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Evaluation ofthe implementation in the Chilean domestic fleet of energy efficiency, ship energy efficiency management and carbon intensity indicator, according to the rules established by the International Maritime Organization

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EVALUATION OF THE IMPLEMENTATION IN THE CHILEAN DOMESTIC FLEET OF ENERGY EFFICIENCY, SHIP ENERGY EFFICIENCY MANAGEMENT AND CARBON INTENSITY INDICATOR, ACCORDING TO THE RULES ESTABLISHED BY THE INTERNATIONAL MARITIME ORGANIZATION

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A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of Master of Science in Maritime Affairs

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

(Signature):

(Date): Malmö, September 26th, 2023

Supervised by: Professor Dr. Aykut I. Ölçer

Supervisor's affiliation: …………………………..

NB The supervisor's signature is not required.

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Abstract

Title of Dissertation: **Evaluation of the implementation in the Chilean domestic fleet of Energy Efficiency, Ship Energy Efficiency Management and Carbon Intensity Indicator, according to the rules established by the International Maritime Organization.**

Degree: **Master of Science**

The Maritime Community has been working on the prevention of air pollution from ships since 1997 with the application of MARPOL Annex VI, and today, the aim includes GHG emissions reduction through decarbonisation and energy efficiency. However, all those initiatives are implemented for international shipping, leaving the decarbonisation of domestic shipping as a task for each country.

Chile, as a Member State of the International Maritime Organisation, has had part of its national framework all regulations of MARPOL; nevertheless, in the domestic environmental aspect, there is a lack of protocols to reduce GHG emissions from cabotage vessels. In consequence, the Author is convinced of the necessity to implement any framework over the national reality to address national maritime transport to become a green energy industry, in line with the efforts made by the entire international community to tackle climate change.

Consequently, this research presents an evaluation of the implementation of the regulations established in Chapter Four of MARPOL Annex VI in the domestic and inland merchant fleet with the objective of reducing GHG emissions generating for this sector to achieve net zero emissions by 2050, which is the aim defined by the national framework.

Accordingly, the proposal will describe a literature review related to international studies, regulations, experience, and national aspects interesting to analyse. Then, it will present a characterisation of the Chilean merchant fleet to understand how the maritime industry works. Another Chapter will study some cases of EEDI, EEXI and CII applications and how the impact of the results can be improved with the use of the technical and operational solutions available in the market. The next chapter will offer a roadmap proposing an action plan to achieve the implementation evaluated in this research, describing some barriers and constraints expressed by experts who work in the industry.

Finally, it will show some conclusions and recommendations in the case of the maritime administration of Chile decided to develop this new environmental regulatory requirement.

KEYWORDS: Decarbonisation, GHG emissions, Energy-efficiency, Domestic Shipping.

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List of Abbreviations

CII	Carbon Intensity Indicator
C_F	Conversion factor between fuel consumption and CO_2 emission
CO_2	Carbon Dioxide
CPP	Controlled Pitch Propeller
DIRECTEMAR	General Directorate of Maritime Territory and Merchant Marine of Chile
DCS	Data Collection System
DNV	Det Norske Veritas Classification Society
DWT	Deadweight of the ship
EE	Energy Efficiency
EEDI	Energy Efficiency Design Index
$EEDI_{Att}$	Energy Efficiency Design Index Attained
$EEDI_{Req}$	Energy Efficiency Design Index Required
$EEDI_{Ref}$	Energy Efficiency Design Index Reference
EEXI	Energy Efficiency Existing Ship Index
$EEXI_{Att}$	Energy Efficiency Existing Ship Index Attained
$EEXI_{Req}$	Energy Efficiency Existing Ship Index Required
EGR	Exhaust Gas Recirculation
EPL	Engine Power Limitation
FPP	Fixed Pitch Propeller
GHG	Greenhouses Gasses
GT	Gross Tonnage
IMO	International maritime Organization
LNG	Liquified Natural Gas
LBG	Liquid Biogas
LWT	Lightweight of the ship

MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee
NDC	Nationally Determined Contribution
NM	Nautical Miles
NOx	Nitrogen Oxides
ODS	Ozone Depleting Substances
RO	Recognized Organization
SCR	Selective Catalytic Reduction
SDG	Sustainable Development Goals
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Certified Specific Fuel Consumption
SHaPoLi	Shaft Power Limitation
SOx	Sulphur Oxides
VOC	Volatile Organic Compound
UN	United Nations
WHR	Waste Heat Recovery System

Chapter 1. Introduction

1.1 Background.

Over the last three decades, the International Maritime Organization (IMO) has been taking several measures to improve environmental issues regarding climate change and emissions from ships, including measures the better quality of fuels, new standards for engines, and improvements in efficiency on board, among other requirements for vessels according with International Law frameworks (MARPOL Annex VI, 1997).

