UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES

– MSc in Shipping Management

MASTER THESIS

Subject: “Techno-economic and environmental analysis of the application of Onshore Power Supply onboard a bulk carrier: a case-study approach”

MND20010 KONSTANTINOS DEDES

Thesis statement

Which was submitted to the Department of Maritime Studies of University of Piraeus as part of the requirements for obtaining a postgraduate degree in Shipping Management.

Piraeus, June 2023

ABSTRACT

The shipping industry plays a significant role in global greenhouse gas emissions, and efforts to reduce its environmental impact are crucial. This thesis investigates the potential of onshore power supply (OPS) to mitigate emissions by analyzing its impact on the Carbon Intensity Indicator (CII) of a bulk carrier vessel trading between Canada and China.

The study addresses several research questions, including how OPS affects the CII, whether OPS adoption alone can meet international emission reduction targets, and the financial implications for shipowners and operators considering fuel savings. Operational data from the specific vessel, MV BulkCarrier-N1, was collected from voyage reports and performance monitoring databases for the period from January 2021 to December 2022.

Two scenarios, IMO-Low and IMO-High, based on International Maritime Organization (IMO) trajectories, were developed to project future emission reduction targets. A Python model was then developed to analyze the impact of OPS and speed optimization on CIIs and fuel savings. The model incorporated inputs such as drydocking schedules, OPS installation timing, capital and operating expenses for OPS, annual revenues, speed ranges, and fuel prices.

The findings indicate that speed optimization alone can meet the IMO-Low targets until 2028 and the IMO-High targets until 2027. However, sustaining the desired efficiency levels beyond these years would require additional measures. When OPS was combined with speed optimization, the impact on CIIs was found to be minimal, primarily due to the relatively small contribution of the auxiliary engine's fuel consumption to the overall fuel usage.

Although OPS showed minor improvements in CIIs, it did contribute to fuel savings. The comparison between the IMO-Low and IMO-High scenarios revealed higher short-term financial gains under the more ambitious trajectory. However, achieving long-term sustainability and meeting ambitious emission reduction targets will necessitate the implementation of additional efficiency measures.

This study underscores the complex relationship between OPS adoption, speed optimization, and the achievement of international emission reduction goals. While OPS and speed optimization have potential benefits, they may not be sufficient on their own to achieve long-term sustainability in the shipping industry strategies and measures are needed such as the use of biofuels or alternative fuels (i.e. green methanol, ammonia etc.), to drive significant emissions reductions and ensure a more environmentally friendly shipping sector.

Contents

List Of Figures

List Of Tables

List of Abbreviations

Abbreviations	***Explanations***
AER	Annual Efficiency Ratio
CII	Carbon Intensity Indicator
CO2	Carbon Dioxide
DCS	Data Collection System
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
GT	Gross Tonnage
IMO	International Maritime Organization
MDO	Marine Diesel Oil
MRV	Monitoring, Reporting and Verifying
MT	Metric Tones
NM	Nautical Miles
NOx	Nitrogen Oxides
OPS	Onshore Power Supply
SEEMP	Ship Energy Efficiency Management Plan
SOx	Sulphur Oxides

1. Introduction

The shipping industry plays pivotal role in the international trade and transportation, and it is closely correlated to economic development and economic growth (IMO, 2018). In recent years, there has been a growing global emphasis on sustainability and environmental stewardship across various industries. The maritime sector, in particular, has come under scrutiny due to its significant contribution environmental degradation and more particularly to air and water pollution, leading to adverse effects on air quality, climate change, and public health (Marine Insight, 2017). The industry's reliance on fossil fuels and the operation of vessels using traditional onboard generators have led to several environmental challenges.

In 2018, the carbon dioxide (CO2) emissions from maritime industry represent approximately the 3% of the global emissions (European Commission, 2023). However, according to International Maritime Organization (IMO), an increase in Greenhouse Gas emissions from seaborne trade has been predicted ranging between 90% and 130% compared to 2008 levels if no measures are taken (IMO, 2020). According to Cames et. al. (2015) emissions from shipping are expected to be increased up to 250% by 2050. Under this case, the contribution of the shipping sector to the global emissions will account the 17%.

The majority of maritime regulatory bodies have introduced stringent environmental regulations in order to mitigate the seaborne emissions' increase, through the implementation of tighter emission controls. They proposed a differentiation in the energy mix through the introduction of alternative fuels and several technologies which increase the energy efficiency of the vessels (IMO, 2018). More precisely, IMO, European Commission, and US Clean Shipping Act introduced the mandatory application of Onshore Power Supply (OPS), or 'cold ironing', to vessels during their stay at ports which presents an innovative, practical, and potentially transformative approach to reducing maritime carbon emissions and other pollutants.

Onshore Power Supply (OPS) is the process of providing shore-based electrical power to a docked vessel, enabling the shutdown of its main and auxiliary engines. Traditionally, even when berthed, vessels rely on their engines to supply on-board electrical power, thereby continuing to burn marine diesel or heavy fuel oil. This practice results in substantial greenhouse gas emissions and other pollutants such as CO2, sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter, which have deleterious impacts on local air quality, global climate, and human health.

The utilization of OPS can circumvent these issues, providing a viable strategy for the maritime sector to align itself with global sustainability goals. However, despite the clear environmental benefits and increasing regulatory pressures, the adoption of OPS has been slow. The reasons for this are multifaceted and complex, encompassing technical, economic, and regulatory challenges.

The lack of standardization in OPS technology and infrastructure, the high upfront costs of OPS implementation, and the absence of universally accepted regulatory frameworks are key impediments to wider adoption.

This research will focus on the comprehensive exploration of the application of OPS onboard vessels and more precisely on bulk carriers by taking as a typical case study a Bulk Carrier. This category has been chosen as the demand for dry bulk is expected to rise in 2023 and also bulk carriers represent the 21% of the total world fleet (UNCTAD,2022), also another factor that played a crucial role in the selection of this type of vessel is that the average age of the bulk carrier fleet is approximately 11.1 years (UNCTAD, 2022), fact that may lead to an easier retrofit on board the vessel.

1.1 The research problem

The initial phase of this research of the research problem is to evaluate the technical and economic feasibility of the OPS application onboard vessels. This will be achieved through the assessment of the environmental benefits of OPS implementation. Quantify the reduction in greenhouse gas emissions, resulting from the use of OPS instead of onboard generators and more precisely auxiliary engines during port stays. Operational and trading consideration will be also taken into account as operational and infrastructure challenges or constraints related to OPS will be identified. Another aspect investigated under this research is the economic benefit of the shipowner through the application of OPS compared to the fuel savings.

1.2 The research objectives

One of the goals of this research is to thoroughly examine the topic from multiple perspectives. This will be achieved by presenting the results of previous studies and relevant topics in a systematic and analytical manner. Another objective is to ensure that the research relies solely on actual data rather than theoretical physics models. Both Environmental and Economic benefits will be assessed. More precisely, the potential of OPS to reduce GHG emissions, and its contribution to achieving international sustainability targets will be evaluated. Also, the impact of OPS on energy efficiency, as measured by the Carbon Intensity Indicator (CII) will be measured. The economic feasibility of OPS adoption is crucial for assessing its viability from financial standpoint. This analysis would involve evaluating the initial investment costs associated with installing OPS infrastructure, as well as the operational costs and potential fuel savings for ship operators/ shipowners.

1.3 Structure of this Thesis

The rest of this thesis is structured as follows: Section 2 encompasses a literature review highlighting several studies and the existing background of ship generated emissions both at sea and at port. Moreover, International and European legislative frameworks are also presented addressing ship-generated emissions focusing as well on the onshore power supply (OPS) and the impacts of these regulations on vessel operations. It also highlights relevant studies and research regarding the utilization of onshore power supply denoting the benefits, barriers and challenges. Further, Section 3 presents the proposed methodology, which includes the Research Design presenting how this research is formed, the data collection, Carbon Intensity Indicator's calculations, a case study of a vessel, and general information regarding the model used. Section 4 delves into the data analysis, featuring an analysis on the environmental performance of the vessel, correlation study of factors affecting the CIIs, the development of two scenarios based on the IMO's current and proposed trajectories and the results from running the model. Section 5 offers a recap of these methodologies, alongside a suggestion for future research.

1.4 The research questions

- How the Carbon Intensity Indicator (CII) is affected through the application of onshore power supply?
- Do international targets imposed by regulatory bodies are met solely by the OPS adoption during vessel's stay at port?
- Which is the benefit or the cost of the shipowner or ship operator by the implementation of OPS by taking into account the fuel savings?

2. Literature Review

In this section, it is important to offer the reader a broader perspective by discussing certain key points that are closely related to the subject under investigation. The objective is to present a thorough literature review that encompasses various aspects of the topic, whether they are directly or indirectly linked to it, rather than solely focusing on summarizing previous research outcomes. Emphasizing the necessity for further exploration of this subject matter is of utmost importance.

2.1 Ship-generated Emissions

During the last years, numerous studies have focused on the advancement of sustainable transportation. The definition of the sustainable transportation is clearly outlined by the OECD (1996) as a form of transportation that does not endanger public health and has minimal effect on the environment. This concept of sustainable transportation encompasses various aspects such as legislation, policies, systems, and technologies, as stated by the Global Development Research Center (2018). Many guidelines, regulations, and systems have been established to promote sustainable transportation through measures aimed at enhancing energy efficiency. The Paris Agreement under the UNFCCC set forth objectives to decrease global greenhouse gas (GHG) emissions, aiming to limit the increase in global temperatures to 2°C above pre-industrial levels, with a further aspiration to restrict it to 1.5°C. To achieve these targets, significant measures to mitigate emissions must be implemented. According to IEA (2022), the transportation sector plays a significant role in the generation of carbon dioxide (CO2) emissions, responsible for approximately 7.7 GtCO2 in 2022, as the demand for transportation services rebounded following the COVID pandemic's restrictions (IEA, 2022).

The maritime sector's total contribution to global GHG emissions is estimated to 1.08 GtCO2eq, including international, domestic, and fishing activities (IMO 2020, European Commission 2018). Consequently, sustainability is recognized as a significant challenge that the shipping industry must address. Shipping companies are required to depart from conventional business practices in order to adapt to this shift. At this point, it should be stated that shipping operations are mainly relied on bunker fuels, fact that leads to the increase of the emissions during voyages and at ports.

