ulstein Thor concept bunker vessel.[48]

Among various emerging bunker vessel concepts, one noteworthy example is coming from UK-based start-up Zephyrus Marine.[49] They are building a fully-electric ”mothership” that will recharge fully-electric crew transfer vessels (CTVs). The refueling works as a traditional battery swap where fully charged batteries for the CTVs are swapped at the ”mothership” once their batteries are drained.

Figure 2.16: The Zephyrus mothership.[49]

Bunker vessels can also use replenishment at sea (RAS) or underway replenishment (UNREP) methods. These are methods where a bunker vessel matches the speed of the vessel they are servicing and refuels them at speed. UNREP was developed by and for naval vessels that would often have the need to be mobile, and long standstill bunkering times are considered dangerous in war. This method has previously had no civil application as bunkering times often are less than or equal to loading/unloading time. In the case of a green corridor where a vessel might have to refuel between the origin and destination ports of its route, and a lot of time might be lost to refueling, using these methods might be viable.

2.5 Stakeholders

In order to create a sustainable green corridor, there needs to be an across-value-chain collaboration between stakeholders both on the supply and demand side. To get an overview of the different stakeholders it is suitable to utilize stakeholder theory to divide primary and secondary stakeholders in a model, as shown in Figure 2.17.[50] This model includes all stakeholders who create value, advocate for, or in other ways play an important role in the creation of a green corridor.

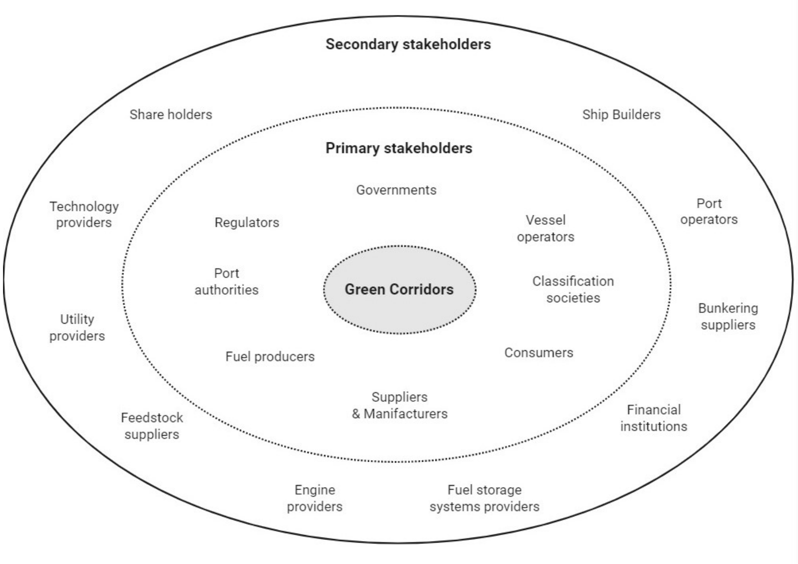


Figure 2.17: Primary and secondary stakeholders in a green corridor.

In the context of green corridors, the distinction between primary and secondary stakeholders is related to their direct involvement and influence on the operation of the corridor. Primary stakeholders, such as governments and vessel operators, are directly involved with the planning and creation of a green corridor as well as the day-to-day operation once a green corridor is established. Secondary stakeholders are entities that are not directly involved with a green corridor creation or operation, but will still have an interest in its outcomes and be affected by the choices made. Examples of secondary stakeholders related to green corridors are engine providers and fuel storage system providers. The choices made in alternative fuel for the corridor will affect what engines are built or fuel storage systems utilized and may affect their value chains as well.

When the stakeholders are identified, it is important to understand how the different stakeholders interact with each other and what their main purpose and needs are in the green corridor value chain.Figure 2.18 displays a flowchart of primary and secondary stakeholders and their interactions.

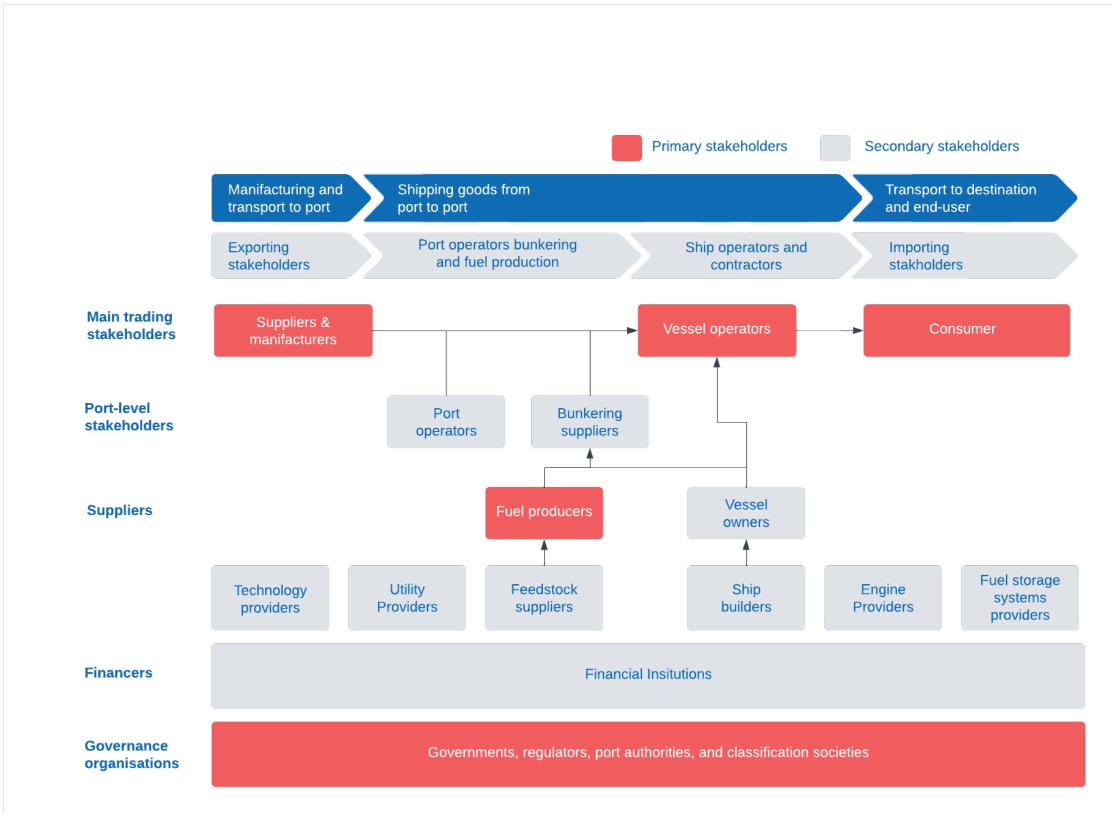


Figure 2.18: Primary and secondary stakeholder interaction flowchart.[5]

Chapter 3

Optimization model

This chapter aims to create an optimization model for exploring how the offshore bunkering options that are discussed in Section 2.4.3 can be utilized and to find the optimal placement of fixed or dynamic refueling facilities along a possible green corridor. Such a model can aid the aforementioned primary stakeholders in decision-making when creating a green corridor.

3.1 Linear programming

The optimization models in this thesis will be solved using the linear programming (LP) method, which is used to solve optimization problems where both the objective function and its constraints are linear. The method provides a systematic approach to either maximize or minimize the objective function, in order to find an optimal solution while simultaneously satisfying all constraints. The constraints of an LP problem are represented as linear equations or inequalities and are used to determine the values of one or more decision variables that in turn optimize the objective function.[51]

Linear programming has many applications, this thesis will utilize two of these, facility location problem and network optimization problem.

3.1.1 Facility location problem

Facility location problem (FLP), is a sub-category of linear programming where the objective is to find the optimal placement of facilities in a supply chain such as factories and warehouses, or in this instance refueling facilities of a green shipping corridor. This is achieved by either minimizing cost, maximizing efficiency or balancing workload across the supply chain.[52]

3.1.2 Network optimization problem

Network optimization problems are used to find optimal flow in transportation, communication, or other supply chain networks. The various components in the network such as distribution centers, cities, or in this instance, ports and refueling points are represented as nodes. These nodes are linked by either edges or arcs. The network optimization methods involve finding what arcs to utilize between the nodes in the network in order to minimize cost or time usage or maximize network performance.[53]

3.2 Optmization process and implementation

The optimization process in this thesis will be iteration based where each iteration introduces complexity to the model. Figure 3.1, displays the possible iteration steps in the optimization process. (1) Is one vessel and one refuel point, (2) is one vessel and n number of refueling points, (3) is n number of vessels and one refueling point, and (4) is n number of vessels and n number of refueling points. This thesis will address the first two iteration steps.

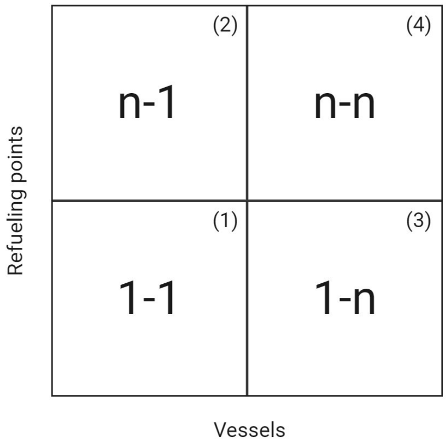


Figure 3.1: Optimization iteration matrix.