On the other hand, the IMO agreed with the Maritime Community on applying the Initial Strategy for reducing Greenhouse gas emissions from ships with two main objectives. The strategy started its application in November of 2022 with different levels of ambitions. It is found to decrease the GHG emissions from ships by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to the levels registered in 2008 (MEPC, 2018). Objectives were modified in the last revision of 2023 to achieve a more ambitious challenge, such as becoming the maritime shipping net zero by 2050 and increasing up to 40% of the Carbon Dioxide (CO_2) emissions by 2030 (IMO, 2023).

Despite all measures taken by IMO until today, the Fourth IMO GHG Study revealed that the GHG emissions of the total shipping sector, including international, domestic, and fishing, contributed with an increment of 9.6% from 2012 to 2018, which is equivalent to growth from 962 million tonnes in 2012 to 1,076 in 2018. In relation to the projection of emissions from Ships, in the same study, it is possible to observe an increase in the projections from about 90% of 2008 emissions in 2018 to 90 - 130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios (IMO, 2020).

Notwithstanding, IMO has been criticised for moving too slowly regarding developing efficient GHG regulation (Bach et al., 2023), which shows the need to improve the ambition of the Strategy, increasing the measures taken until today.

On the other hand, in the Final Report of the Study on the Decarbonization of the Belgian Maritime Sector for small vessels ($<$ 5000 GT) (Boschmans et al., 2021), it is possible to note how it was demonstrated the importance of covert the emissions of domestic and inland maritime shipping, which also contributes with the GHG emissions to the atmosphere. For example, in the case of Belgium, its small domestic vessels generated 401 kilotons of CO_2 in 2018; this amount is equivalent to 0.48% of Belgium's total CO_2 emissions. They captured those vessels that are currently largely exempt from decarbonising legislation.

To succeed in the task of increasing the efforts to achieve the level of ambition in 2030 and 2050 on the reduction of GHG emissions from vessels, this research will evaluate the implementation in the Chilean domestic and inland vessels fleet of the Energy Efficiency Index (EEDI – EEXI), Ship Energy Efficiency Management Plan (SEEMP) and Carbon Intensity Indicator (CII) for Ships, according to the rules established by the Organization in Chapter 4, Annex VI of the International Convention for the Prevention of Pollution from Ships.

1.2 Problem Statement.

Currently, the primary law to deal with the climate change effects generated by vessels is Annex VI of the MARPOL, modified during the last years according to the current requirements of science and society.

Regardless of having this excellent tool to manage GHG emissions from ships, there is an environmentally unprotected maritime sector that includes all vessels on cabotage services for every country because MARPOL is only applicable to

International Maritime Transportation; therefore, all sorts of domestic and inland vessels are excluded from its regulations.

Chile has more than 400 vessels dedicated to the cabotage between different places in the country, and there is no specific national framework for reducing GHG emissions from this kind of internal transportation. For that reason, this research will try to understand how to apply the technical and operational measures developed by IMO entering into force by the implementation of Chapter Four of MARPOL Annex VI for vessels under the Chilean Flag Statement to contribute to the international effort to cope climate change to discover the barriers and solutions for such implementation and attainable improvements for the energy efficiency of ships.

1.3 Motivation.

The motivation is related to the lack of regulations for GHG emissions reduction for domestic and inland vessels worldwide, especially in Latin America, where no country has any initiative to mitigate or stop the pollutant emissions from ships.

Moreover, it is essential to mention that the national contribution of Chile to climate action includes the implementation of a Climate Change Framework Law to be Net zero emission by 2050; in consequence, the maritime transportation sector should have a strategy to be part of the national effort bringing the necessary decrease to achieve the final goal.

1.4 Aims and Objectives

The aims of this research are part of humankind's effort to stop the global warming condition of the world, where GHG emissions and their mitigation play a crucial role in the measures taken by all sectors of society. Certainly, maritime transport is part of human society; therefore, each labour conducted to decrease GHG emissions should include vessels.