Another aspect that falls under the scope of this research is ship-generated emissions at ports. According to Ballini and Bozzo (2015), approximately the 70% of the emissions generated by the maritime industry are concentrated in close proximity to port regions, with docked ships accounting for 60% to 90% of these emissions. The emissions originating from ports are especially worrisome due to their close proximity to the population residing in port cities, which leads to detrimental effects on both the environment and public health. This fact can be justified by various predictions which indicate that by 2050, ships berthed will generate approximately 70 million tons of CO2, 1.3 million tons of NOx, and 0.16 million tons of SO2 (Merk, 2014). However, even through the adoption of measures related to cleaner fuels, emissions stemming from the maritime sector are expected to contribute to as many as 250,000 fatalities and 6.4 million instances of childhood asthma in annual basis (Sofiev et al., 2018).

Early investigations have already made estimates regarding the amount of fuel consumed by ships in ports. Dalsøren et al. (2009) discovered that 5% of a ship's fuel consumption occurs while it is at berth resulting to equivalent percentage of emissions. According to other researches, the Port of Piraeus accounted for 2% of NOx emissions, 2.5% of SOx emissions, and 0.23% of PM10 emissions on national level (Progiou et. al., 2021). The results from the "Fourth IMO GHG Study" revealed that, on average, 16% of CO2 emissions are generated when ships are at berth or at anchorage (IMO, 2022).

2.2 Legislative Framework

Throughout the years, the lack of regulation in anthropogenic emissions from maritime transport was striking. As a result, there has been a need to create and enforce maritime policies and regulations. These measures aim to ensure adherence to safe emission limits and prevent swift environmental degradation (Aksoyoglu, Prévôt and Baltensperger, 2015). Below, the current regulatory framework regarding ship-generated emissions in conjunction with the application of onshore power supply is presented.

First and foremost, IMO under MARPOL (Annex IV) introduces measures in order to mitigate air pollution generated by vessels' GHG emissions. Under this Annex, several measures both operational and technical have been proposed in order to increase the energy efficiency of vessels resulting in lower fuel consumption and consequently to lower emissions.

In 2016, IMO introduced the Data Collection System (DCS) which plays a pivotal role in facilitating the collection, analysis, and utilization of fuel consumption and carbon emissions data from ships (IMO, 2016). By implementing the DCS, the IMO has created a framework that enables comprehensive data gathering and reporting on a global scale (IMO, 2016). The primary objective of the DCS is to provide valuable insights into the carbon performance of the shipping industry (IMO, 2016). By collecting data on fuel consumption and associated emissions, the DCS allows for a thorough assessment of the sector's environmental impact (IMO, 2016). This data includes information on various types of fuels used, energy efficiency measures implemented, and the corresponding carbon dioxide (CO2) emissions (IMO, 2016). The DCS also serves as a means for the IMO to assess the effectiveness of its existing regulations and initiatives. By monitoring and analyzing the reported data, the IMO can evaluate the progress made towards achieving emission abatement targets and identify any gaps or areas where further action may be required (IMO, 2016). The DCS was used as an instrumental in improving current policies and developing regulatory framework by designing effective strategies to address climate change challenges in the shipping industry (IMO, 2016).

Another practical tool introduced by IMO in 2013 was the Ship Energy Efficiency Management Plan (SEEMP) which applies to ships above 400GT and enforces operators to implement energy efficiency management plan for their existing vessels outlining strategies and best practices to optimize energy consumption in order to reduce carbon footprint (DNV GL, 2023). More specifically, SEEMP promotes energy efficiency technologies such as LED lights, Waste Heat

Recovery Systems (WHRS), Batteries etc. but operational measure as well, such as speed optimization, hull cleaning, propeller polishing, hull coating/painting (DNV GL, 2023).

In 2018, IMO acknowledged for the first time the need for significant decarbonization efforts and thus developed the “Initial GHG Strategy” setting clear ambitious goals to reduce GHG emissions by 50% in 2050 compared to 2008 levels (IMO, 2023), where short-term and long-term measures and targets are highlighted. To be more precise, the IMO's strategy establishes specific goals for the gradual elimination of carbon emissions and advocates for a minimum reduction of 40% in CO2 emissions from shipping activities by 2030, relative to the levels recorded in 2008 (IMO, 2023). Additionally, this strategy acknowledges the barriers that exist and emphasizes the need to foster technological advancements to overcome these obstacles (IMO, 2018). Regarding the long-term vision, IMO encourages the development and deployment of innovative technologies and alternative fuels, such as hydrogen, methanol ammonia, or biofuels, to achieve carbon neutrality in the future (IMO, 2023).

IMO also introduced the “4th GHG Study” in 2020, examining the current and projected levels of emissions from the shipping sector and assesses the effectiveness of existing and potential measures to reduce these emissions promoting as well further actions and measures and revisiting existing targets (IMO, 2023). For that reason, in order to monitor and measure the efficiency of the ships, IMO developed mandatory indicators such as Carbon Intensity Indicator (CII) and Energy Efficiency Existing Ship Index (EEXI), which came into force from 1st January 2023 (IMO, 2023).

- Carbon Intensity Indicator (CII) was developed to measure and track the carbon emissions intensity of ships. More precisely, calculates the necessary annual reduction factor to ensure ongoing enhancement vessel’s carbon intensity within a particular rating level (IMO, 2023). Both the achieved annual operational and the required CII are reported and verified in order to identify the alignment of the vessel’s CII with the IMO’s imposed targets (IMO, 2023).
- Energy Efficiency Existing Ship Index (EEXI) of a ship demonstrates its energy efficiency in relation to a reference point. The ship's attained EEXI is then compared to a required Energy Efficiency Existing Ship Index, which is determined based on a specified reduction factor expressed as a percentage provided by the Energy Efficiency Design Index (EEDI) (IMO, 2023). This indicator is applicable to every vessel above 400GT, highly dependent on vessels’ types and size categories (IMO, 2023). The calculated attained EEXI value for each individual ship must be lower than the required EEXI to assure the compliance with a minimum energy efficiency standard (IMO, 2023).

In European level, several policies and initiatives were developed, introducing measures and targets to address emissions abatement of the shipping sector, highlighting the recognition of shipping emissions as a significant contributor to climate change and air pollution. For that reason, EU introduced both operational, technical and market-based measures.

To begin, the MRV Regulation “Monitoring, Reporting and Verifying” (Regulation (EU) 2015/757) has been adopted by member states and entered into force in 2018 signifying the fist reporting period (LR, 2023). Under this Regulation, shipowners and ship operators are obliged to monitor and report both vessels’ emissions and fuel consumption in annual basis for trips that are taking place on EU territorial waters or calling European ports (LR, 2023). More specifically, in order the MRV Regulation to be applicable, at least one port of call during the voyage must fall within the jurisdiction of an EU member state, regardless of the flag under which the ship is registered (ICS Shipping, 2016). The MRV Regulation is considered an initial phase in the gradual integration of maritime transport emissions into the European Union's greenhouse gas (GHG) reduction commitment (LR, 2023).

Moreover, EU introduced the “FuelEU Maritime” as part of the “Fit For 55” package, under this initiative, the European Commission has put forth a proposal to implement a progressive and goal-oriented target for the greenhouse gas (GHG) intensity of fuels used in shipping (Transport & Environment, 2022). This target would necessitate ships that visit EU ports to decrease the carbon footprint of the energy consumed onboard (Transport & Environment, 2022). The target is quantified in terms of Well-to-Wake (WTW) CO2-equivalent emissions, which includes the complete life-cycle GHG emissions (CO2, CH4, N2O) associated with various fuels and applicable engine technologies (Transport & Environment, 2022). In 2023, set new more aggressive targets towards maritime decarbonization, such as 14.5% and 80% reduction in GHG intensity of the energy used onboard vessels for 2030 and 2050 respectively, compared to 2020 levels (European Commission, 2023).

The EU Emissions Trading System (EU ETS) is a well-established cap-and-trade system that has been effective in reducing greenhouse gas emissions in sectors such as energy production, manufacturing, and aviation (European Commission, 2023). Thus, maritime industry is also included in the EU ETS, which provides economic incentives for emission reductions (European Commission, 2023). By bringing shipping into a market-based mechanism, ship operators would be required to obtain allowances for their emissions, creating a financial cost for exceeding their allocated emissions cap (European Commission, 2023). This can incentivize the adoption of cleaner technologies, fuels, and operational practices to reduce emissions and mitigate associated costs (European Commission, 2023).

2.3 OPS and regulatory Framework

In May 2019, the International Maritime Organization (IMO) approved a resolution called MEPC.323(74), which aimed to encourage cooperation between member states to voluntarily reduce greenhouse gas (GHG) emissions from ships (IMO, 2023). This resolution focuses on promoting various measures in the port sector, including regulatory, technical, operational, and economic actions. One of the initiatives supported by this resolution is shore power, which is also known as Cold Ironing (CI), Alternative Marine Power (AMP), and Onshore Power (Yu et. al, 2019).

In EU level, the EU has been actively pursuing sustainable shipping practices and has implemented regulations to promote OPS utilization. Directive 2014/94/EU on the deployment of alternative fuels infrastructure sets the framework for developing alternative fuel infrastructure, including OPS, in the transportation sector (European Parliament, 2014). Member states are required to develop national policy frameworks that facilitate the development of OPS infrastructure in ports (European Parliament, 2014). The directive also establishes targets for OPS availability in ports, encouraging the integration of OPS into port infrastructure planning (European Parliament, 2014).

The EU's Trans-European Transport Network (TEN-T) policy is another important initiative that supports OPS implementation (European Commission, 2022). It aims to improve the efficiency and sustainability of the EU's transport network. The policy includes provisions for the development of OPS infrastructure in designated ports, ensuring the availability of shore power for vessels (European Commission, 2022).

In addition to all above, through the provisional agreement of “FuelEU Maritime”, European Commission, states the mandatory use of onshore power supply while the vessel is berthed in EU ports (European Commission, 2023).

In the United States, the Environmental Protection Agency (EPA) has been actively involved in promoting OPS to reduce emissions from ships (EPA, 2022). The EPA's National Clean Ports Initiative encourages ports to voluntarily adopt measures to reduce emissions, including the use of OPS (EPA, 2022). This initiative provides guidance and technical assistance to ports interested in implementing OPS programs (EPA, 2022). Several states, such as California, have implemented their own regulations to mandate OPS utilization in certain ports (EPA, 2022). Moreover, Clean Shipping Act (2022) states that all vessels should generate zero emissions while their berthing or anchorage at US ports (US Congress, 2022).