The mathematical formulations of the models in this thesis are implemented in Python and are solved using the FICO Xpress optimization solver for linear programming.[54] Python is also used to visually present the problem layout and results as plots.

3.3 General problem description

A green corridor is proposed between two ports. The choice of alternative fuel for the corridors will either limit the sailing distance or the cargo-carrying capacity of the vessels in the corridor. Implementing fixed or dynamic offshore refueling stations are proposed as a solution, utilizing emerging technology for renewable alternative fuel production offshore. The objective is to find the optimal placement of refueling points or bunkering facility locations. The model will also serve the purpose of investigating what quantum and combinations of refueling facilities are optimal for a given route.

The bunkering facilities will in the models be described as energy islands and bunker vessels, there are however many applications to the models, and the choice of bunkering facilities is not limited to the ones specifically used in this thesis. In these models, the energy island represents a supply hub where alternative fuel is produced using renewable energy from offshore wind, and the bunker vessel is used as a means to supply the fuel to the vessels in the corridor. In addition to being a production facility, the energy island also serves as a potential refueling facility. The model could also represent onshore supply hubs and fixed offshore refueling stations connected to shore by pipes, or multiple offshore production and refueling facilities.

The placement of offshore fuel production facilities will depend on the placement of offshore wind farms, which in itself is a facility location problem. In these models, it is assumed that the placement of production facilities is where the optimal placement of offshore wind farms is already found.

3.3.1 Iteration (1): One vessel and one refueling point

In the first iteration, one vessel traveling between the two ports in a straight line is considered. In proximity to the green corridor route an energy island is established, that produces alternative fuel from its excess renewable energy. The vessels can either sail to the energy island to refuel, or a bunkering vessel can travel from the energy island and refuel the vessel in one of the potential refueling points, as shown in Figure 3.2. The objective is to minimize the total cost of the voyage and the refueling operation. As the problem is presented it can be solved as a facility location problem.

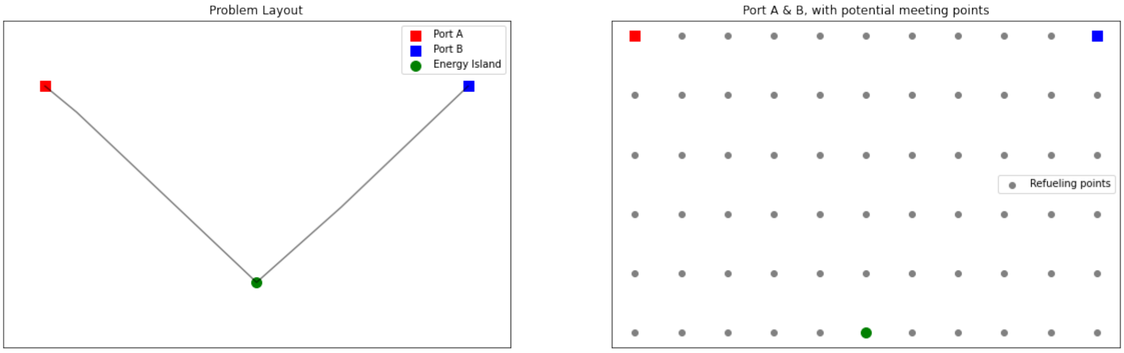


Figure 3.2: Problem layout displaying port A and B, energy island and potential refueling points.

The vessel has a total fuel and cargo capacity (Q), where q is its variable fuel storage capacity, meaning the more fuel the vessel has to bring the less cargo it can transport. In order to be profitable, it is in the best interest of the shipping company to bring as much cargo as possible, so a lost opportunity cost (C^L) parameter is introduced. This is the accumulative cost of the cargo that was not brought in favor of fuel. There is also a sailing cost (C^S) associated with the vessel. In addition, there is a cost for operating the bunker vessel (C^{OR}). The sets, parameters, and variables of the facility location problem model are shown below.

Sets	
P	Set of ports, indexed by p.
R	Set of potential refueling points, indexed by r.
Parameters	
C^S	Sailing cost of the vessel, per distance unit.
F^C	Fuel consumption of vessel, per distance unit.
C^{OR}	Cost of operating bunker vessel, per distance unit.
C^L	Lost opportunity cost due to fuel occupying potential cargo space.
Q	Total fuel and cargo storage capacity for vessel
D_{ij}	Distance between node i and j
Variables	
q	Fuel capacity for the vessel.
z_j	1 if vessel refuels at node j, 0 otherwise.

Objective function

The objective function is a minimum cost function, where the objective is to sail between port A and port B with the least cost. The objective function is made up of three components. The first one is minimizing the cost of sailing for the vessel between the ports and a potential refueling point. The second is the lost opportunity cost, which is calculated by how much of the total capacity is used for fuel. The third is the operational cost of the bunker vessel that similar to the other vessel is calculated by the distances sailed from the energy island to the vessel.

$$min \sum_{j \in R} (z_j(D_{Aj} + D_{jB})C^S + qC^L + \sum_{j \in R} z_j D_{Ej} C^{OR}$$

Subject to:

At least one of the potential meeting points is visited.

$$\sum_{j \in R} z_j = 1 \tag{3.1}$$

The vessel can't take on voyages that have a fuel demand larger than the fuel capacity of the vessel.

$$F^C D_{ij} z_j \leq q, \qquad i, j \in R \tag{3.2}$$

The fuel capacity is non-negative and is less than or equal to the total capacity of the vessel.

$$0 \leq q \leq Q \tag{3.3}$$

Binary constraint.

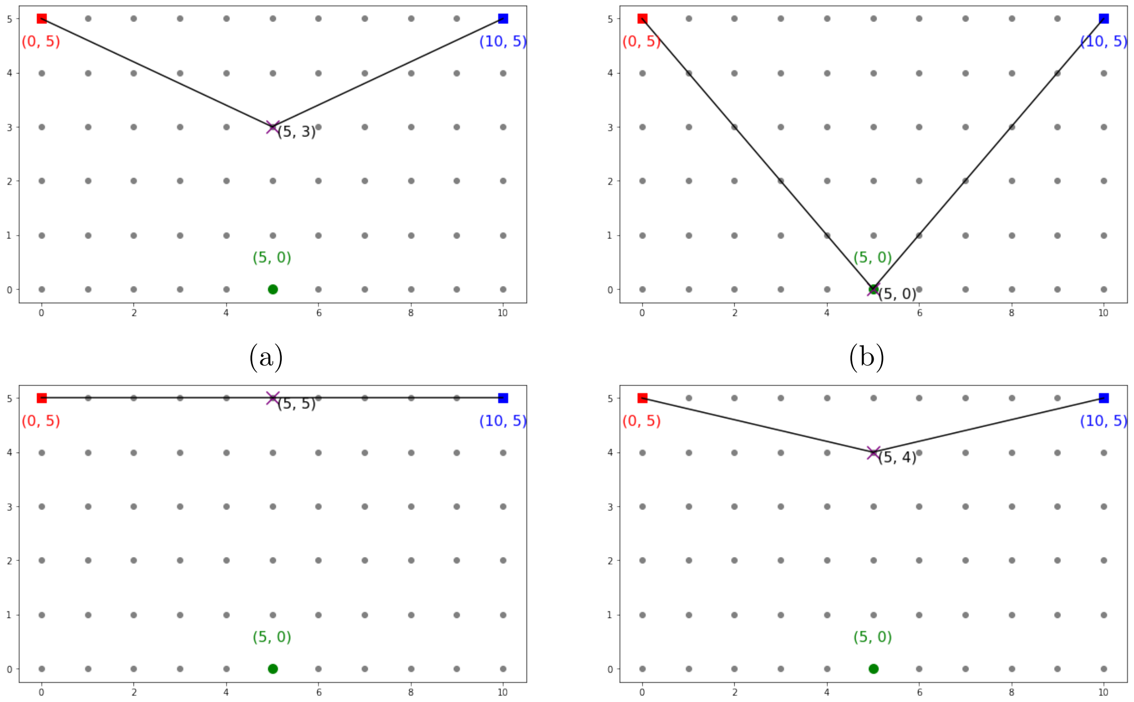
$$z_j \in \{0, 1\}, \qquad j \in R \tag{3.4}$$

3.3.2 Test scenarios

In order to test the implementation of the model, four cases were run with different parameters. Parameters and optimal refueling points for the different parameter combinations are shown in Table 3.1 and Figure 3.3 respectively.

Table 3.1: First iteration test parameters.

	(a)	(b)	(c)	(d)
C^S	1	1	1	**2**
F^C	1	1	**2**	1
C^{OR}	1	**3**	1	1
C^L	1	1	1	1
Q	10	10	10	10



(a) (b)

(c) (d)

Figure 3.3: First iteration test scenarios.