Although IMO has established an international framework to cover the pollution from ships, this is only applicable to International Shipping. Therefore, it is relevant to assess how to implement regulations for inland and domestic vessels in every country as a national contribution.

This research aims to evaluate if it is possible to perform the current maritime framework to reduce GHG emissions from ships over the Chilean Domestic Fleet to comply with national and international environmental efforts and live up to what the planet needs.

1.4.1 Specific Objectives.

- To describe the rules established in Chapter 4, Annex VI of the MARPOL Convention related to the EEDI AND EEXI, SEEMP and CII for Ships.
- To identify the fleet of domestic and inland vessels of Chile in which rules can be applied.
- To apply the rules over domestic and inland vessels of Chile.
- To propose an action plan according to the outcomes obtained in the evaluation.

1.4.2 Significance of the Study.

The research is an example of applying an international maritime environmental framework over a domestic fleet to reduce GHG emissions generated by vessels. Then, according to the outcomes and barriers existing in the Chilean reality, it will propose solutions that improve the index of efficiency and carbon intensity, providing a roadmap for future policies and implementation. Overall, this research allows us to put over the table every possible constraint that today could make it challenging to fulfil environmental maritime regulations at the national level.

1.5 Research and Questions.

Based on the objectives outlined, it is possible to define the following research questions:

a) Which energy efficiency rules are established in Chapter 4, Annex VI of the MARPOL Convention?
b) How do we apply those rules over ships?
c) How domestic and inland vessels of the Chilean cabotage fleet can be involved in the frameworks of the energy efficiency rules of Chapter 4, Annex VI of MARPOL?
d) What are the barriers and benefits to compliance with the requirements defined in the MARPOL Annex VI?

1.6 Hypothesis.

The following hypothesis was defined for this research:

Is it possible to apply the International Maritime Environmental framework to the Chilean domestic fleet to reduce GHG emissions from ships as a national contribution to the global effort to stop or mitigate climate change?

1.7 Key Assumptions and Limitations.

For the development of this research, the following key assumptions and potential limitations will be considered.

1.7.1 Key Assumptions

a) The measures of the Initial IMO Strategy on reducing GHG emissions from ships seem insufficient to reduce GHG emissions from ships.
b) There are an essential number of domestic and inland vessels to which the rules of MARPOL can be applied to improve due to projections of GHG emissions increase over the years, though with the implementations of the current measures established.
c) It is potentially possible to implement for domestic and inland vessels the EEDI and EEXI, SEEMP and CII for Ships, according to the rules established by the Organization in Chapter 4, Annex VI of the MARPOL Convention, to increase the effort to reduce GHG emissions from vessels.

1.7.2 Potential Limitations.

a) The data collected from the Maritime Administration basis could be incomplete. In that case, it will be necessary to ask stakeholders or ownership.
b) It could be necessary to adjust the rules and regulations of MARPOL with the objective of implementing them over domestic and inland vessels.
c) The final purpose of this research should be presented and managed with the stakeholders and ownership involved to avoid possible rejections and against positions.
d) In the future, IMO Strategy will be updated and improved with amendments and new regulations; for that reason, it will be necessary to reassess policies applied by the Chilean Maritime Administration constantly.

1.8 Scope.

The Chilean Merchant Fleet involves several types of vessels that are part of National and International shipping; however, this research only considers the assessment of inland and domestic fleets to evaluate the international framework's application for GHG emissions reductions. This scope engages cases of study that calculate the energy efficiency index and carbon intensity indicator for some specific type of ships, which are the majority in terms of the number of the Chilean Ships Register.