In Canada, Transport Canada's Marine Environmental Protection Directorate (MEPD) promotes sustainable shipping practices, including OPS utilization. The MEPD has issued guidelines and recommendations for OPS implementation in Canadian ports (Port of Vancouver, 2022). These guidelines provide information on OPS infrastructure requirements, electrical system compatibility, and best practices for implementing OPS programs. Canadian ports, such as the Port of Vancouver, have actively implemented OPS programs and infrastructure to support the adoption of OPS by vessels (Port of Vancouver, 2022).

2.4 OPS in shipping

Taking into account, all the above regulations regarding the ship-generated emissions, and the ways that the regulatory bodies are tackling this issue, the electrification of ships seems to be one the key components towards the decarbonization of maritime sector. Onshore power supply involves providing ships at berth with energy by connecting them to the local power grid or alternative sources, with the purpose of meeting their energy requirements (Zis, 2019). Currently, ships generate energy using their auxiliary engines onboard, which are mainly operated with Marine Diesel Oil (MDO), fact that leads to a notable negative effect on the environment (Zis, 2019).

It has been observed that battery operated ships are gaining ground nowadays, fact that can be justified by the DNV GL registration of newbuilding ships which indicates that the electricity demand increases denoting that there is a trend towards the electrification of marine transport (Alnes, Eriksen, and Vartdal, 2017). The constant demand for electric power will invariably raise efficiency issues and encourage the adoption of electric and shore power technologies on board (Alnes, Eriksen, and Vartdal, 2017). Additionally, ships can utilize batteries for various purposes, such as regenerative crane braking, zero-emission operations, emergency power backup, optimization of auxiliary engine use, and so forth (Alnes, Eriksen, and Vartdal, 2017). All newly designed electric and hybrid ships will require shore power links to recharge their batteries, facilitate zero-emission activities, achieve fuel savings, and access affordable energy (Alnes, Eriksen, and Vartdal, 2017).

Tseng and Pilcher (2015) in their research regarding the adoption of OPS in the port of Kaohsiung, Taiwan, they concluded that the environmental, financial, and social advantages of implementing shore power (Tseng and Pilcher, 2015). However, they recognized the high initial investment required fact that may impede the adoption of OPS (Tseng and Pilcher, 2015). Zis et al. (2014) found that shore power usage could lead to reductions ranging from 48% to 70% for CO2 emissions, 3% to 60% for SO2 emissions, 40% to 60% for NOx emissions, and 57% to 70% for black carbon (BC) emissions in ports. Consequently, widespread adoption of shore power would significantly alleviate air quality concerns.

Additionally, Ballini and Bozze (2015) examined the socioeconomic impact of air pollution in Copenhagen Port caused by cruise ships in ports and proposed a cost-benefit analysis of shore power. More precisely, they found that by supplying 60% of the power demand of cruise ships, with OPS, the resulting health-related cost benefits could amount to $3.35 million USD annually

(Ballini and Bozze, 2015). They also estimated that health cost savings would allow the capital investment in shore power infrastructure to be recovered within a period of 12-13 years (Ballini and Bozze, 2015).

At this point, also barriers and challenges should be identified in order to have a clearer view regarding the adoption of OPS onboard vessels. To begin with, according to Zis (2029), one of the significant obstacles related to shipowners is the substantial expense involved in retrofitting vessels. Even though the difference in costs between local electricity and fuel oil may eventually cover these expenses, the lengthy payback period could potentially dampen the interest of ship owners in retrofitting their vessels (Zis, 2019). For instance, the retrofitting of an ultra-large container ship costs approximately one million USD, and such a ship spends nearly a quarter of its time docked at ports to complete loading and unloading operations (Zis, 2019).

Thus, for on-board investments to be economically feasible, fuel cost savings must reach certain benchmarks. These benchmarks fluctuate based on the type of ship and factors such as reductions in fuel consumption, fuel prices, and the cost of the Onshore Power Supply (OPS) service (Christodoulou, and Cullinane, 2020). These elements can vary due to factors like grid charges

Another factor that plays crucial role in the adoption of OPS is the type of vessel in conjunction with the time spent at port. More precisely, Martínez-López, Romero and Orosa (2021) conducted a study for the port of Cartagena and the results showed that bulk carriers have the longest port stays (average 71.85 hours) while cruise ships have the shortest (Martínez-López, Romero and Orosa, 2021). Therefore, when comparing with other emissions-reducing technologies, investing in Onshore Power Supply (OPS) may not be the best choice for ship owners who only make occasional and brief port calls (Martínez-López, Romero and Orosa, 2021).

Another aspect that should be considered by the shipowners, stakeholders and operators is the the cost difference between using fuel and electricity as it determines the financial viability of the investment (Seddiek, 2015). Seddiek (2015) states that when calculating costs, all pathways of the energy production systems, including installation costs, operations, and maintenance activities, should be taken into account to accurately represent the real cost of energy production. Decreased fuel expenditure is a crucial element in enticing prospective users towards OPS, and it's noted that certain ports, like the port of Gothenburg, have increased the allure of OPS by offering free electricity (Innes and Monios, 2018).

Last but not least, at this point it should be stated that there are limited studies regarding the implementation of OPS onboard vessels. The majority of researches are focusing on the port infrastructure and the feasibility of such investment.

3. Research Methodology

In this section, we will detail the methodology used to conduct this study and answer the research questions. More specifically, the layout of the study is established through the research design, and the techniques used for data collection, along with their credibility and validity, are also discussed. Importantly, the research approach is critical in formulating conclusions as it influences the design and highlights potential limitations and boundaries. In addition to these, the specifications of the vessel, employed as a case study, are also outlined in this chapter. Last but not least, the narrative behind the calculations and the estimations will be introduced in order to estimate the environmental performance of the IMO's Carbon Intensity Indicator (CII).

3.1 Research Design

Firstly, this dissertation was carried out by analyzing quantitative secondary data, due to its unequivocally quantified nature and the exploratory, analytical aims of this research. This can be justified by the objective to explore and describe the interplay among the input variables, evaluate their response under varying IMO targets, and ultimately model and how they affect the revenues of a company.

The application of the previously mentioned methodology will result in the use of descriptive and analytical tools. A model will be created and utilized to combine the inputs and the variables in order to fulfill the objectives of this study. This model will be developed by using existing equations, previous researchers findings and industry’s insights and it will be utilized in a case study aiming not just to select the optimal combination of input variables but also to investigate the potential financial impact. Alongside this, the case study approach is also adopted, as a small-scale study will be undertaken, allowing for the exploration and examination of the impact of the adoption of OPS onboard a bulk carrier in Carbon Intensity Indicators (CII).

To construct a precise this model factors like vessel’s speed, fuel consumption (both at port and at sea), distance, main engine and auxiliary engine loads, vessel’s DWT, hours spent at sea, hours spent at port, specific fuel consumption, speed-power curves, CII targets will be utilized. After the testing, the training process will be initiated to understand the complex relationships between the input variables and the output.

Furthermore, a projection for the years from 2023 until 2050 will take place in order to identify the CII targets, this will be achieved by taking into account the current imposed by IMO in conjunction with the implementation of linear interpolation for the remaining years not provided by the IMO. Thus, a trajectory will be developed which will be used in the model which will be used as a target for comparing vessel’s efficiency. The interrelationship between CII and the variables such as the speed and the age of the vessel.

3.2 Data Collection

The foundation of this study primarily rests on the operational data recorded from the ship, as illustrated in voyage reports. This dataset, drawn from the performance monitoring database includes: the date, time, voyage number, vessel speed, port of calls, voyage duration,), engine loads, carrying cargo, time spent at sea and at ports, total fuel consumption for each voyage, fuel type (MGO and HFO), CO2 emissions and GHG emissions. The data are entered in the database by the crew every 24 hours, sourced from the measurement instruments during the voyage and the vessel's time at port. The dataset derived by the performance monitoring database represent the total and the average values of previously mentioned data, which does not reflect the ship's operation under real-time conditions through sensor measurements onboard vessels. Thus, even though these reports are acquired from the company, they are manually recorded by crew members. This could cast doubt on their validity, as these log data might be susceptible to human errors.

The data cover the period from 1st January 2021 until 31st December 2022 for a vessel trading in the route between Canada and China and more precisely, the port calls of this specific vessel are Vancouver (Canada), Qingdao (China), Shanghai (China) and Singapore (Singapore). The data supplied by the Shipping Company consists of an Excel file providing all the aforementioned valuable information for the model development. The trading data for this specific vessel are also verified by the Clarkson’s SIN database, denoting that the vessel operating in this particular route (Clarksons’ SIN, 2023).

It's important to note that the collected data is presumed to be valid as the company's Operations department regularly reviews, supervises, and assesses the information recorded in the voyage reports. If implausible data or errors arise, the department maintains ongoing communication with the ship's officers to rectify any inaccurate observations.

Moreover, it should be stated that the Company also provided information regarding the environmental performance of its specific vessel more precisely, CII calculations and ratings for 2019, 2020 and 2021 are also incorporated into the data. Furthermore, in order to build the model, data such as the specific fuel consumption (SFOC) in combination with speed-power curves and the reference speed are also supplied by the Company through the EEXI and EEDI. At this point it should be stated that other information regarding the added resistance or hull specifications are not provided by the company as they are considered sensitive data and are incorporated in the model tests. Thus, it’s important to note that this limitation could potentially affect the performance of the model.

Additionally, the phased out and the drydocking schedule of this specific vessel are also provided by the shipping Company as they are valuable information for the model development. Data regarding the engine specifications of the vessel are provided by the IHS database (IHS, 2023) in order to identify whether the engines are mechanically or electronically controlled, fact that affects the adoption of OPS onboard.

Other variables that are used in the model is the fuel prices for HFO and MDO (fuel used by the vessel) and the revenues. Fuel prices are denoted as the average value for this specific year and the revenues are provided by the company. Fuel specifications such as density, low calorific value, emission factors are provided by FuelEu Maritime through the Annex II (European Commission, 2022).