Results

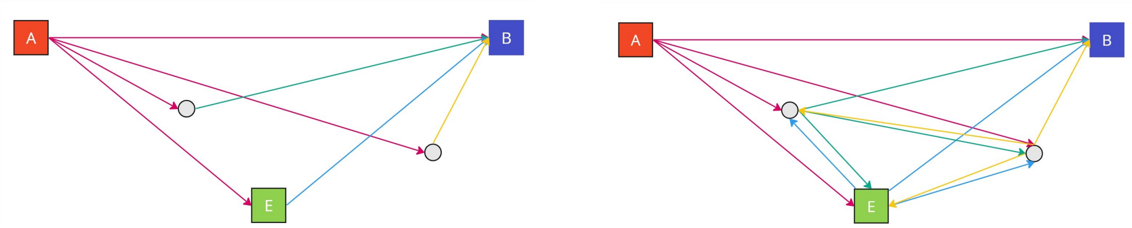
The results of the tests are as expected and the model can be considered to be working as intended. In the case of test run (a), when all parameters are equal with the exception of total capacity, the interception point is where the vessel's course deviation is equal to the sailing distance of the bunker vessel. As shown in Table 3.2, $q = 5.4$, which means it is able to bring enough fuel and at the same time maximize cargo capacity, in order to minimize cost due to the lost opportunity cost parameter. When the operational costs exceed a certain point, as is the case in test case (b), the operation is less costly when the bunker vessel is not in operation and the vessel refuels at the energy island itself. When the fuel consumption is doubled, (c), the vessel has to use its entire capacity for fuel and sail straight to port B without cargo. In the last test case, (d), the sailing cost for the vessel is doubled, and as expected the sailing distance is shortened and the bunker vessel sails longer in order to intercept.

Table 3.2: First iteration q and cost results.

	(a)	(b)	(c)	(d)
q	5.4	7.1	10.0	5.1
Tot Cost	19.2	21.2	25.0	29.5

3.3.3 Iteration (2): One vessel and multiple refueling points.

For the second iteration, the same problem layout is used, the model will however allow for multiple refueling points to be utilized by the vessel. In iteration (1), the vessel's refueling options were either the energy island or a bunkering vessel with its associated costs, now multiple bunker vessels can use the energy island as a base and refuel the vessel along its route. This introduces new sets, parameters, and variables as the model now can be considered as a network optimization model with a set of arcs between nodes which in this instance are the ports and possible refueling points. This significantly increases the complexity of route selection for the vessel. Where it previously sailed directly to port B after refueling, it can now sail to any other node that is not the node it just sailed from. A figure of route selection possibilities for the first and second iterations is shown below in Figure 3.4, where only three possible refueling nodes are displayed for simplicity.



(a) Route selection possibilities, first iteration.

(b) Route selection possibilities, second iteration.

Figure 3.4: Network optimization route selection possibilities.

In order to reduce complexity in the model, the sets R and P have been merged into one set, P that contains all nodes, including the ports, energy island, and potential refueling points. The binary variable z_j that previously determined if a specific node was used as a refueling point, is now changed to z_{ij} that determines whether or not the vessel sails between two nodes i and j. The vessel sailing between two nodes will be unanimous with the nodes i and j being used as refueling points. In addition, the variable C_i^B has been added, which describes the cost of bunkering in node i. C_i^B is precalculated for each node by multiplying the distance from the energy island to the node with the operational cost of the bunker vessel, C^{OR}. This cost is related to the new binary variable y_i, which is 1 if the bunker vessel refuels the vessel in node i, or in other words if node i is utilized as a refueling point. The variable q, which previously was the fuel capacity of the vessel is now the longest distance sailed before refueling. This distance is determined by the fuel consumption F^C. The updated sets, parameters, and variables as well as the model with constraints is shown below.

Sets	
P	Set of nodes, including the start node s (port A), the end node e (port B) and the Energy Island, indexed by p.
A	Set of sailing arcs between nodes, indexed by $a(i,j)$.
Parameters	
C^S	Sailing cost of the vessel, per distance unit.
F^C	Fuel consumption of vessel, per distance unit.
C^{OR}	Cost of operating bunker vessel, per distance unit.
C_i^B	Cost of bunkering in node i.
C^L	Lost opportunity cost due to fuel occupying potential cargo space.
Q	Total fuel and cargo storage capacity for vessel
D_{ij}	Distance between node i and j
Variables	
q	Longest distance sailed between refueling.
y_i	1 if bunker vessel refuels vessel in node i, 0 otherwise.
z_{ij}	1 if vessel sails between node i and j, 0 otherwise.

Objective function

Slight alterations are made to the objective function, in order to adapt to the new problem. The objective function still consists of three components. The first component is the cost associated with the vessel, where the binary variable is multiplied by the total distance traveled between the arbitrary number of nodes and the sailing cost. The second component that adds the lost opportunity cost remains unchanged. In the third component, is the cost of utilizing bunker vessel(s).

$$min \sum_{i,j \in A} z_{ij} D_{ij} C^S + qC^L + \sum_{i \in P} y_i C_i^B$$

Subject to:

Equal flow. All nodes with an incoming arc must have an outgoing arc.

$$\sum_{i \in P} z_{ij} = \sum_{k \in P} z_{jk}, \qquad j \in P \tag{3.5}$$

Must start in node s (port A).

$$\sum_{j \in P} z_{sj} = 1 \tag{3.6}$$

Must end in node e (port B).

$$\sum_{i \in P} z_{ie} = 1 \tag{3.7}$$

If the vessel sails arc z_{ij} then both nodes connected by that arc is a refueling point.

$$\sum_{(i,j) \in A} z_{ij} \leq y_i, \qquad (i,j) \in A \tag{3.8}$$

The distance of any sailing arcs used must be equal to or less than the longest distance sailed before refueling.

$$D_{ij} z_{ij} \leq q, \qquad (i,j) \in A \tag{3.9}$$

The fuel capacity of the vessel is non-negative and is equal to or less than the total vessel storage capacity. The Fuel capacity is set by the fuel consumption on the longest distance sailed between refueling nodes.

$$0 \leq q * F^C \leq Q \tag{3.10}$$

Binary constraints.

$$y_i \in \{0,1\}, \qquad p \in P \tag{3.11}$$

$$z_{ij} \in \{0,1\}, \qquad (i,j) \in A \tag{3.12}$$

3.3.4 Test scenarios

Similar to the first iteration, this model is tested with different parameters to see if desired outcomes are achieved. First, the model was tested with the same base case parameters as before, Table 3.3. As can be observed in Figure 3.5 and Figure 3.6, the same route is obtained for both iterations, which is desired.

Table 3.3: First and second iteration base case test parameters.

C^S	1
F^C	1
C^{OR}	1
C_i^B	1
C^L	1
Q	10

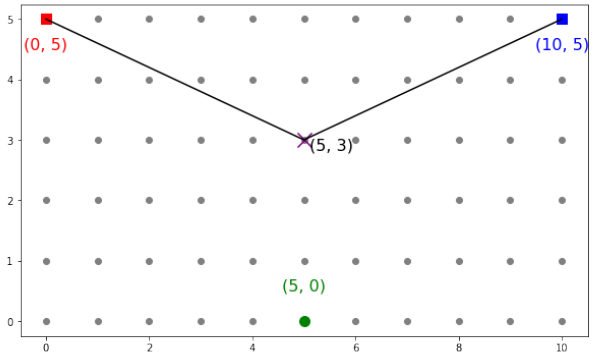


Figure 3.5: Optimal solution with base case test scenario parameters for first iteration.