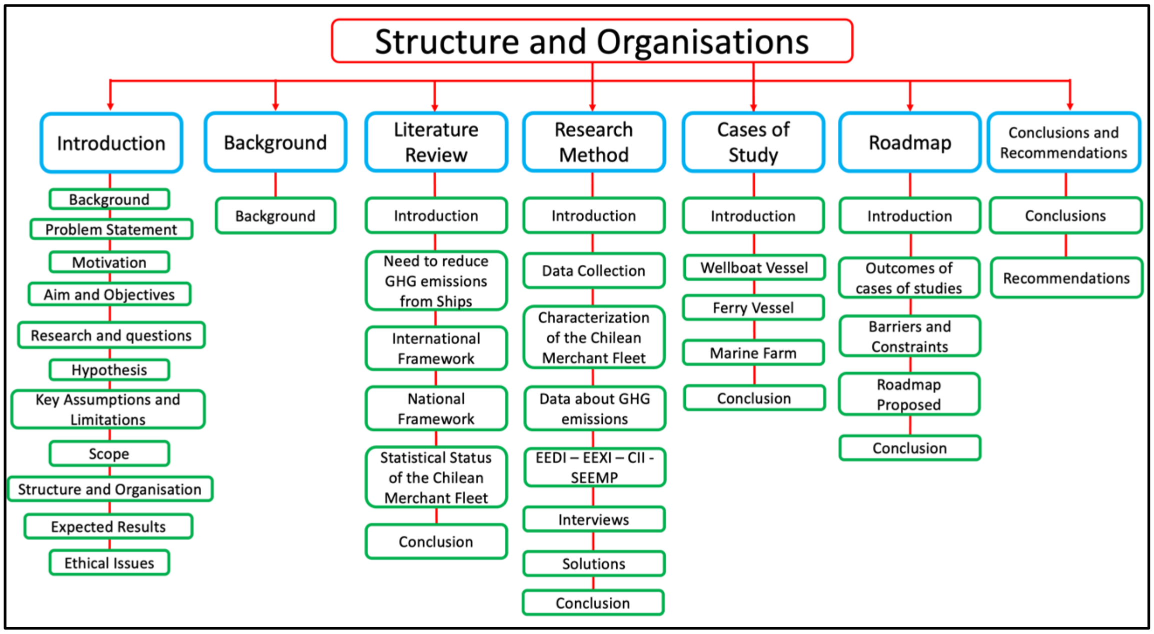
Furthermore, some technical and operational measures will be proposed to improve the results obtained in the cases analysed according to their efficiency index and carbon intensity indicators, reducing the values of emissions reached.

1.9 Thesis Structure and Organization.

This research will be developed through seven chapters based on achieving the expected results. This line of the explanation is considered an introductory Chapter one with the description of background, problem statement, motivation, aim and objectives, specific objectives, research questions, hypothesis, key assumptions, scope, structure, expected results and ethical issues. Then, Chapter Two will analyse the background. The next chapter will examine the literature review to follow Chapter Three's research methods. Chapter Four will evaluate the Cases of Studies applied to different types of vessels. Chapter Six will assess the technical and operational measures to reduce GHG emissions according to the results obtained in the Study Cases, and finally, Chapter Seven incorporate the conclusions and recommendations of the research.

The following figure shows the Research Process Workflow.

Figure 1. Research Process Workflow.



Source: Author, 2023.

1.10 Expected Results.

The expected results of this research proposal are as follows:

a) Understanding of the rules indicated in Chapter 4, Annex VI of the MARPOL Convention related to the EEDI and EEXI, SEEMP and CII for Ships.
b) Comprehensive analysis of the application of the rules over domestic and inland vessels of the Chilean Merchant fleet.
c) Quantifying the possible reduction of GHG emissions from vessels in which rules will be applied.
d) Recommendation for the National Action Plan for the Chilean Maritime Administration in the use of Chapter 4 of Annex VI of the MARPOL Convention

over domestic and inland vessels to improve the reduction of GHG emissions from ships.

1.11 Ethical Issues.

This research will consider the following ethical issues:

a) Informed consent of all participants in the research and data collected. Every person involved will be informed of the purpose of the study and will be required to provide the necessary consent before participating.
b) The confidentiality of the information and participants will be ensured by anonymous data collection.

Chapter 2. Background

Chile's Maritime Industry is composed of more than four hundred vessels, over 400 GT, that sail for more than three thousand kilometres of coast, connecting cargo, industries and people and generating the communications conditions needed to support cities and their habitats. This fleet includes ships dedicated to International Shipping and Cabotage vessels; however, a significant percentage of vessels is constituted of domestic and inland vessels.

Regardless of the current global warming situation due to accelerated climate change, the international maritime community has developed an environmental framework to contribute to climate action plans throughout the IMO and their member states; nevertheless, those regulations apply only to vessels involved in international trading aiming to reduce around 3% of GHG emissions produced by this industry (IMO, 2020). The legal structure proposed technical and operational measures to mitigate the pollutant emissions that are suitable and efficient, and it is possible to attain the first outcome next year with the first CII classification standard for ships. The way selected to implement this strategy is the International MARPOL, specifically Annex VI, “Regulations for the Prevention of Air Pollution from Ships”, with the introductions of new regulations in Chapter Four associated with the Carbon Intensity and Energy Efficiency Management.