3.3 Vessel Case Study

To investigate the impact of OPS on the ships Carbon Intensity Indicator of a bulk carrier, we chose as a reference vessel a bulk carrier Capesize, MV BulkCarrier-N1. This vessel operates in the aforementioned route for more than 2 years and it is under a time charter for 5 years, so the trading route won't be altered and it is owned by a Chinese based shipping Company. This ship is chosen due to the geographical area where it is trading as in these ports, OPS is available. Moreover, in this dissertation, the investigation and analysis primarily depend on the dataset of this specific ship, embodying all the characteristics of a typical Capesize vessel. The Company supplied all the necessary data to conduct this research on this specific vessel, and the suggested model can be universally applied to other Capesize vessels with similar specifications and presumably on its sister vessels without modifying the chosen input variables. The specifications of MV BulkCarrier-N1 are presented on the following table (Table 1)

Table 1: Vessel's Specifications

MV BulkCarrier-N1 Specifications					
Vessel Name	MV BulkCarrier-N1	**Draught (m)**	18.3	**Total KW Auxiliary engines**	2700
Vessel Type	Capesize	**Vref (knots)**	13.96	**Nr. Of AUX engines**	3
DWT	179655	**Engines RPM**	70	**Technology onboard**	Scrubbers
Length (m)	292	**Total KW Main Engines**	15360		
Beam (m)	45	**Block Coefficient**	0.8511		

(source: author)

This specific vessel was built in 2015 and it also has 9 cargo holds and 10 hatches (IHS, 2023). In 2021, this vessel was attained in total 72339 nm operating in the aforementioned route. It should be stated that every five years the ship ceases its operations in order to perform the scheduled drydocking. Regarding the types of fuel utilized in the ship's engines, it's worth mentioning that both main and auxiliary engines consume marine conventional fuels and more precisely, HFO and MGO as scrubbers have been installed in the vessel. Moreover, the Main Engine is electronically controlled fact that allow any potential retrofit towards the use of alternative fuels such as methanol, LNG, ammonia etc.

3.4 Carbon Intensity Indicator

The Carbon Intensity Indicator (CII) is the measurement that it will be used for our analysis and in order to investigate the alignment of the efficiency of the vessel through the usage of OPS with IMO targets. As already presented in the Literature Review section, the CII was introduced by the International Maritime Organization (IMO), which aims to quantify the carbon efficiency of a ship for a specific year. The CII calculation is derived by the following equation:

$$CII = \frac{CO2\ emissions\ (gCO2)}{DWT\ (t) \times miles\ (nm)}$$

Where:

$CO2\ emissions\ (gCO2)$: are the total CO2 emissions emitted by the vessel in annual basis (incorporating generated emissions both at sea and at port)

$DWT\ (t)$: vessel’s capacity

$miles\ (nm)$: the total distance that vessel attained in this specific year

The CII is changing throughout the years as it highly dependent on both emissions and the distance travelled. At this point it should be stated that from the equation presented above the CII is negative correlated to the utilization of the vessel as the higher the utilization (distance travelled) the lower the CIIs, denoting better performance of the vessel. The attained CIIs should be assessed and compared against the required CIIs.

The achieved CII rankings are represented as a rating label selected from five categories (A, B, C, D, and E). These labels respectively indicate a performance level that is significantly above average, slightly above average, moderate, slightly below average, or significantly below average. This rankings are calculated based on the reduction factors provided by the IMO (Table 2)

Table 2: IMO Reduction Factors

IMO Reduction Factors (%)						
2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
1%	2%	3%	5%	7%	9%	11%

(source: IMO, 2022)

However, the reference CII was established for the year 2019 and it is calculated based on the formula below by taking into account technical characteristics of the vessel.

$$CII\ ref = a \times Capacity^{-c}$$

Where:

$Capacity$: is the DWT of the vessel

a, c : factors applied in accordance to DWT

For Bulk Carriers the following factors were provided by the IMO (Table 3)

Table 3: CII Ref Factors

CII Ref Factors			
Vessel Type	**Capacity**	**a**	**c**
Bulk Carriers	DWT ≥ 279,000	4745	0.622
	DWT < 279,000	4745	0.622

(source: IM0, 2022)

As already stated above, in order to estimate the rating of the vessel throughout the years, a comparison between the attained CII and the required CII should take place. More precisely, the ratio should perform under specific ranges which denote each of five categories provided above. For Bulk Carriers the ranges are provided in the following table (Table 4)

Table 4: CII Ratings

Ratings for CIIs	
A	0,86
B	0,94
C	1,06
D	1,18
E	100

(source: IMO, 2022)

Another information that should be stated is that in order to calculate the CIIs for the remaining years we are taking into account the 40% reduction in emissions by 2030 and 70% reduction in emissions by 2050 (as for the remaining years IMO didn’t provide a clear path towards the reduction percentages).

The required CII can be estimated by the following equation denoting that it is clearly related to CII ref.

$$Required\ CII\ = \frac{100 - Z}{100} \times CII\ Ref$$

Where:

Z: is the reduction factor provided by IMO (Table 3)

3.4.1. CII Improvement

To enhance a ship's carbon emission efficiency, the emissions must be reduced per nautical mile traveled and/or reduced or nullified when the ship isn't in motion (for instance, when anchored or docked). Various technical and operational strategies exist to accomplish these goals, some of which are showcased in this section of the document. These solutions can be organized into the following categories:

- Propulsion Technologies: reduce the propulsion power required or optimized at a specific speed or weather conditions
- Auxiliary Power Technologies: reduce the demand for electrical power fo the auxiliary engines, generators and boilers
- Digitalization Technologies – installing onboard digital technologies in order to optimize the fuel consumption, the weather routing and the performance of the vessels by taking into account specific operational conditions.

The onshore power is incorporated into the Auxiliary Power Technologies and it is utilized years by ships with moderate power requirements, typically ranging from 50 to 100 kW. These vessels can leverage the standard grid voltage and frequency, substituting generator-supplied energy with shore power with only minor investments required. The fuel savings arising by the application of OPS range from 3% to 10% to the total fuel consumption of the vessel.

4. Data Analysis

In this section, the main analysis in conjunction with modeling results will take place. More precisely, the analysis regarding the environmental performance of the vessel will be carried out by taking into account operational parameters. Furthermore, both attained and required CIIs will be estimated and the rating of this specific vessel throughout the years will take place. Moreover, in order to investigate the impact of OPS on the CIIs, two different scenarios will be developed based on the IMO's current and proposed targets. Last but not least, the results of the modelling will be presented in this section as well providing information regarding the alignment to IMO targets and the benefits arising from the application of OPS.

4.1 Environmental Performance of MV BulkCarrier-N1

From the data derived by the performance monitoring database the CO2 emissions for the year 2020 were estimated to be 25517 tons while in 2021 the vessel emitted 34303 tons of CO2 followed by 21071 tons of CO2 in 2022. This can be justified by the fact that ship-generated emissions follow the same trajectory as the distance sailed for these years. More specifically, the distance sailed in 2021 was 15% higher compared to 2020 levels but for 2022 the distance sailed was lower by 25% and 35% compared to 2020 and 2021 levels respectively. This observation can be justified by the fact that in 2022 the vessel performed its drydocking and maintenance.

The total Fuel Consumption for 2020 was 8093 MT, the 97% of the total fuel consumption was corresponds to the LFO and the remaining 3% was derived by MGO. For 2021 an increase of 36% was observed in the total fuel consumption compared to 2020 levels accounting 11002 MT, the 94% of which corresponds to the fuel consumption HFO, the 3% for LFO and the remaining 2% for MGO from which the 59% was derived by the consumption at ports. In 2022 the fuel consumption was estimated to 6753 MT, denoting a 15% reduction in the fuel consumption compared to 2020 levels. Moreover, the 94% of the total fuel consumption in 2022 arose by HFO while the remaining 6% from MGO.

We conducted a correlation analysis in order to investigate the interrelationship between the total fuel consumption and the afore mentioned fuels. Positive correlations are denoted between the total fuel consumption and the two variable (HFO, LFO), while negative correlation is observed between fuel consumption and MGO with correlation coefficients r1=0.57, r2= 0.17 and r3=-0.77. This result can be justified by the fact that the quantity of HFO increased throughout the years as scrubbers have been installed onboard the vessel in conjunction with the fact that both HFO and LFO were burnt by Main Engines. Another factor which justifies this finding is that when the vessel navigates in high seas, it experiences more significant speed variations, which lead to fluctuations in the engine's revolutions per minute (rpm). Regarding MGO fuel consumption, this specific fuel was used mainly for Auxiliary engines and boilers when the vessel is at port. At this point it should be stated that the specific vessel for a year is spending on average 68hrs at ports for loading and discharging operations.

4.2 Attained and Required CII calculations

In this section, the calculations of the attained and required CIIs will be conducted. The equations provided in under the Methodology section will be used in combination with the IMO reduction factors depicted in Table 2 and Table 3Table **2** The data that we used will be provided in the following table (Table 5), along with the results (attained CIIs) all the calculations were carried out in an Excel File by taking into account the DWT of the vessel (179655tons). At this point it should be stated that the baseline year used is 2021 as all the data are valid and verified by the DCS.

Table 5: Attained CIIs calculations

Attained CIIs calculations								
CO2 emissions (nm)			*Distance (nm)*			*Attained CIIs*		
2020	***2021***	***2022***	***2020***	***2021***	***2022***	***2020***	***2021***	***2022***
25517,6	34303,2	21070,7	62664	72339	47152	2.267	2.640	2.487

(source: author)

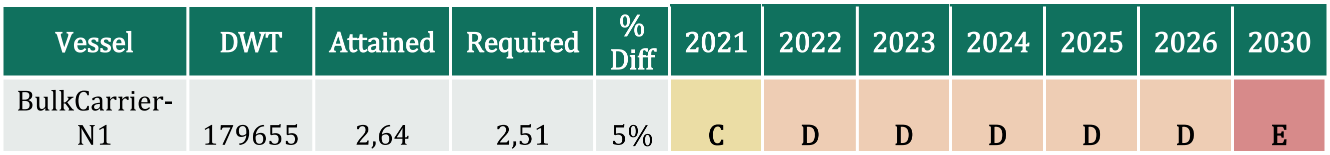
The following table (Table 6) depicts the calculations for the required CIIs from 2021 until 2030 by employing IMO factors.