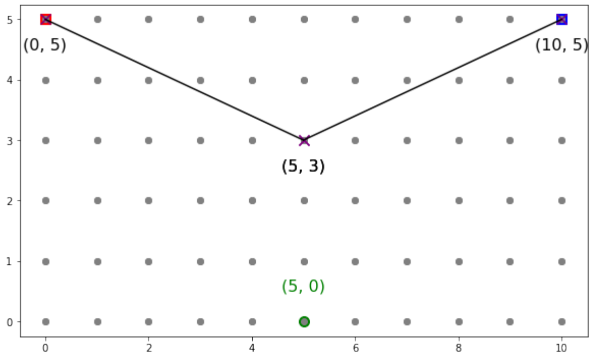
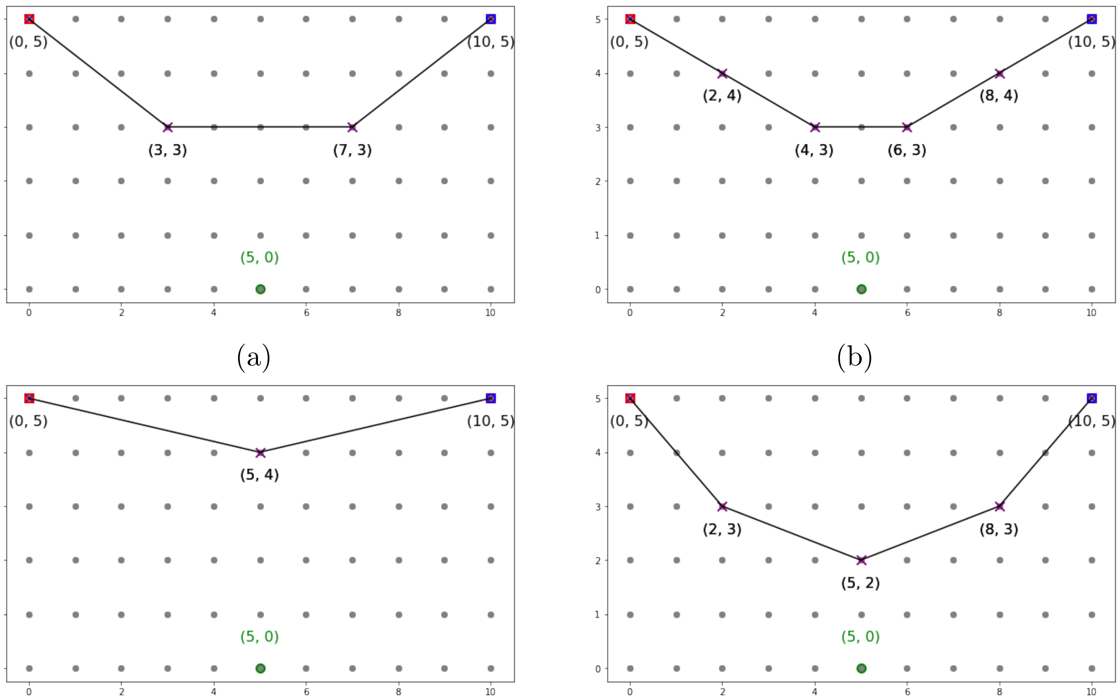


Figure 3.6: Optimal solution with base case test scenario parameters for second iteration.

When it is determined that the model work as intended for the base case parameters, other parameter combinations can be tested to see the response in the optimal solution. The second iteration test parameters as well as the plots displaying optimal solutions are shown below in Table 3.4 and Figure 4.9 respectively.

Table 3.4: Second iteration test parameters.

	(a)	(b)	(c)	(d)
C^S	1	1	1	1
F^C	1	1	1	**3**
C^{OR}	1	1	**2**	1
C^L	**4**	**6**	**4**	1
Q	10	10	10	10



(a) (b)

(c) (d)

Figure 3.6: Second iteration test scenarios.

Results

For the first two test scenarios (a) and (b) the lost opportunity cost is raised to 4 and 6 times the other costs in the model. As can be observed from the plots, the number of refueling points correlates with the lost opportunity cost, when the ports are considered refueling points. Since the sailing cost C^S and operational cost of the bunker vessel C^{OR} are the same in both test scenarios, the routes for both scenarios are the same, only with more refueling points along the route for $C^L = 6$.

In test scenario (c) the lost opportunity cost is the same as in test scenario (a), but the operational cost of the bunker vessel is doubled. Since the cost of bunkering at a certain point C_i^B is determined by the distance from the energy island and the operational cost, it is expected that the number of refueling points along the route is halved as the operational cost is doubled. Since there is now only one leg to sail for the bunker vessels, the refueling point can be set closer to the straight line route in order to reduce the sailing cost C^S.

For the last test scenario (d) the fuel consumption is tripled. It is then reasonable that the number of refueling points also triples compared to the base case. Since all costs are the same in this scenario it is cheaper to get closer to the energy island than it was for the scenarios where the lost opportunity cost was higher.

More test scenarios were run, and the model gives expected results and can be assumed to work as intended. A good indication of this is the fact that all routes are symmetrical, and all legs have the same length. This indicates that the constraints work as they should and that the cargo capacity is maxed out for each leg.

Chapter 4

North Sea dry bulk study

This chapter aims to apply the model made in chapter 3 to a relevant case. The aim of the case study is to see how the creation of a green corridor in the North Sea would affect the routes between ports and the optimal placement of dynamic offshore facilities in the form of bunker vessels. The case study also allows for the gathering of real-life data to be used as parameters in the model, so that a sensitivity analysis can be performed.

4.1 Ports

Five ports are chosen for the case study, they are shown in Table 4.1. They were chosen as they are all ports that handle dry bulk of substantial quantum per annum, and for their location. They represent an equal spread in all relevant celestial directions in relation to the energy island.

Table 4.1: Case study ports.[55][56][57]

Ports	**Country**	**Dry bulk cargo processed [kt/year]**
Rotterdam	Netherlands	78,000
Hamburg	Germany	36,200
Aberdeen	UK	2,606
Kristiansand	Norway	1,988
Oslo	Norway	1,469

Table 4.2 Shows the coordinates for the ports and the energy island, represented by latitudes and longitudes. Figure 4.1 shows a visual of the ports and the energy island, where the ports are represented by blue markers, and the energy island by a red marker.

Table 4.2: Ports and energy island coordinates.

Ports	**Latitude**	**Longitude**
Rotterdam	51.92441	4.47773
Hamburg	53.55108	9.99368
Aberdeen	57.14748	-2.09540
Kristiansand	58.14469	7.99828
Oslo	59.91149	10.75793
Energy Island	56.36268	6.49764

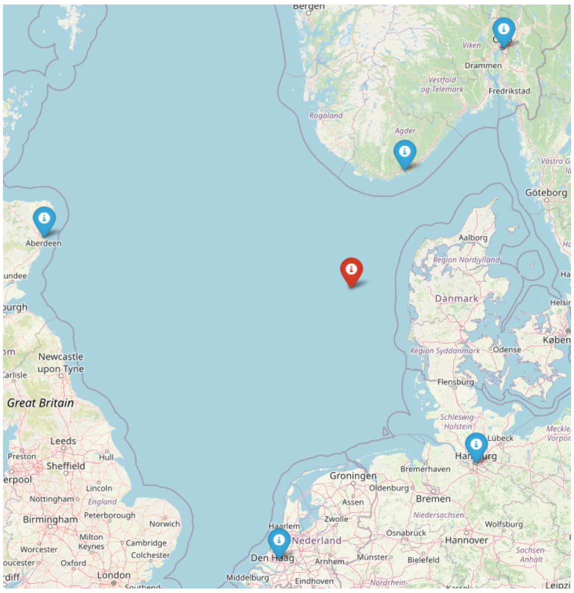


Figure 4.1: Ports and energy island placement.

4.2 Model implementation

4.2.1 Grid of potential refueling points

As with the test implementation of the model, a grid is constructed around the energy island with potential refueling points where the bunker vessel can meet and refuel the sailing vessel. The objective is to have a grid of points that covers most of the relevant areas of the North Sea.

With the energy island as a base, a grid was constructed that stretches 225 nm west, 25 nm east, and 75 nm both north and south. The potential refueling points are spaced with 25 nm between them. The resulting grid is a rectangle that is 250 nautical miles by 150 nautical miles, with 77 potential refueling points including the energy island. The grid is shown in Figure 4.2, where the energy island is represented by a green dot, and the additional potential refueling points are red. Figure 4.3 Shows the grid in relation to the ports.

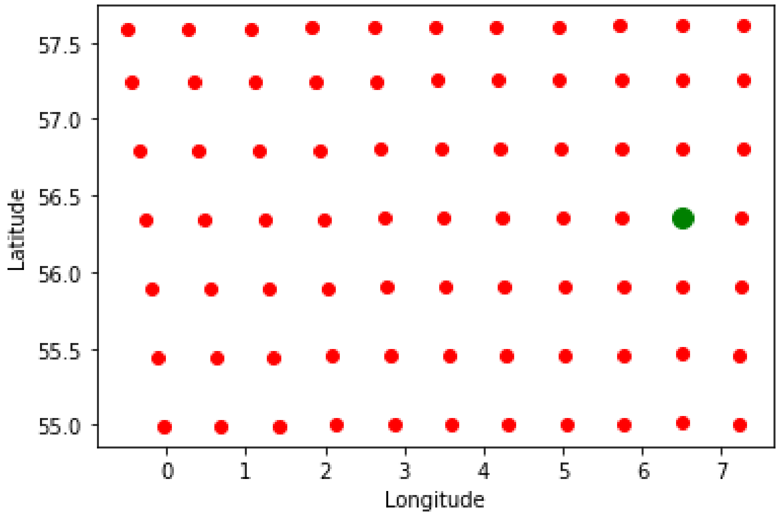


Figure 4.2: Grid of potential refueling points.