Nevertheless, according to international law, which rules IMO, MARPOL Annex VI apply only to International Shipping, letting each country develop its own environmental regulations for GHG emissions from ships. If we read the literature review about national contributions corresponding to tackling pollutant emissions from domestic vessels, it is difficult to find strategies or plans established by developing countries, even though it is challenging among developed countries because national frameworks should be elaborated and implemented in conformity with each national reality.

In the case of Chile, last year, it entered into force a new environmental law that was enacted (EMC, 2022), in general terms, the country should be net zero by 2050, involving all sectors in this task and counting the domestic and inland vessels. The problem lies in the fact that there is no specific statute or policy for this sector; therefore, the application is uncertain, as well as its results.

Taking into account this problem, besides the experience attained by IMO during the development of the GHG emissions regulations, it seems to be a good way to go forward; the implementation of the MARPOL Annex VI protocol over the Chilean cabotage fleet to reduce the GHG emissions emitted by their vessels, adapting those rules to the cases of Chile and its many types of ships enclosed in the industry, such as General Cargo, TUG, Wellboats, Containers, Ferries, among others.

Certainly, the implementation should be analysed and evaluated, which is the main objective of this research being presented in the following chapters. For that purpose, some cases of study where concepts such as EEXI, EEDI and CII will be calculated over some types of ships with the intention of evaluating if those examples can achieve the MARPOL standard or not. Moreover, it will examine barriers and constraints comprehended in a probable implementation, taking into account the experience of some countries which established internal frameworks and some opinions of experts from the Maritime Industry. Finally, it will be proposed a roadmap with the outcomes obtained to implement the code mentioned as part of the national maritime framework.

Chapter 3. Literature Review

3.1 Introduction

Nowadays, our planet is trespassing a climate warming situation because of the increment of GHG emissions from all kinds of sectors. This increment became evident in the 19th century with the rapid development of the Industrial Revolution, which required huge amounts of energy to produce their material and services using fossil fuels as the best source at that moment, no matter the environmental impact.

This chapter will present the reasons for reducing GHG emissions from vessels represented in international studies and agreements and explain how they were achieved. Besides, some countries have introduced their own environmental regulations as national contributions to climate action, including the Chilean reality with a description of its climate change policy and how it shaped its domestic maritime fleet.

3.2 Need to reduce GHG Emissions from Ships.

In the following paragraphs, it will be presented the international studies and framework that explain and fundament the reasons to address GHG emissions from ships leading to global warming produced by climate change.

3.2.1 Second IMO Greenhouse Gas Study 2009.

The Second IMO Greenhouse Gas Study was presented in 2009, nine years after the first report. This report presents several aspects related to the pollution produced by international shipping and its estimated impacts on the climate.

Furthermore, it is possible to check a comparison of emissions between maritime transport and other transport modes.

In other terms, this report provides a good starting point to evaluate the technologies and policy options for the GHG reduction that existed more than ten years ago.

Nevertheless, the main consideration to take into account is the fact that the total estimated emissions of CO_2 from shipping were equal to 1,046 million tonnes in 2007, equivalent to 3.3% of the global emissions during the same year. Besides, the input in the emission of CO_2 of international shipping for the global emissions is 2.7% with 870 million tonnes. Those numbers allow us to understand how GHG emissions from ships can support climate change, even if it is low compared with other industries.

At the same time, this study develops many alternatives to improve the number of emissions shown before using efficiency as the key element in order to stop or mitigate climate change, taking special interest because the projected scenarios presented by this report demonstrate that CO_2 emission would increase by 2050 becoming between 12% and 18% of the global total, as long as nothing happened to improve the current situation (International Maritime Organization [IMO], 2009).