Table 6: Required CIIs calculations

Required CIIs calculations								
CII ref	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2030*
2.558	2.533	2.507	2.482	2.431	2.379	2.28	2.277	1.535

(source: author)

After estimating the attained and the required CIIs, we will apply the ratings for each year. At this point it should be stated that we will assume that the vessel will operate the same as 2021, thus the CII will remain constant throughout the years. The results are provided on the



Vessel	DWT	Attained	Required	% Diff	2021	2022	2023	2024	2025	2026	2030
BulkCarrier-N1	179655	2,64	2,51	5%	C	D	D	D	D	D	E

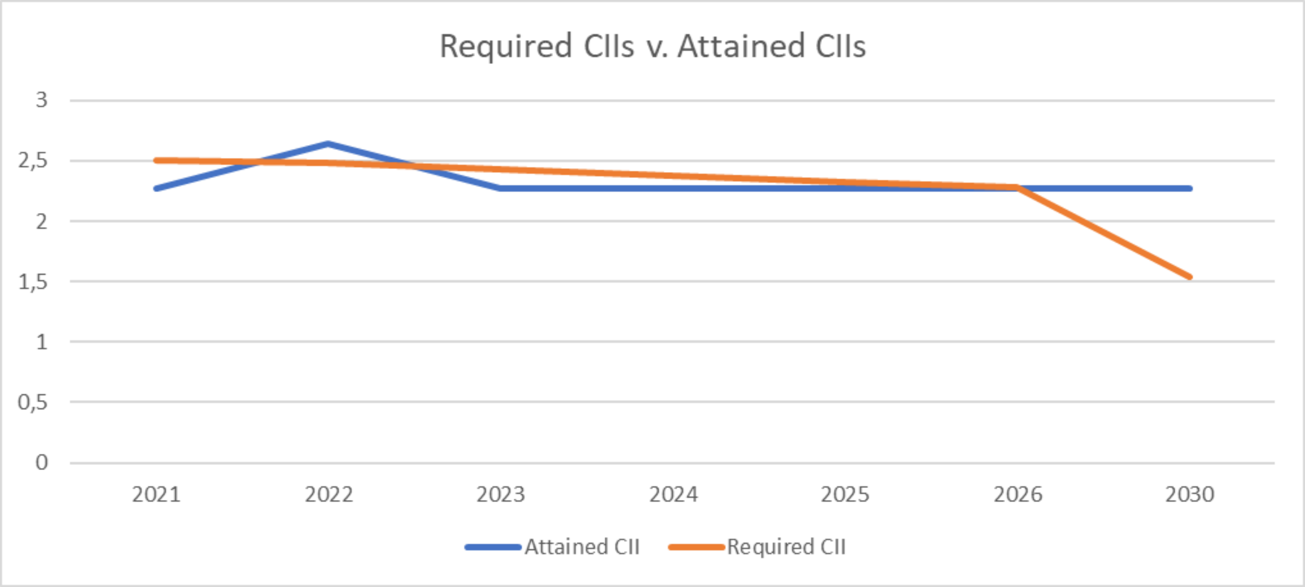
Table 7

Table 7: CII Ratings

(source: author)

From the afore table above, it is observed that the vessel in 2021 is rated with C and from 2022 and until 2026 is rated with D in the business-as-usual (BAU) scenario. However, according to IMO (2022), corrective measures and immediate actions are required in order the CII to be lowered as the vessel cannot be rated with D for more than three consecutive years. Moreover, it is observed that in 2030 by applying 40% reduction in emissions, the vessel is rated with E.

Figure 1: Required CIIs v. Attained CIIs



(source: author)

The Figure 1 denotes the trajectory and the differences observed between attained and required CIIs. It is observed that in 2021 the vessel is in compliance with IMO targets while in 2022 the vessel is overperforming. However, from 2023 by applying the BAU scenario (baseline year 2021) the vessel is underperforming from environmental perspective resulting to -32% difference in 2030.

4.3 Scenarios Development

In this section, the development of two scenarios based on IMO trajectories will be presented as these two scenarios will be used in order to estimate the impact of Onshore Power supply onboard the vessel.

As it is already presented in the literature review, IMO has already enforced reduction targets until 2026 in combination with the long-term strategy of 40% and 70% emissions reduction by 2030 and 2050 respectively. In 2023 in MEPC 80, the Committee proposed more robust measures and targets for the energy transition of the shipping sector. Although, this proposal is under consideration, in this research, these targets will be taken into account for the development of the second scenario. The rationale behind the aforementioned, is to develop 2 scenarios Low and High in order to investigate the impact. Thus, the description of these two Scenarios is the following:

A. ***Scenario 1: IMO – Low***
   Aligned with the initial trajectory proposed by IMO envisioned a higher reduction in CIIs in 2030 and 2050, by 40% and 70% respectively compared to 2008 levels.
B. ***Scenario 2: IMO – High***
   i. Aligned with the initial trajectory proposed by IMO until 2026
   ii. Aligned with new proposed (under discussion) IMO trajectory for GHG emissions.
   2030: 65% reduction in CO2 emissions compared to 2022levels
   2040: 96% reduction in CO2 emissions compared to 2022 levels
   2050: net zero CO2 emissions

In order to develop and implement the afore mentioned scenarios some assumptions have been made. To begin, under both scenarios the trajectory is the same for the period from 2021 until 2016 by applying IMO's targets as denoted in MEPC 76 and also highlighted in the Table 2 in the Research Methodology section. Differentiation in CII reduction is applied from 2027 and onwards (until 2050) due to the different proposed targets. Another assumption is that 2021 is considered the baseline taking into account that current and proposed targets will be compared to emissions and CIIs of this year and not 2008 due to data limitation. Last but not least, the activity (distance) of the vessel will remain the same with 2021 levels throughout the years considering that the vessel will operate under same trading patterns.

The methodology used in order to develop these scenarios on the Linear Regression and Linear Interpolation, More precisely, we investigated the relationship between the CIIs and the emissions and it was found that the R Square is 0.75 which indicates that the 75% of the variability in the CIIs can be explained by the model and it is considered a strong fit. So, we used the following relationship in order to project CIIs for the period from 2027 until 2020:

$$y = \ 0.958 * \ 10^{-5} * x - 0{,}392$$

Where:

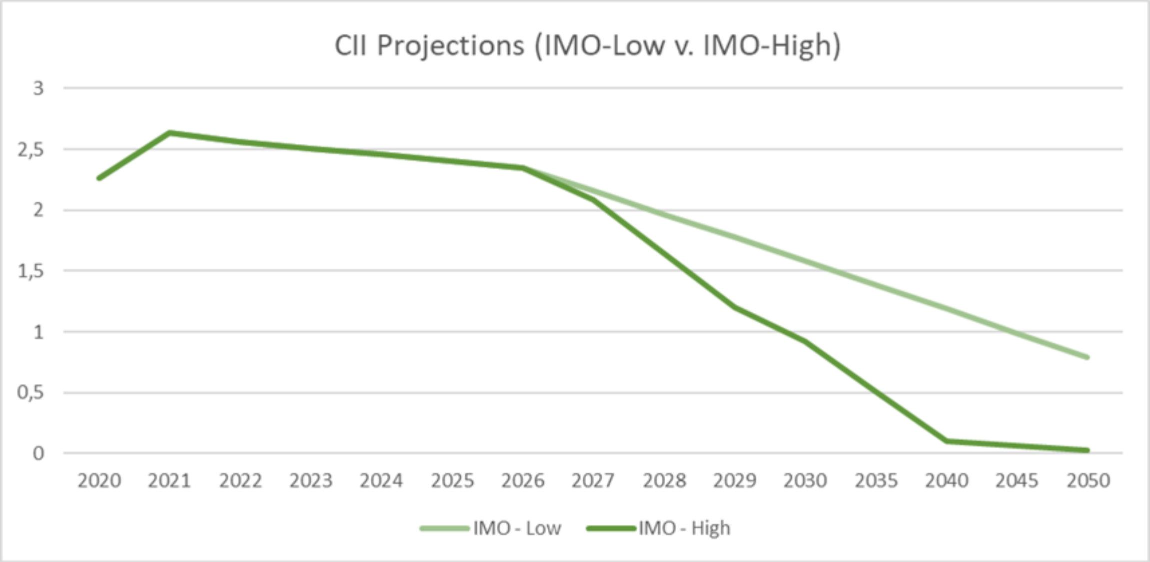
x : is CO2 emissions

y : is CIIs

At this point it should be stated that CO2 emissions for the period from 2027 until 2030 were estimated through the employment of Linear Interpolation. And thus, we used these results in order to project CIIs. Both CO2 emissions and CIIs for the years 2035 and 2045.

After implementing all the above, the results can be found in the following chart **Figure 2: CII Projections**

Figure 2: CII Projections (IMO-Low v. IMO-High)



(IMO-Low v. IMO-High) Figure 2

(source: author)

From the graph above, the difference between these two scenarios was estimated to be -42% in 2030, -91% in 2040 and -97% in 2050. Under the 2nd Scenario (IMO-High) the CII trajectory is more aggressive compared to 1st Scenario (IMO-Low), fact which indicates that in order to vessel to be in compliance with this trajectory, more robust measures promoting efficiency improvements should be implemented. Last but not least, these two trajectories will be implemented in the model in order to consider the pathway that the vessel should follow in order to be in compliance through the application of OPS.

4.4 Model Results

As it has already stated above, a model developed in Python in order to calculate the impact of the OPS on vessel's CIIs throughout the years (for the period from 2021 until 2050) and also to investigate the financial benefit that the OPS offers to shipowners and ship operators through the quantification of fuel savings. At this point, the inputs for the model should be presented. To begin with, the targets presented in the Section Scenarios Development will be incorporated, the baseline emissions for the year 2021, the drydocking schedule (2028 is the first year of available Drydock), the year of OPS installation is also provided, which will assume that it will take place during Drydocks as major installments and retrofits should be made. Another input factor is the Capital expenses (CAPEX) and (OPEX) for the installation of OPS. OPS. More precisely, according to GLOMEEP (2023) the CAPEX required for OPS were estimated to be $350,000.00 while the OPEX were about $25,000.00.

Regarding the Revenues, this information is deemed confidential and cannot be declassified by the shipowner. However, we assumed that the annual Revenues are approximately $50000000 considering the trading route and the market conditions. Another input factor that can be considered of major of importance is the speed, as the model is mainly a speed optimization model. More precisely, it determines the most efficient speed for a vessel's voyage in order to optimize fuel efficiency, reduce costs, and align scheduling requirements. Thus, the objective function of this model typically minimizes the total fuel consumption in order to meet the afore mentioned targets for a given year, given these constraints. So, we assumed that the speed would range between 10knots and 13 knots, which considered typical speeds for a bulk carrier and they are also aligned with the operational profile of the vessel. This model was chosen as also operational measures should be considered in order the targets to be met. Regarding the fuel costs we took into account an average price for conventional fuels (LFO, HFO, MDO) which will be applied throughout the years which is estimated to be around 450 USD/ton.