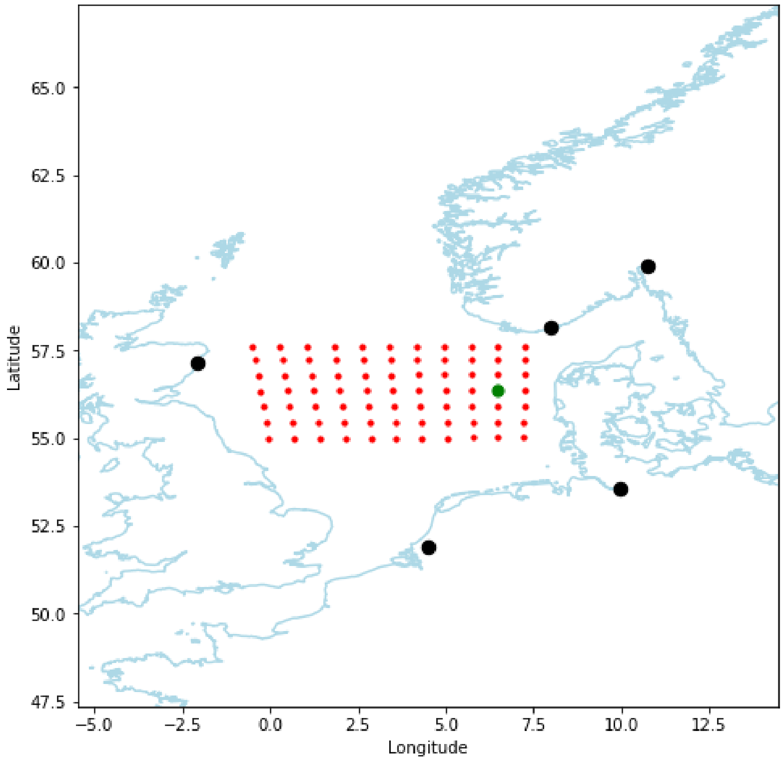


Figure 4.3: Grid of potential refueling points in relation to the relevant ports.

4.2.2 Haversine formula

When creating the model in chapter 3 the nodes were in a 2D Euclidean plane, and described by Cartesian coordinates on the form (x, y). To calculate the distances between the nodes the following formula was used:

$$d = \sqrt{(x2 - x1)^2 + (y2 - y1)^2} \tag{4.1}$$

Now that the coordinates are given as latitudes and longitudes on a spherical earth, the distances are calculated using the Haversine formula. This formula ignores the ellipsoidal effects of the earth, it is however deemed accurate enough for the purpose.[58] The Haversine formula is shown in Equation 4.2.

$$d = 2r \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\theta_2-\theta_1}{2}\right) + \cos(\theta_1)\cos(\theta_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right) \tag{4.2}$$

Where r is the radius of the earth, θ_1 and θ_2 are the latitudes of the two points, and λ_1 and λ_2 are the longitudes of the two points, in radian.

As the energy island is not built, its exact position is yet to be determined. As previously described in Section 2.4.3, the energy island will be located approximately 100km off the coast of the Danish town of Thorsminde. The coordinates for the energy island were found by using inverse Haversine, 100km west of Thorsmindes coordinates.

4.3 Parameters

In this section, parameters for the model are found using various sources. All the parameters are dependent on a multitude of factors, such as vessel size, efficiency, routes, and day-to-day fluctuation in costs and prices, that are difficult to generalize. Reasonable assumptions are made to get parameters that are in the correct scale in relation to each other.

4.3.1 Fuel consumption

Fuel consumption is heavily reliant on vessel size, speed, and efficiency. Table 4.1 Shows the annual average fuel consumption for bulk vessels of different sizes running on fuel oil.

Table 4.3: Average fuel consumption and sea speed of bulk carriers by size category.[59]

Size category [dwt]	**Annual average total fuel consumption [t]**	**Average at sea speed [kn]**	**Average at sea days per annum**
10000-34999	3528	11,4	168
35000-59999	4828	11,8	173
60000-99999	6781	11,9	191
100000-199999	9777	11,7	202
200000-+	12310	12,2	202

Given the average speed and average sea days per annum, the fuel consumption per nautical mile can be calculated. Assuming the same efficiency in diesel, ammonia, and hydrogen the fuel consumption for future vessels running on these alternative fuels can be calculated. The fuel consumption for the respective fuels is shown in Table 4.4.

Table 4.4: Fuel consumption per nautical mile of bulk carriers by size category.

Size category $[dwt]$	**HFO** $[m^3/nm]$	**Ammonia** $[m^3/nm]$	**Hydrogen** $[m^3/nm]$
10000-34999	0,076	0,243	0,327
35000-59999	0,098	0,313	0,420
60000-99999	0,123	0,394	0,530
100000-199999	0,171	0,547	0,735
200000-+	0,206	0,660	0,887

4.3.2 Sailing cost

The sailing cost C^S is based on the charter rates for the different size categories. The charter cost is given in USD/day, since the model parameter is per distance unit, this figure is converted to USD/nm by utilizing the average at sea speed from Table 4.3, and assuming 24-hour days. The sailing cost corresponding to each size category is shown in Table 4.5.

Table 4.5: Dry bulk 1-year time charter rates (USD/Day), by size category.[60]

Size category	**dwt**	**USD/Day**	**USD/nm**
Handysize	25 000	$10500	$38
Supramax	58 000	$14500	$51
Panamax	75 000	$16000	$56
Capesize	180 000	$21500	$77
Newcastlemax	208 000	$26500	$91

4.3.3 Lost opportunity cost

Lost opportunity cost depends upon a number of factors like cargo type, supply, demand, routes and more and is therefore difficult to approximate. In order to have a parameter for the base case, all vessel sizes are considered to have the same lost opportunity cost, and the cargo type is assumed to be generic. The lost opportunity cost is given as $\$43/m^3$, as was the Gulf rate in 2021.[61]

4.3.4 Bunker vessel operational cost

The operational cost of bunker vessels that can supply vessels with alternative fuels is yet to be determined. The model will be tested for multiple operational costs that are scaled based on the sailing cost C^S. For the base case, the operational cost will be set to the time charter rate of an Aframax tanker vessel, which is commonly used in the North Sea. As with the time charter rates of dry bulk vessel, this number fluctuates. The number is based on the average daily earnings of $\$22,000$ and an average speed of 12.1 knots.[62] This yields an operational cost of 76 USD/nm.

4.3.5 Total fuel and cargo storage capacity

The total fuel and cargo storage capacity parameter will be based on gross tonnage, which is the total enclosed volume of a vessel. This measurement varies depending on vessel parameters and design. Example bulk vessels will therefore be used to determine gross tonnage in the different size categories. The example vessels and their gross tonnage is shown in Table 4.6.

Table 4.6: Total fuel and cargo storage capacity by size category.[63]

Size Category	**Ship Name**	**Dead Weight**	**Gross Tonnage**
Handysize	21 Happy	28, 471	17,433
Supramax	Abdullah	45,663	26,070
Panamax	Edwin H. Gott	76,012	35,592
Capesize	Aanya	179,628	93,693
Newcastlemax	Aegan Clover	209,649	107,060

4.4 Results

The aim of this section is to run the model with the parameters presented previously in the chapter. The model will be run with multiple parameter combinations to be able to observe how they affect the optimal placement of the refueling points. The benchmark results from the base case will be used as a basis for comparison when the parameters are altered.

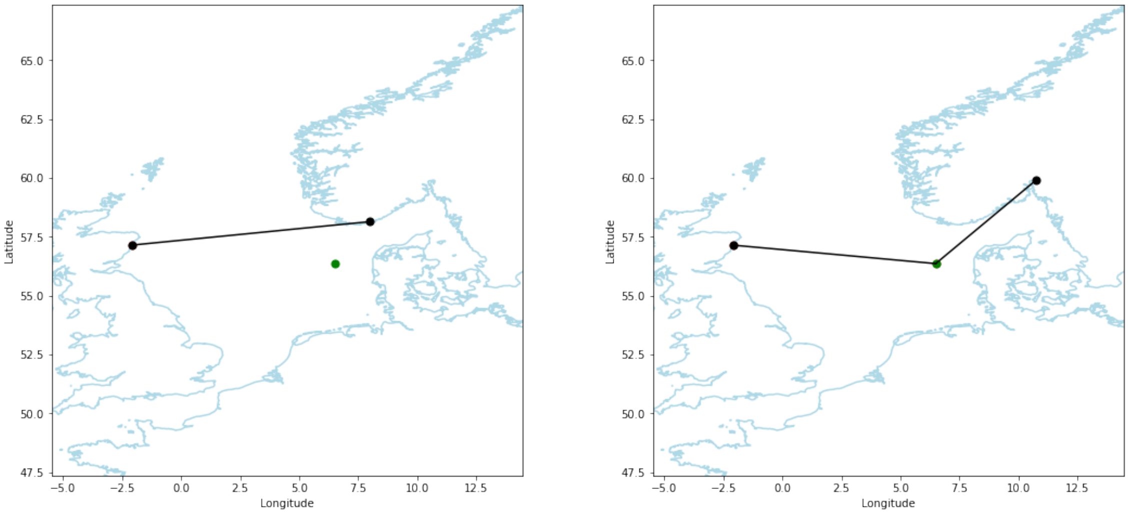
4.4.1 Base case

The base case will look at a Handyseize dry bulk carrier sailing from the UK port of Aberdeen to the mainland European ports, using ammonia as fuel. The base case parameters are those who were derived in the previous section and are shown in Table 4.7.

Table 4.7: Base case parameters.