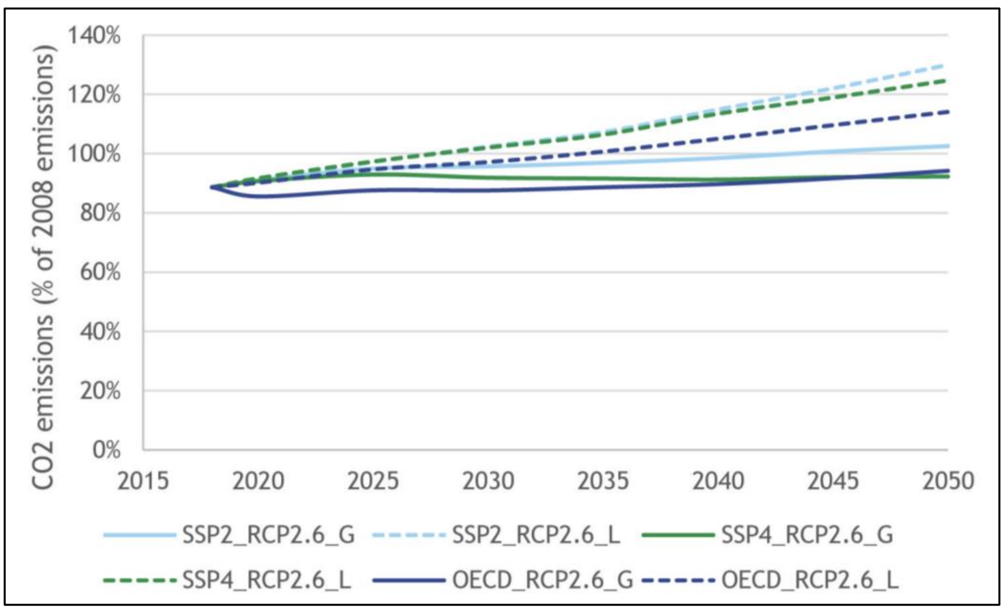
3.2.2 Fourth IMO Greenhouse Gas Study 2020.

The fourth and the last IMO Greenhouse Gas Study presents details of the emission inventory from vessels, which is a similar term to the second study, but now there are particular features such as a summary of emissions related to its kind, projection, comparison with other years, carbon intensity performance, among other that are important to consider for the purpose of this report.

In some of the tables presented, it is possible to observe how CO_2 emissions increased between 2012 and 2018 (IMO, 2020), demonstrating a tendency to grow, even with the implementation of some measures over ships, such as SEEMP, for example. Such a matter is essential if it considers the need to decrease GHG emissions due to the commitment established in many international agreements and the IMO Strategy on reducing GHG emissions from ships adopted in 2018.

The projection shown in the study reflects a potential increase from 90% to 130% of 2008 emissions by 2050 if the economic and energy scenarios do not change. Additionally, emissions projection could be higher depending on the economic growth rate, which logically is supported by the support and demand law.

Figure 2. Projections of maritime ship emissions as a percentage of 2008 emissions.



Source: Fourth IMO GHG Study 2020.

The information presented in the fourth study is the last picture taken of the GHG emissions from ships, which is really important to consider for the analysis and evaluation, mainly because it is a baseline for the future measures proposed for GHG reduction.

3.3 International Framework to Decrease GHG Emissions in Maritime Transport.

Nowadays, the main framework existing regarding the reduction of GHG emissions for all sectors is international, being applicable to international and national shipping as well, according to the existing agreement between states. The following section will describe those international agreements that are relevant to this research in order to understand how maritime national environmental matters are connected with international initiatives to reduce GHG emissions.

3.3.1 Kyoto Protocol.

This Protocol was created in 1997 as part of the United Nations Framework Convention on Climate Change, laying one of the first foundations to reduce and limit pollutant emissions for the air by implementing different commitments in order to improve aspects such as energy efficiency, reduction of GHG emanation, promoting the use of renewable energies, among others, in all kinds of sector, including maritime transportation (Kyoto Protocol, 1997). In fact, Article 2 expressly mentions the need to control the emissions of GHG originating from the combustion of marine fossil fuels and maintaining the global average temperatures below 2º C, trying to limit the increment to 1.5º C compared with the pre-industrial ranges.

Chile has been part of this protocol since 2002, considering its importance in stabilising the GHG concentration in the atmosphere and limiting its negative impacts on the climate system (Environment Minister of Chile [EMS], 2023). Therefore, it is crucial to consider and develop national policies and measures to comply with this compromise, decreasing the anthropogenic negative effects produced by GHG.

3.3.2 Paris Agreement.

Paris Agreement is an accordance between most countries to enhance and strengthen the commitment achieved in the Kyoto Protocol, taking into account the outcomes of the United Nations Convention on Climate Change held in New York in 1992, on the one hand, and the scientific evidence available to the threat of climate change for the whole world (Paris Agreement, 2015). One of the objectives of this treatment considers reaching global peaking of GHG emissions as soon as possible, which is in line with the IMO 2023 Strategy on Reduction of GHG Emissions from Ships.