In order to better interpret the modeling results in the existing scenarios, we added two more cases for each scenario, leading to total four scenarios. More precisely:

Scenario 1: IMO – Low

- Applying speed optimization in order to check whether the new CIIs are aligned with the CIIs provided under this specific scenario.
- Applying both speed optimization and onshore power supply while the vessel is at port. The installation of OPS will take place on the first scheduled drydocking of the vessel.

Scenario 2: IMO – High

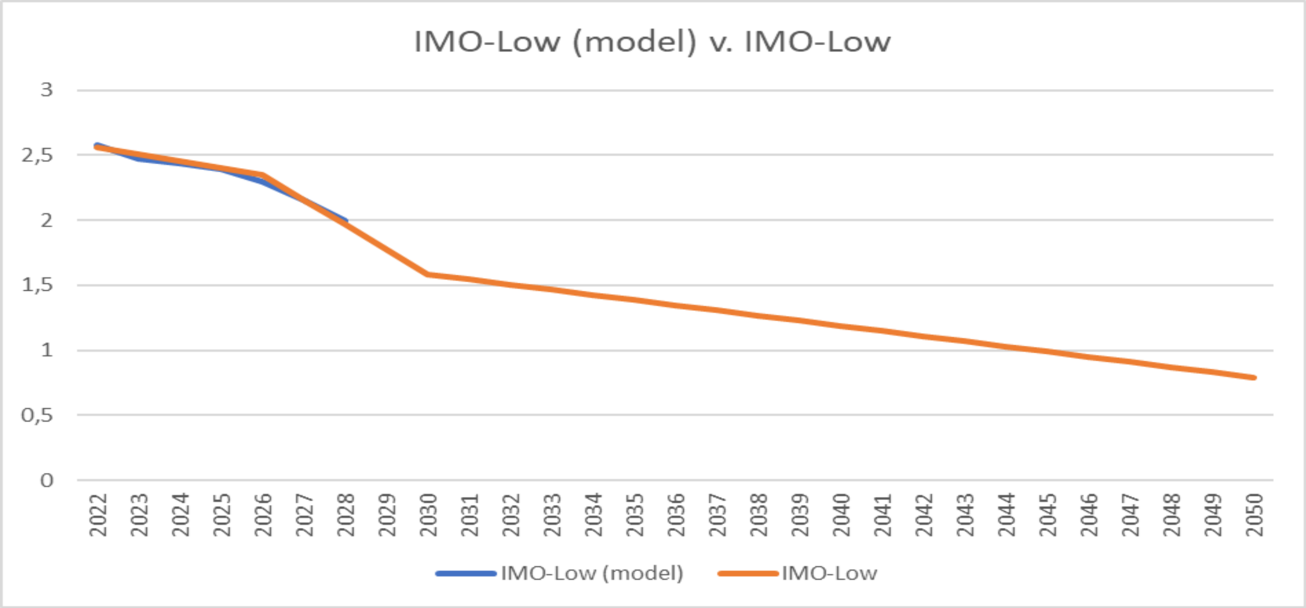
- Applying speed optimization in order to check whether the new CIIs are aligned with the CIIs provided under this specific scenario.
- Applying both speed optimization and onshore power supply while the vessel is at port. The installation of OPS will take place on the first scheduled drydocking of the vessel.

4.4.1 Scenario 1: IMO – Low

I. Speed Optimization

The results after running the model under the Scenario 1 and applying only speed optimization as efficiency measure showed that the targets set under the IMO-Low (Figure 2) can only be met until 2028 and after this year another measure should be implement in order to achieve the efficiency required. The speed variations are observed between 10 to 10.5. Moreover, another interesting output is that the revenues from fuel savings ranging between 1.5% for 2022 (the first year of the application of speed optimization), 5.9% by 2025 and it increases by 17.4% for 2028 compared to the baseline year. Regarding the annual total fuel cost the decrease is ranging between 4% for 2022 and 37.1% for 2028 which is considered a significant amount in operating expenses of this specific vessel.

Figure 3: IMO-Low (mode) v. IMO-Low



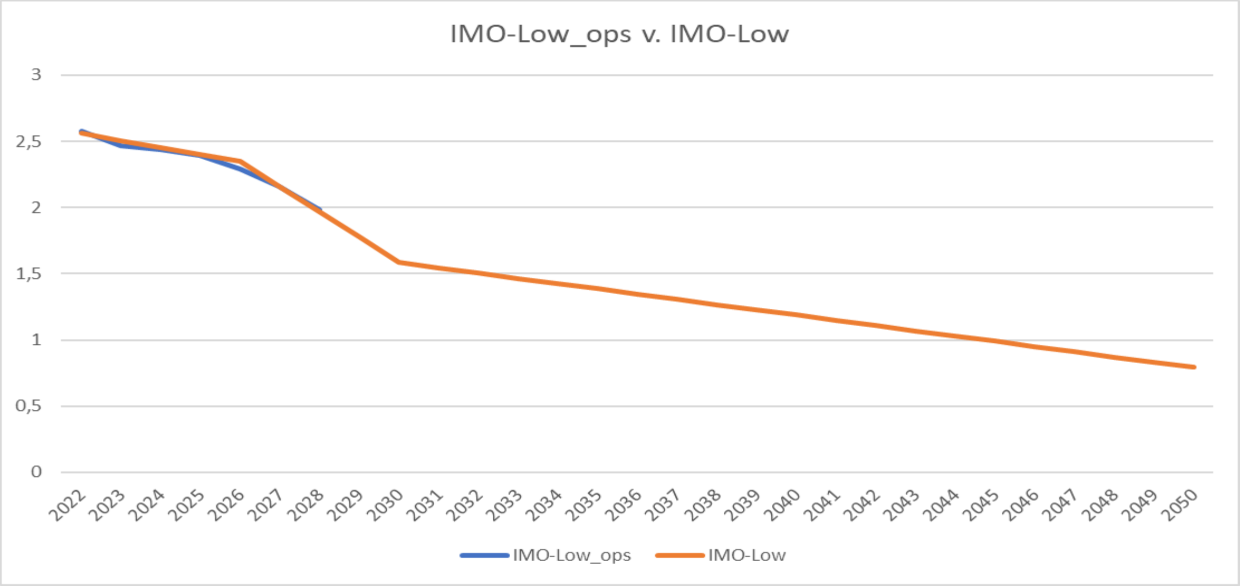
(source: author)

The figure above(Figure 3) depicts the trajectories of CIIs under scenario IMO-Low (model) which derived from the model compared to IMO-Low trajectory. It is observed that the trajectory under scenario IMO-Low (model) is ceased in 2028 which is already explained above and the speed optimization cannot satisfy the stricter trajectory.

II. OPS combined with Speed Optimization

Under this scenario (Figure 4) we applied both speed optimization and OPS, the results are quite similar with the former scenario. More precisely, in Figure 4 it is observed that CIIs from 2022 until 2027 are the same, as the installation of OPS was performed in 2028 during the drydock period. The trajectory ceased in 2028 as well but the CII attained that year is 0.5% lower compared to the former scenario. This fact indicates that the OPS offer minor benefit to the improvement of CII as the percentage of improvement refers to the Auxiliary Engine fuel consumption which consumes an insignificant percentage of the total fuel consumption.

Figure 4:IMO-Low_ops v. IMO-Low



(source: author)

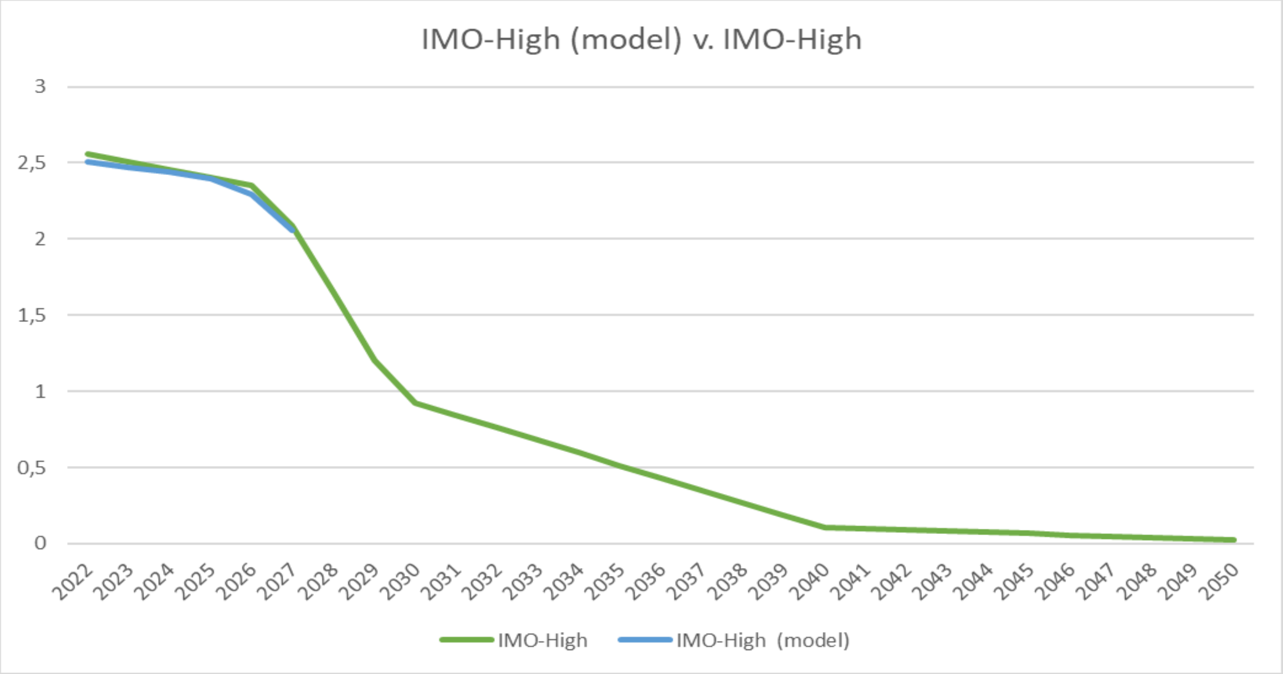
Improvements are also observed regarding the fuel savings as a percentage to the total revenues for the period from 2022 until 2027 the percentages are the same as those referred previously, but in 2028 a 17.4% difference has been observed compared to 2021 levels. Concerning the fuel costs a decrease of approximately 37.4% was also estimated, fact which also indicates that the OPS has a minor contribution to the fuel consumption and consequently to emissions.