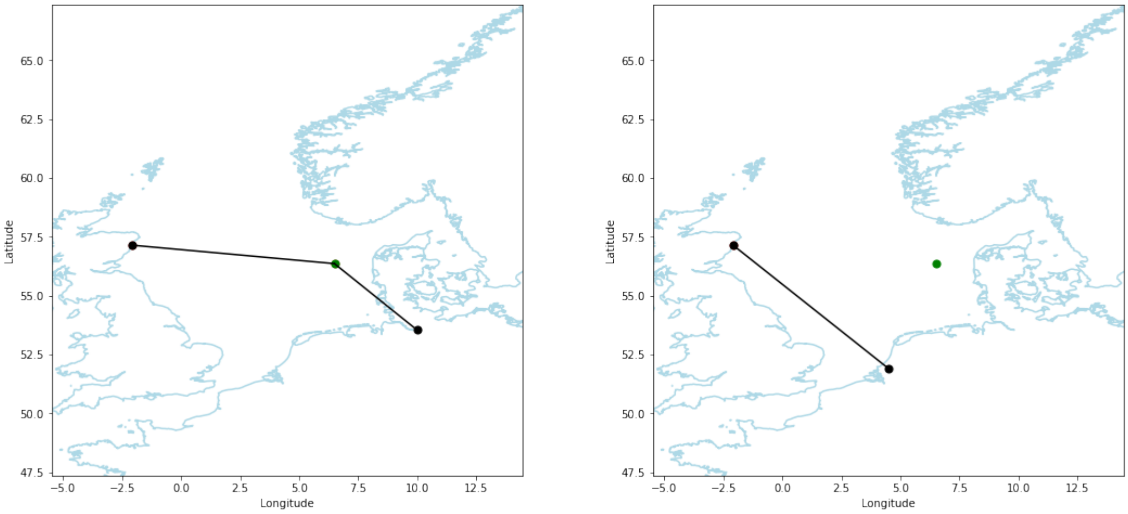
F^C	0,243	m^3/nm
C^S	38	USD/nm
C^L	43	USD/m^3
C^{OR}	76	m^3/nm
Q	17433	m^3

As can be observed in Figure 4.4, the base case parameters yield results where the two shortest routes sail straight from their origin port to their destination without a fuel stop. For longer voyages, the energy island is utilized as a refueling point, this results in less required fuel capacity, as can be seen in Table 4.8.



(a) Aberdeen - Kristiansand

(b) Aberdeen - Oslo



(c) Aberdeen - Hamburg

(d) Aberdeen - Rotterdam

Figure 4.4: Base case optimal routes.

Table 4.8: Base case required fuel capacity and total cost for optimal routes.

Start port	**End port**	**Required fuel capacity** [m^3]	**Total Cost** [$]
Aberdeen	Kristiansand	80,1	57398
	Oslo	69,4	73731
	Hamburg	69,6	68626
	Rotterdam	94,3	74155

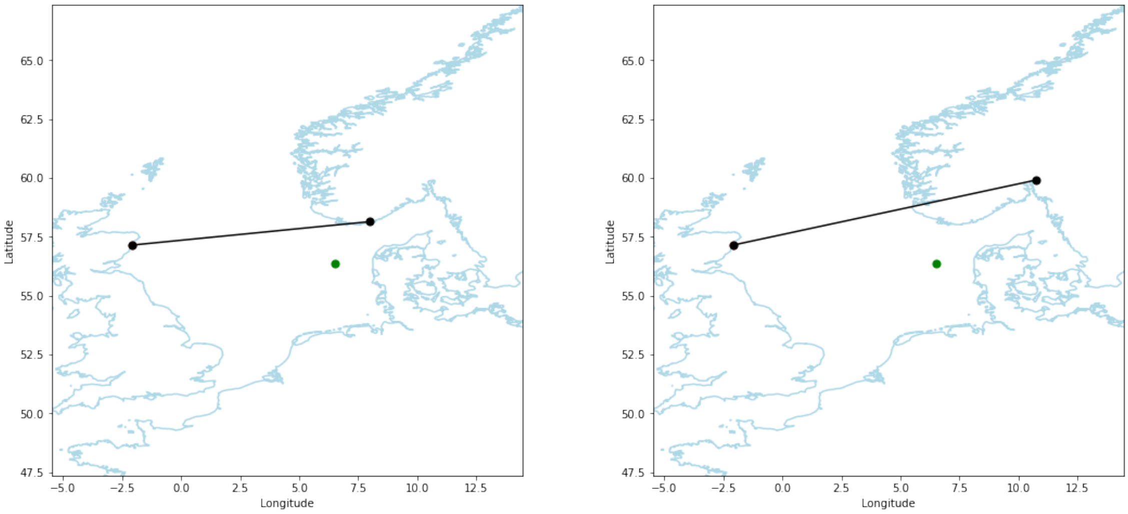
4.4.2 Variance in lost opportunity cost

Lower lost opportunity cost

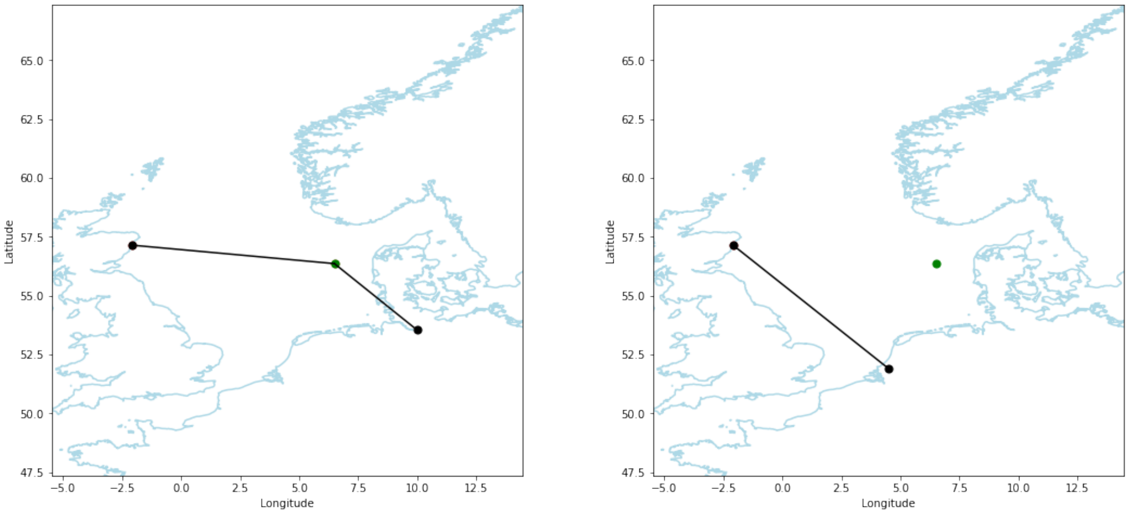
When the lost opportunity cost is halved, the second-to-longest route from Aberdeen to Oslo no longer has a refueling stop, as can be seen in Figure 4.5. All other routes remain the same as with the base case parameters. The route between Aberdeen and Hamburg is approximately 30 nautical miles longer than Aberdeen - Oslo, and will still rely on a refueling stop under these conditions. Table 4.10 Shows the percentage difference in required fuel capacity and total costs for the routes compared to the base case.

Table 4.9: Lower lost opportunity cost parameters.

F^C	0,243	m^3/nm
C^S	38	USD/nm
C^L	21.5	USD/m^3
C^{OR}	76	m^3/nm
Q	17433	m^3



(a) Aberdeen - Kristiansand (b) Aberdeen - Oslo



(c) Aberdeen - Hamburg (d) Aberdeen - Rotterdam

Figure 4.5: Lower lost opportunity cost optimal routes.

Table 4.10: Percentage difference compared to the base case for lower lost opportunity cost.

Start port	**End port**	**Required fuel capacity** [m^3]	**Total Cost[$]**
Aberdeen	Kristiansand	0 %	-12 %
	Oslo	52 %	-9 %
	Hamburg	0 %	-9 %
	Rotterdam	0 %	-11 %

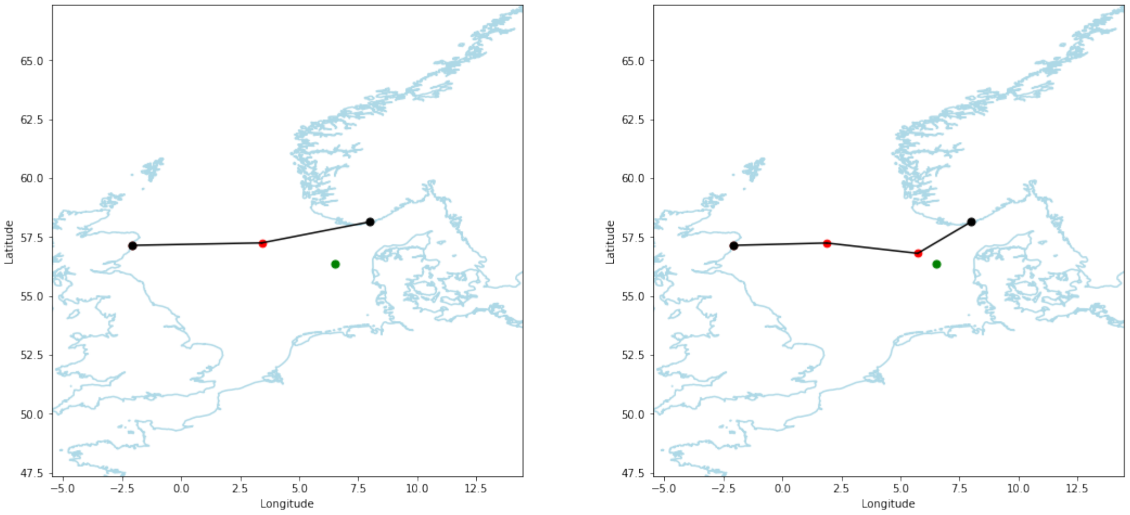
Higher lost opportunity cost

In the figures below the lost opportunity cost has been doubled and tripled respectively, as shown in Table 4.11, whilst the other parameters remain the same as with the base case.