The Chilean Government ratified this commitment on September 20, 2016, and is adjusting the national environmental framework to reach net zero by 2050 in relation to the Paris Agreement and its definition of nationally determined contributions. For that reason, this arrangement should be extensive to the transport sector and, hence, to the maritime sector as a contributor to GHG emissions (Foreign Affairs Minister of Chile [FAM], 2020).

3.3.3 United Nations Sustainable Development Goals.

In 2015, the United Nations adopted an agenda for sustainable development with 17 goals to reach a sustainable future by means of a master plan that has involved different global challenges such as poverty, education, and gender equality, among others; however, there are two that are directly related to the climate change and thus, related to decrease the GHG emissions (Department of

Economic and Social Affairs of the United Nations [DESA], 2015). Those Sustainable Development Goals (SDG) are:

Figure 3. UN SDG Goals 7, 12 & 13.

Source: Google images, 2023.

- **7 – Affordable and Clean Energy**: This means guaranteeing a change in the type of energy available globally, prioritising the production and use of a new clean and sustainable energy source. This objective can be part of the solution for the transport sector to decrease or eliminate the GHG emission generated during fossil fuel combustion because it will be possible to use alternative fuels with low or zero air pollution.

- **12** – **Responsible Consumption and Production**: to ensure sustainable consumption and production patterns are totally applicable to the measures for the reduction of GHG emissions from ships in order to decrease the footprint emitted by maritime transport according to the ambition established by IMO and every country in its own national framework.

- **13 – Climate Action**: In the case of SDG 13, the main objective is to tackle climate change in order to stop it and mitigate its impacts. Therefore, any measure taken to address the transport sector to reduce GHG emissions can be used to achieve this goal.

Certainly, SDG should be part of any strategy that aims to reduce GHG emissions from ships, and every nationally determined contribution should take into account.

3.3.4 2023 IMO Strategy on Reduction of GHG Emissions from Ships.

IMO, as a United Nations specialised Agency, has established a strategy concerning the GHG emissions from ships involved in International Shipping in order to be part of the global effort to reduce the pollution that increases the negative effects of climate change, according to the Paris Agreement and the UN 2030 Agenda for Sustainable Goals.

Last July 2023, IMO, with a wide consensus among member states, adopted a Strategy with the aim to eliminate GHG emissions from international shipping as soon as possible, determining four levels of ambition. The first is related to improving ship design requirements with the intention of optimising energy efficiency. The second ambition is to reduce carbon intensity, decreasing CO_2 emissions by a minimum of 40% by 2030, compared with 2008. The third instruction is to implement on-board better technologies to reach zero emissions using alternative sources of energy by at least 5% by 2030. The fourth and final ambition is to attain the peak of GHG emissions as soon as possible and move to net-zero GHG emissions by or around 2050 (International Maritime Organization Strategy on Reduction of GHG Emissions from Ships, 2023).

Taking into account the ambitions, clearly, the strategy is to achieve a substantial reduction of GHG emissions by 2050 as well as every international framework; nevertheless, this approach is directed only towards international shipping.

To complete the ambitions, the strategy considers three GHG reduction measures, which are short-term, mid-term and long-term measures, divided according to the period of time by its implementation. For example, short-term measures were implemented on 1 January 2023 and shall be completed by 2026. There is still discussion for its promulgation in the case of mid-term and long-term measures.

The short-term measures were implemented under the regulations of MARPOL Annex VI; for that reason, it will be explained in further detail in the following paragraph.

3.3.5 Regulations for the Prevention of Air Pollution from Ships.

Currently, the prevention of air pollution from international maritime transport is regulated by MARPOL Annex VI, which includes different types of emissions from vessels and operational measures to ensure minimal pollution induced by ships. This framework contains four chapters, and the third covers emissions such as ozone-depleting substances, nitrogen oxides, sulphur oxides and particular matter and volatile organic compounds. On the other hand, the fourth chapter describes operational issues for the energy efficiency of ships and carbon intensity reduction (Resolution MEPC.328(328), 2021).

The regulations existing in Chapter Four to reduce GHG emissions from ships were developed in a combination of technical and operational elements, including measures to decrease the emission by slowing down the speed of vessels on one part and another part, incorporating measures to improve the energy efficiency as an operational measure.