4.4.2 Scenario 2: IMO – High

I. Speed Optimization

The model's findings, when operated under Scenario 2 and utilizing only speed optimization as a method for enhancing efficiency, indicate that the goals laid out in the IMO-Low (as seen in Figure 2) can only be achieved until the year 2027. After this year, additional measures need to be introduced to maintain the desired level of efficiency. The speed appears to fluctuate between 9 and 10.5. Another significant observation is that fuel savings, which translate to revenue, range from 3.2% in 2022 (the initial year of speed optimization implementation) to 5.9% by 2025, and show a marked increase to 14.9% by 2027 when compared to the base year. With regard to the yearly total fuel expenses, there's a decline varying from 8.1% in 2022 to a substantial 33.8% by 2028. This decrease is notable, given the operational costs associated with this particular vessel.

Figure 5: IMO-High (model) v. IMO-High



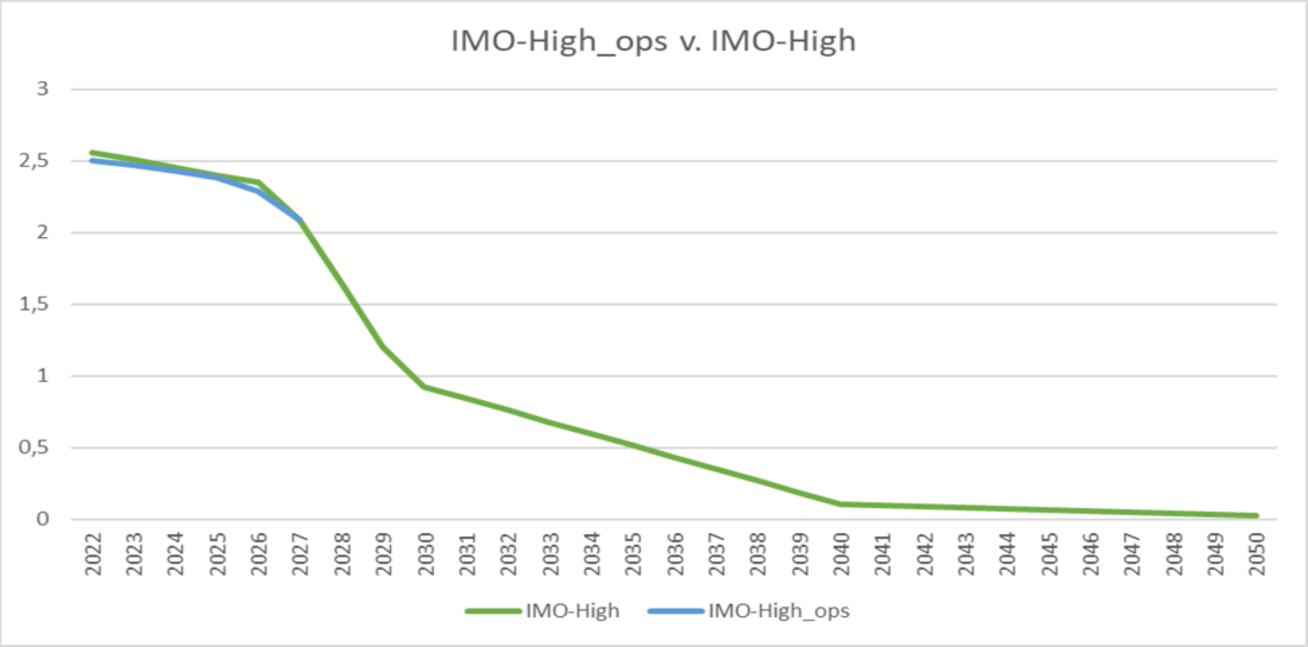
(source: author)

The chart shown in Figure 5 illustrates the paths followed by CIIs (Carbon Intensive Industries) in the IMO-Low scenario as derived from the model, compared to the trajectory of IMO-Low. The diagram reveals that the trajectory in the IMO-Low (model) scenario comes to a halt by 2027, as mentioned earlier. Additionally, it is evident that the speed optimization fails to meet the more stringent trajectory requirements.

II. OPS combined with Speed Optimization

In the present scenario (depicted in Figure 6), we implemented both speed optimization and OPS (Onboard Power Supply). The outcomes are slightly different compared to the previous scenario. Specifically, in Figure 6, it can be observed that CIIs from 2022 to 2026 doesn’t follow the same trajectory, as the installation of OPS took place in 2024 as exemption. Similarly, the trajectory comes to a halt in 2027, but the CII achieved in that year is 2% higher compared to the previous scenario, due to different optimization of speed in this specific year. This indicates that OPS provides only a minor advantage in improving CII, as the percentage improvement relates to the fuel consumption of the Auxiliary Engine, which constitutes an insignificant portion of the total fuel consumption. Another observation is that the higher impact is arising by the speed optimization due to higher effect on the Main Engines fuel consumption.

Figure 6: IMO-High_ops v. IMO-High



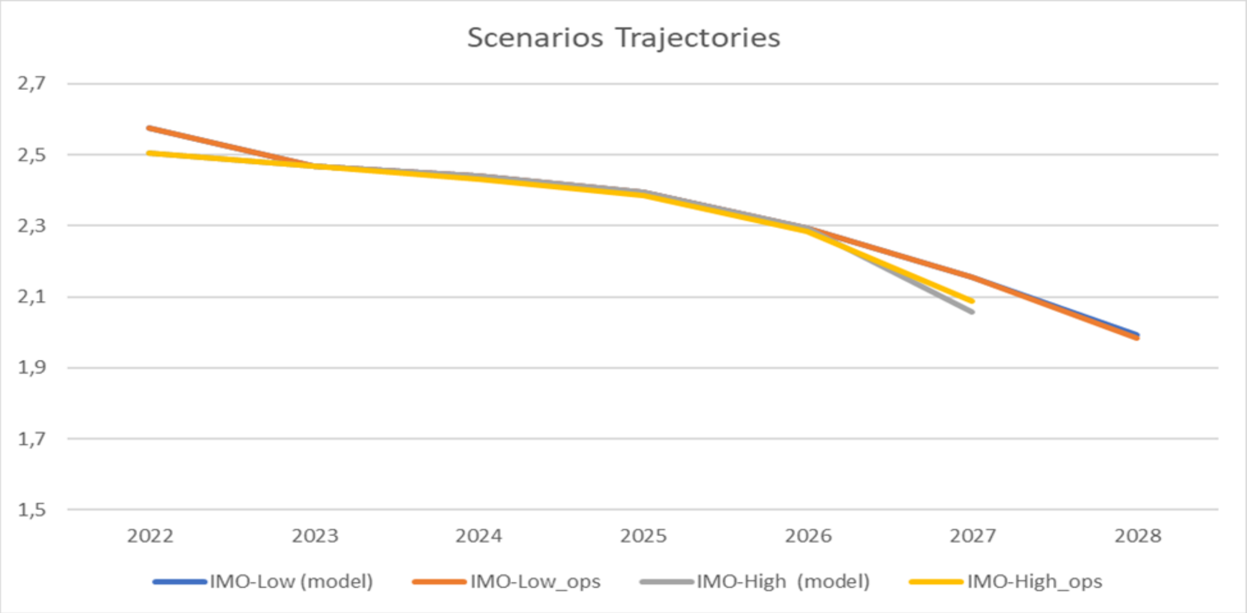
(source: author)

Significant improvements are evident in terms of fuel savings as a percentage of total revenues. Another noteworthy finding is the significant variation in fuel savings, which directly impact revenue and are not consistent with the previously mentioned figures under the scenario IMO-High (model). The savings start at 3.2% in 2022, the first year of implementing speed optimization, and gradually increase to 6% by 2025. Subsequently, there is a notable surge to 14% by 2027 when compared to the base year. Additionally, fuel costs are estimated to decrease by approximately 32%. This further suggests that the contribution of OPS to fuel consumption and, consequently, emissions is relatively minor.

4.5 Scenarios Comparison

In this section, we will conduct a comparative analysis of the four scenarios that have been developed. The basis for this comparison will be the efficiency measures associated with each scenario.

Figure 7: Scenarios Comparison



(source: author)

4.5.1 IMO-Low v. IMO-High

An in-depth comparison of two scenarios (IMO-Low and IMO-High) of speed optimization as an efficiency measure for a specific vessel offers significant insights. In Scenario, speed optimization achieves the IMO-Low targets until 2028, suggesting that this single measure is viable for about six years. However, beyond 2028, this approach will need to be supplemented with other strategies to maintain the required efficiency levels.

The speed variation in Scenario 1 is quite narrow, ranging from 10 to 10.5, indicating that the vessel's performance is perhaps already near optimal within these parameters. Thus, it may not allow for significant further improvements without involving additional measures. On the financial front, revenues from fuel savings display a positive, albeit gradual, growth over time. They start from 1.5% in 2022 and rise to 12.2% by 2027. Despite the increase, the pace of revenue growth might not align with long-term financial targets.

Moreover, the vessel's annual total fuel costs decrease steadily from 4% in 2022 to 28.3% in 2027, a reduction that could positively impact the vessel's operating expenses. However, without introducing other efficiency strategies, these savings might not extend beyond 2027.

IMO-High provides a contrast. Although the efficiency measure achieves the targets until 2027—a year less than in IMO-Low—the speed variation range is broader, from 9 to 10.5. This wider range could potentially allow for further optimization and improvements, enhancing overall performance.

Fuel savings start at a higher point of 3.2% in 2022 and increase to 14.9% by 2027. This faster growth rate implies better short-term financial gains. However, this scenario may demand the implementation of other efficiency measures earlier than Scenario 1—by 2027—to sustain efficiency levels. The annual total fuel cost reduction is more pronounced in Scenario 2, ranging from 8.1% in 2022 to 33.8% in 2028. While the savings are substantial, similar to IMO-Low, sustaining them will likely require other efficiency measures post-2027.

4.5.2 IMO-Low_ops v. IMO-High_ops

In comparing the two scenarios, both employing speed optimization and Onshore Power Supply (OPS), we can identify some crucial differences. IMO-Low_ops, integrates OPS during the drydock period in 2028, resulting in Carbon Intensity Indicators (CIIs) from 2022 to 2027 identical to those in the scenario IMO-Low. The trajectory ends in 2028, similar to the earlier situation, but the CII achieved this year is marginally lower by 0.5%. This disparity signals that OPS offers minor enhancements to CII, primarily affecting the Auxiliary Engine's fuel consumption, a small fraction of the total fuel consumption. Fuel savings, expressed as a percentage of total revenues, from 2022 to 2027 align with those of the previous scenario, but by 2028 a 12.2% increase is noticed compared to 2021 levels. Meanwhile, fuel costs decrease by approximately 28.3%, further indicating OPS's minimal impact on fuel consumption and consequent emissions.