Table 4.11: Higher lost opportunity cost parameters.

F^C	0,243	m^3/nm
C^S	38	USD/nm
C^L	86/129	USD/m^3
C^{OR}	76	m^3/nm
Q	17433	m^3

The Aberdeen to Kristiansand route, which previously had no refueling stops, now has one and two respectively.

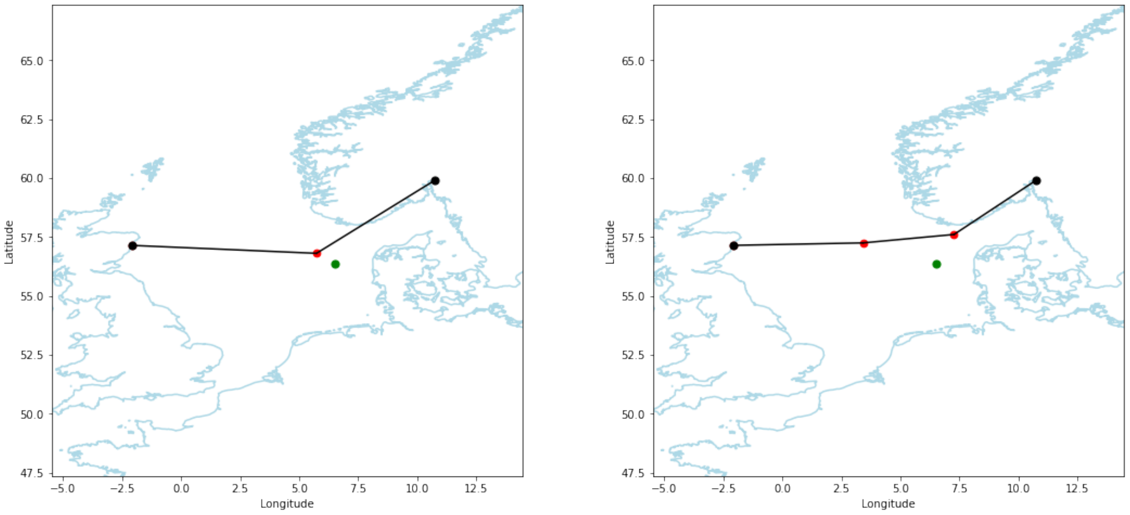


(a) $C^L = 80$

(b) $C^L = 129$

Figure 4.6: Aberdeen - Kristiansand

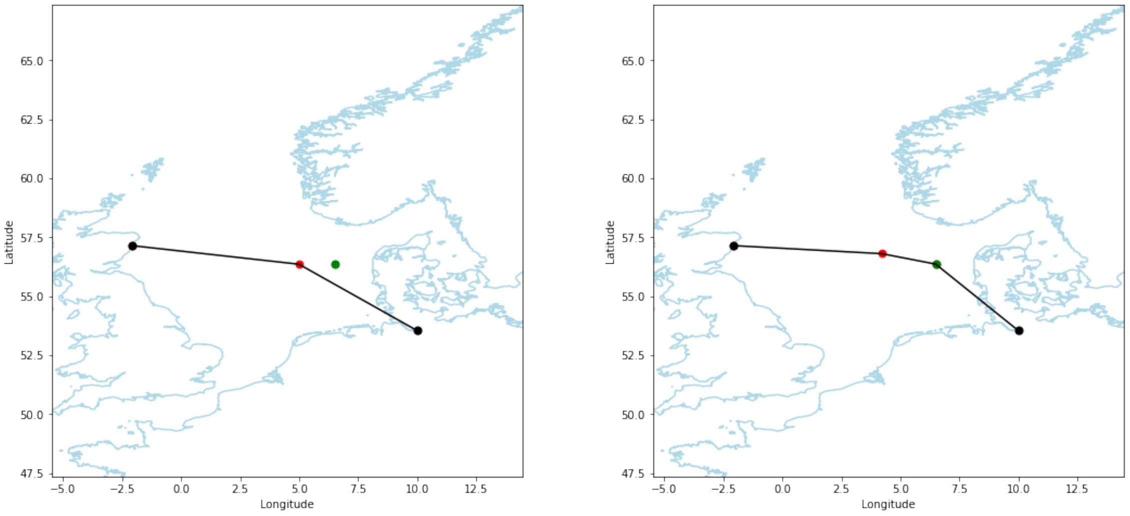
Results from the Aberdeen-Oslo route under base case conditions had one stop at the energy island as the optimal route. Now that the lost opportunity cost is higher, the energy island has been switched out for bunker vessel(s). when the lost opportunity cost is tripled the vessels stop twice at bunker vessel locations and the last stop is as close to the en port as possible keeping within the grid.



(a) $C^L = 80$ (b) $C^L = 129$

Figure 4.7: Aberdeen - Oslo

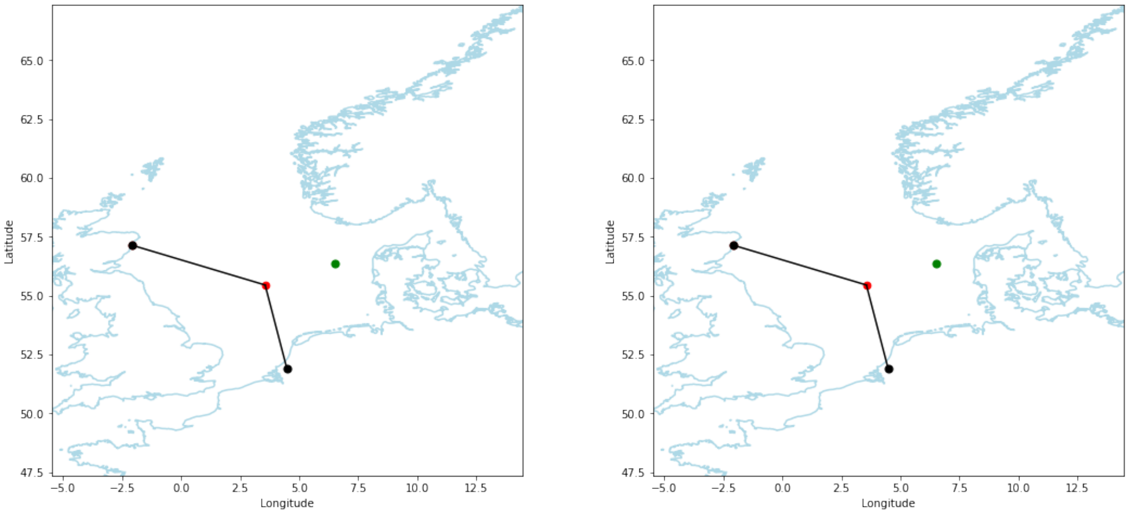
When the lost opportunity cost is doubled a bunker vessel closer to the straight line route is optimal, instead of the energy island. When tripled the vessels sails to one bunker vessel and the energy island for fuel. the leg between the bunker vessel and the energy island is shorter given the sailing cost and the operational cost.



(a) $C^L = 80$ (b) $C^L = 129$

Figure 4.8: Aberdeen - Hamburg

Both doubling and tripling the lost opportunity cost yield the same optimal placement of the bunker vessels when the energy island is far from the straight line route between the ports as is the case for Aberdeen-Rotterdam.



(a) $C^L = 80$ (b) $C^L = 129$

Figure 4.9: Aberdeen - Rotterdam

The percentage difference in required fuel capacity and total cost for the respective routes are shown in Table 4.12

Table 4.12: Percentage difference compared to the base case for higher lost opportunity cost.

Start port	**End port**	**Required fuel capacity** $[m^3]$		**Total Cost**[$]	
		$C^L = 86$	$C^L = 129$	$C^L = 86$	$C^L = 129$
Aberdeen	Kristiansand	-46%	-61%	18 %	49%
	Oslo	-20%	-37%	16 %	49%
	Hamburg	-28%	-45%	18 %	49%
	Rotterdam	-45%	-45%	17 %	49%

4.4.3 Bunker vessel operational cost

The operational cost of the bunker vessels, as previously discussed, introduces an element of uncertainty. In the base case, it is based on the charter rates of an Afromax tanker, which is most likely not representative. What is more significant is the operational cost relative to the other costs.