Contrastingly, IMO-High_ops, implements OPS in 2024. This change disrupts the CII trajectory from 2022 to 2026, resulting in a 2% higher CII in 2027 compared to IMO-Low_ops due to variable speed optimization. Similar to Scenario 1, IMO-Low_ops contributes modestly to CII improvement. A significant deviation arises in fuel savings as a percentage of total revenues, starting at 3.2% in 2022 and rising to 6% by 2025, before a substantial increase to 14% by 2027. Meanwhile, fuel costs are reduced by roughly 32%, reinforcing OPS's limited influence on fuel consumption and associated emissions. Therefore, while both scenarios employ speed optimization and OPS, varying implementation times, and optimization degrees result in different CIIs, fuel savings, and fuel cost reductions, underscoring the need for strategic deployment of these measures.

5. Conclusion

In conclusion, this thesis aimed to investigate the impact of onshore power supply (OPS) on the Carbon Intensity Indicator (CII) of a bulk carrier vessel trading between Canada and China. The research questions focused on how OPS affects the CII, whether OPS adoption alone can meet international targets, and the benefits and costs for shipowners and operators considering fuel savings.

The study utilized operational data from a specific vessel, MV BulkCarrier-N1, obtained from voyage reports and performance monitoring databases. The data covered the period from January 2021 to December 2022, including information on vessel speed, port calls, fuel consumption, CO2 emissions, and GHG emissions.

Two scenarios were developed based on International Maritime Organization (IMO) trajectories, namely IMO-Low and IMO-High. The IMO-Low scenario aimed for a 40% reduction in CIIs by 2030 and a 70% reduction by 2050 compared to 2008 levels. The IMO-High scenario incorporated more ambitious targets proposed by the IMO, including a 65% reduction in CO2 emissions by 2030, a 96% reduction by 2040, and achieving net-zero CO2 emissions by 2050.

The study employed a model developed in Python to assess the impact of OPS and speed optimization on CIIs and fuel savings. The model included inputs such as the vessel's drydocking schedule, capital and operating expenses for OPS, annual revenues, speed ranges, and fuel prices CII targets. The model results were compared across the four scenarios: IMO-Low, IMO-Low with OPS, IMO-High, and IMO-High with OPS.

Under the speed optimization measure alone, the results showed that the IMO-Low targets could be met until 2028, while the IMO-High targets could be achieved until 2027. However, additional measures would be required beyond those years to maintain the desired efficiency levels.

When OPS was combined with speed optimization, the impact on CIIs was found to be minimal. The installation of OPS during the vessel's drydocking period did not significantly improve CIIs, as the fuel consumption of the auxiliary engine, which OPS primarily affects, constituted a small portion of the total fuel consumption. Nonetheless, OPS did contribute to some fuel savings, with varying percentages based on the scenarios.

Comparing the two trajectories, IMO-Low and IMO-High, it was observed that the latter provided higher short-term financial gains in terms of fuel savings and reductions in total fuel costs. However, sustaining these gains beyond 2027 would likely necessitate the implementation of additional efficiency measures.

In conclusion, the findings of this thesis highlight the complex relationship between OPS adoption, speed optimization, and the achievement of international emission reduction targets. While OPS and speed optimization can contribute to some improvements in fuel efficiency and emissions reduction, they may not be sufficient to meet more ambitious targets alone. The implementation of additional measures and strategies will be necessary to achieve long-term sustainability in the shipping industry.

Proposed areas for future research encompass the examination of biofuel implementation as a short-term measure and vessel's retrofit for alternative fuels such as green methanol, ammonia etc. as a sustainable long-term solution, with the objective of achieving global emission reduction targets.

6. References

Aksoyoglu, S., Prévôt, A. and Baltensperger, U. (2015). Contribution of ship emissions to the concentration and deposition of air pollutants in Europe. Atmospheric Chemistry and Physics Discussions, [online] 15(21), pp.30959-30986.

Alnes, O., Eriksen, S. and Vartdal, B.-J. (2017) 'Battery-powered ships: A class society perspective', IEEE Electrification Magazine, 5(3), pp. 10–21. doi:10.1109/mele.2017.2718823.

Ballini, F. and Bozzo, R. (2015) 'Air pollution from ships in ports: The socio-economic benefit of cold-ironing technology', Research in Transportation Business &amp; Management, 17, pp. 92–98. doi:10.1016/j.rtbm.2015.10.007.

Cames, M., Graichen, J., Siemons, A., & Cook, V. 2015. Emission reduction targets for international aviation and shipping. European Parliament. Retrieved from http://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/ IPOL_STU(2015)569964_EN.pdf

Christodoulou, A. and Cullinane, K. (2020) 'Potential for, and drivers of, private voluntary initiatives for the decarbonisation of Short Sea Shipping: Evidence from a Swedish ferry line', Maritime Economics &amp; Logistics, 23(4), pp. 632–654. doi:10.1057/s41278-020-00160-9.

Clarksons; SIN (2023) Shipping Intelligence Network. Available at: https://sin.clarksons.net/.

Dalsøren, S.B. et al. (2009) 'Update on emissions and environmental impacts from the international fleet of ships: The contribution from major ship types and ports', Atmospheric Chemistry and Physics, 9(6), pp. 2171–2194. doi:10.5194/acp-9-2171-2009.

DNV GL (2023) Decarbonize shipping, DNV. Available at: https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/seemp.html.

EPA (2023) Shore Power Technology Assessment at U.S. Ports, EPA. Available at: https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports.

European Commission (2022) Ten-T revision, Mobility and Transport. Available at: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t/ten-t-revision_en.

European Commission (2023) Reducing emissions from the shipping sector. Climate Action. Available at: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en.

European Commission (2023) FuelEU maritime initiative: Provisional agreement to decarbonise the the maritime sector, European Commission. Available at: https://www.consilium.europa.eu/en/press/press-releases/2023/03/23/fueleu-maritime-initiative-provisional-agreement-to-decarbonise-the-maritime-sector/.

European Parliament (2014) Directive 2014/94/EU of the European Parliament and of the council . Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094.

Glomeep (2023) Technology groups. Available at: https://glomeep.imo.org/technology-groups/.

ICS Shipping. (2016). European Union MRV Regulation. [online] Available at: http://www.icsshipping.org/docs/default-source/resources/ics-guidance-on-eu-mrv.pdf?sfvrsn=10

IHS (2023) IHS , Index - home. Available at: https://maritime.ihs.com/EntitlementPortal/Home/Index?autoLogin=True.

IMO (2016) IMO data collection system (DCS), International Maritime Organization. Available at: https://www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx.

IMO, 2020. Fourth Greenhouse Gas Study 2020, International Maritime Organization (IMO). Available at: https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

IMO. (2023). Energy efficiency and the reduction of GHG emissions from ships. [online] Available at: http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx

IMO (2023) Fourth Greenhouse Gas Study 2020, International Maritime Organization. Available at: https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.

IMO (2023) EEXI and CII - ship carbon intensity and rating system, International Maritime Organization. Available at: https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx.

Innes, A. and Monios, J. (2018) 'Identifying the unique challenges of installing cold ironing at small and medium ports – the case of Aberdeen', Transportation Research Part D: Transport and Environment, 62, pp. 298–313. doi:10.1016/j.trd.2018.02.004.

LR (2023) EU MRV Regulation, Lloyd's Register. Available at: https://www.lr.org/en/eu-mrv-regulation/.
Merk, O. (2014) 'Shipping emissions in ports', International Transport Forum Discussion Papers [Preprint]. doi:10.1787/5jrw1ktc83r1-en.

Martínez-López, A., Romero, A. and Orosa, J.A. (2021) 'Assessment of cold ironing and LNG as mitigation tools of short sea shipping emissions in port: A Spanish case study', Applied Sciences, 11(5), p. 2050. doi:10.3390/app11052050.

Port of Vancouver (2023) Shore Power, Port of Vancouver. Available at: https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/climate-action-at-the-port-of-vancouver/shore-power/.

Progiou, A.G. et al. (2021) ‘Air Pollutant Emissions from Piraeus Port: External costs and air quality levels’, Transportation Research Part D: Transport and Environment, 91, p. 102586. doi:10.1016/j.trd.2020.102586.

Seddiek, I.S. (2015) ‘Two-step strategies towards fuel saving and emissions reduction onboard ships’, Ships and Offshore Structures, 11(8), pp. 791–801. doi:10.1080/17445302.2015.1070945.

Seddiek, I.S. (2015) ‘Two-step strategies towards fuel saving and emissions reduction onboard ships’, Ships and Offshore Structures, 11(8), pp. 791–801. doi:10.1080/17445302.2015.1070945.

Sofiev, M. et al. (2018) ‘Cleaner fuels for ships provide public health benefits with climate tradeoffs’, Nature Communications, 9(1). doi:10.1038/s41467-017-02774-9.

Tseng, P.-H. and Pilcher, N. (2015) ‘A study of the potential of shore power for the Port of Kaohsiung, Taiwan: To introduce or not to introduce?’, Research in Transportation Business &amp; Management, 17, pp. 83–91. doi:10.1016/j.rtbm.2015.09.001.

Transport & Environment (2022) Fueleu Maritime. Available at: https://www.transportenvironment.org/wp-content/uploads/2021/08/FuelEU-Maritime.pdf.

UNCTAD (2022) Merchant fleet, UNCTAD Handbook of Statistics 2022. Available at: https://hbs.unctad.org/merchant-fleet/.

US Congress (2022) Text - H.R.8336 - 117th Congress (2021-2022): Clean Shipping Act of 2022. Available at: https://www.congress.gov/bill/117th-congress/house-bill/8336/text?r=7&s=1.

Yu, J., Voß, S. and Tang, G. (2019) ‘Strategy development for retrofitting ships for implementing shore side electricity’, Transportation Research Part D: Transport and Environment, 74, pp. 201–213. doi:10.1016/j.trd.2019.08.004.

Zis, T. et al. (2014) ‘Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at Ports’, Maritime Economics &amp; Logistics, 16(4), pp. 371–398. doi:10.1057/mel.2014.6.

Zis, T.P.V. (2019) ‘Prospects of cold ironing as an emissions reduction option’, Transportation Research Part A: Policy and Practice, 119, pp. 82–95. doi:10.1016/j.tra.2018.11.003.