Considering that higher lost opportunity costs resulted in the use of one or two bunker vessels for all routes, the relationship between these lost opportunity cost values and the operational cost is examined. The other parameters remained the same as with the base case. The aim is to find the threshold where a bunker vessel is no longer favored for the routes. The results are presented in Table 4.13, where C^{OR} represents the highest operational cost before bunker vessels were no longer preferred for the specific routes, and only the energy island is utilized as a bunkering point.

Table 4.13: Variance in operational cost results.

Start port	**End port**	$C^L = 86[\$/m^3]$		$C^L = 129[\$/m^3]$	
		$C^{OR}[\$/nm]$	C^{OR}/C^L	$C^{OR}[\$/nm]$	C^{OR}/C^L
Aberdeen	Kristiansand	115	1,3	225	1,7
	Oslo	110	1,3	205	1,6
	Hamburg	105	1,2	215	1,7
	Rotterdam	125	1,5	195	1,5

4.4.4 Impact of increased sailing costs

When examining the longest voyage from Aberdeen to Hamburg for all size categories with their base case scenario parameters, the optimal route is the same for all, involving one refueling stop at the energy island. Considering that the sailing cost in the base case scenarios relies on regularly fluctuating average time charter cost, it becomes important to assess the impact of increased sailing costs on the refueling infrastructure. To evaluate this, the model was tested for each size category using their respective base case parameters. The sailing cost, C^S, was incrementally increased until reaching a point where utilizing a bunker vessel became more optimal than relying solely on the energy island. The results are seen in Table 4.14, where the maximum sailing cost represents the cost at which a bunker vessel would be optimal. The percentage is the sailing cost increase from the base case.

Table 4.14: Maximum sailing cost increase before bunker vessels are utilized for Aberdeen - Hamburg route.

Size category	**Max C^S**	**Percentage increase**
Handysize	102	168 %
Supramax	102	100 %
Panamax	104	86 %
Capesize	101	31 %
Newcastlemac	100	10 %

Chapter 5

Discussion

5.1 Parameters

The parameters involved in the analysis in chapter 4 are subject to uncertainty. The cost parameters are market-based, and might not reflect future costs. Factors such as possible subsidies, stakeholder interactions, and technology advancements that might change the costs are not taken into account. Furthermore, it is assumed that all ports are capable of handling all ship-size categories. In reality, certain ports will have size restrictions when it comes to accommodating the larger vessels and handling their cargo.

5.2 Results

The base case model test results highlight the need for offshore refueling facilities in green corridors when low-energy density alternative fuels such as ammonia are implemented. Based on the results, facilities such as an energy island will be in demand for longer voyages more so than for shorter ones. Even the longest sailings in the North Sea case can be considered short when compared to trans-Atlantic and Pacific shipping routes, and yet the optimal solution involved refueling during the route.

In the pursuit of establishing green corridors promptly, in order to align with IMO and Paris Agreement goals, utilizing facilities such as an energy island can prove to be a viable option. Given uncertainties in future costs, and the impact the costs had on the results, implementing additional dynamic refueling facilities such as bunker vessels that use on- and offshore energy hubs will also be an important part of green corridor refueling infrastructure.

5.2.1 Lost opportunity cost

As previously described, the lost opportunity cost will in real-life scenarios vary from day to day. When the lost opportunity cost decreases, overall costs decrease, and in some instances, it may be possible to reduce the number of refueling stops if the fuel capacity allows for non-refueling routes. When the lost opportunity cost is increased, two- and threefold, the number of refueling stops increases, and bunker vessels are utilized in all test routes. For most routes, each increase in lost opportunity cost introduced an additional refueling stop as optimal. When the lost opportunity cost is high and the operational cost is relatively low the bunker vessels are utilized in favor of the energy island to shorten the overall length of the voyage.

In the case where the energy island is far from the straight-line route, Aberdeen to Rotterdam, one refueling stop is first introduced when the lost opportunity cost is doubled from base case values. This route is optimal also for triple lost opportunity cost as an extra refueling stop would entail sailing too far from the original route, thus increasing the overall cost due to the sailing cost.

Although the total cost increases with higher lost opportunity costs, the decrease in required fuel capacity is more significant when bunker vessels are used. Depending on future energy prices, this could prove to be cheaper than base-case alternatives.

5.2.2 Bunker vessel operational cost

The relationship between lost opportunity cost and bunker vessel operational cost was examined. The higher the lost opportunity cost, the higher the operational cost can be before they are deemed too expensive to be optimal. The operational cost can exceed the lost opportunity cost and still be considered optimal, as can be seen in Table 4.13. The maximum allowable operational cost increase depends on the length of the route and its geographical proximity to the energy island. For routes where the energy island is far from the original route, the tolerance for the operational cost to increase is higher compared to routes that naturally sail closer to the energy island.

5.2.3 Sailing cost

Considering that it was optimal for all combinations of ship categories and routes using base case parameters to only utilize the energy island as a refueling point if any, bunker vessels might not be needed to support a possible green corridor. The results show that for smaller vessels, the base case sailing costs are so low that sailing to energy island is optimal up to an increase of 168% for the smallest Handysize vessels. The plausibility of this increase is debatable, but could in combination with high lost opportunity cost have an impact on the optimal route. When the vessels get bigger, and subsequently the sailing costs higher, the allowed increase in sailing cost is reduced to 10%. This is within reasonable fluctuations in chartering costs, which the sailing costs are based on, and the necessity for bunker vessels in the refueling infrastructure is evident.

5.3 Model

5.3.1 Limitations

The optimization model utilized in this analysis, although providing valuable insight, has relevant limitations that should be acknowledged as they impact the results and their real-life applicability.

The model only allows for the examination of one sailing vessel at a time, whereas a green corridor would have multiple vessels or fleets sailing simultaneously on a route. This limitation overlooks the possible strain that multiple vessels would have on the refueling infrastructure. A closely related model limitation is the lack of time periods, that could be used to examine how sailing time and loading/unloading time for sailing vessels and bunker vessels impact the optimal placement and quantum of refueling facilities.

The model considers route distances as a straight line between the ports and refueling facilities and does not consider geographical challenges such as navigational obstacles and weather conditions. The simplification of straight-line routes should not affect the results of this particular study, however, ship-to-ship refueling requires certain levels of calm sea and storms will affect the optimal placement of bunker vessels.

The grid of points created as potential refueling points is limited to a certain area of the case study and the points are spread out with 25 nautical miles between them, thus excluding some route compositions. While this limitation ensured a compact and manageable optimization process, a real-life scenario would necessitate considering every square nautical mile of the case study area as a potential refueling point. Expanding the grid would provide more in-depth analysis, but would also introduce computational challenges.

5.3.2 Expansions

The iteration process discussed in Section 3.2 could have been followed through until the model was expanded to handle multiple vessels and multiple refueling facilities at a time. By incorporating this, the model would be able to account for more complex operations and multiple logistical considerations that are not taken into account in the current model. In addition, the model limitations can be addressed in order for the model to include time periods, geographical constraints, and an expanded grid of alternative refueling points. This would improve the real-life application of the model.

Another relevant expansion is implementing optimization of fuel type. This could be done by adding a fuel variable that appointed optimal fuel based on criteria such as cost, environmental impact, and availability.

Chapter 6

Conclusion

In this thesis, the utilization and potential benefits of fixed and dynamic refueling facilities for green corridor refueling infrastructure were examined, specifically focusing on bunker vessels and energy islands. Through the optimization model, analyzing costs, ship categories, and routes, valuable insight was gained.

The results from the North Sea case study illustrate the cost benefits of implementing offshore refueling infrastructure for green corridors, especially for longer routes where larger vessels are utilized. Green corridors supported by facilities like energy islands and bunker vessels performing ship-to-ship fuel transfers have the potential to speed up the green transition and promote the adoption of alternative fuels and renewable energy.

The optimal solutions for base case parameters in specific combinations of routes and ship types indicate the viability of both fixed and dynamic refueling facilities. It is however important to acknowledge the uncertainties surrounding the parameters and model limitations when interpreting the results. These uncertainties and limitations calls for further research and model expansions to provide a more comprehensive and accurate representation of real life.

Chapter 7

Further Work

In order to build upon the results of this thesis there are several avenues for further work. Expanding the model to incorporate fleet dynamics and temporal dimensions would offer a more comprehensive analysis of the strain of the refueling infrastructure and enhance the applicability of the model. By identifying bottlenecks in the refueling infrastructure, appropriate measures can be taken. Exploring alternative fuel optimization within the model would address the uncertainty around what fuel is optimal, and would give valuable insight into what parameters influence fuel choice.

Further work in the area of parameter research will also be necessary to strengthen the results. This would involve collecting extensive data on key parameters and doing an in-depth analysis of trends to represent future conditions. Methods such as probabilistic modeling could be employed to forecast the possibility of future results and capture the range of possible outcomes.

By conducting the aforementioned work on the model and its parameters, the model outputs can be fine-tuned to represent the most accurate results. This will in turn enable more informed decision-making in the development of green corridors.

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