Operational measures apply for international trading ships of 400 GT or above, establishing an obligation to calculate the following index:

- **Energy Efficiency Design Index (EEDI):** Applicable for new ships under the definition of regulation 22 of this Annex. On the one hand, it is necessary to calculate a required EEDI using the instruction described in regulation 21 of Annex VI, which, basically, is provided according to the type of vessel. Besides, it should calculate an attained EEDI from the result of an equation with several variables, such as the type of vessel, fuel consumption, conversion factor of fuel, different fuel oils, and deadweight, among others. Finally, both EEDIs should be compared, and the attained EEDI must always be minor or equal to the required EEDI.

- **Energy Efficiency Existing Ship Index (EEXI):** In that case, the concept is similar because there is an attained EEXI which is calculated on the basis of an equation provided by regulations, and this index must be minor to the required EEXI which is obtained from the regulation 25 of Chapter Four. It is important to note that EEXI only applies to existing ships that are not considered new vessels under the definition.

- **Ship Energy Efficiency Management Plan (SEEMP):** Its specifications are described in Regulations 22 and 26 of MARPOL Annex VI. Fundamentally, it is a procedure which is mandatory for every ship of 400 GT or above dedicated to international trading and contains instructions to develop a plan to manage the use of energy in an efficient way, optimising every aspect included in that definition, such as operational speed, use of auxiliary engines, among others. The Administration should approve this plan for the vessel, and it will be kept on board. The importance of this element is that it should be used as a complement to other technical and operational measures to reduce the total GHG emissions produced during the operation of the vessel.

- **Carbon Intensity Indicator (CII):** This indicator is part of the operational measures because it is a mathematical relation between emissions and transport work of every ship, and the results of this equation will allow rating every ship according to its performance; in other words, every ship with low emissions can be rated in letter A, B or C, in contrast, if one vessel obtains a high level of emissions during a calendar year should be rated in letter D or E. It is a mandatory regulation for vessels of 5000 GT or above. Similarly, to EEDI and EEXI, CII attained should be compared with CII obtained from the reference lines defined in Chapter Four.

- **Data Collection System (DCS):** This system collects data about fuel consumption on board, distance travelled, and hours underway in a calendar year, and many other variables to know the ship's operational performance. Besides, it will be used during the 2024 certification period as the procedure to bring the CII rating result for vessels through the issue of a Statement of Compliance provided by the Administration. Undoubtedly, it is connected with the SEEMP because when a ship CII is rated in D or E for three consecutive years, it must present a plan of corrective actions within the SEEMP to achieve a better qualification.

- **2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI)**: Those Guidelines were developed to define the methodology of calculations of the attained EEDI in order to comply with the instruction established in Chapter Four of Annex VI. The attained EEDI is crucial for the evaluation of the energy efficiency performance of every vessel compared with the reference defined in the regulations. Those formulas and equations were implemented by Resolution MEPC.308(73), adopted in 2018 for the IMO.

- **2021 Guidelines on the Method of Calculation of the Attained Energy Efficiency Existing Ship Index (EEXI)**: Similarly to the EEDI calculation, Attained EEXI will be calculated under the instruction of Resolution MEPC.333(76) and compared with the reference incorporated in Chapter Four of MARPOL Annex VI and then, those coefficients will be compared to interpret if the vessel analysed to fulfil the IMO protocol.

- **2022 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines)**: In the case of calculation of the carbon intensity, as an operational measure, its formula is contained in the Guidelines developed by IMO in 2021 and implemented by Resolution MEPC.352(78). Those instructions used several parameters to define an indicator regarding fuel consumption. For a better understanding, chapter 4 of this research will employ those guidelines for some cases of study.

3.3.6 A Practical Guide to the selection of Energy Efficiency Technologies for ships.

This document was elaborated in 2022 by the GreenVoyage 2050 Project Combination Unit as a guideline to implement energy efficient measures or improve it over ships according to the IMO standard about the topic of the reduction of GHG emissions from vessels, including suggestions of the use of technologies related with the mitigation of climate change (GreenVoyage 2050 Project Coordination Unit [GV2050], 2022).

Its different chapter presents the option to be helpful for saving energy in vessels without retrofit; meanwhile, there are alternatives for the same purpose of retrofitting the main engine or other points of a high level of energy consumption.

Besides, this guide brings user applications for EEDI and EEXI index to make those more useful indicators and improve the energy efficiency onboard, directly using the regulations Annex VI of MARPOL Conventions.

Finally, this reference is the best option existing nowadays to apply energy efficiency equipment to improve the ship's performance.

3.4 National Framework to Decrease GHG Emissions in Maritime Transport.

Chilean national law was established in 2022 to face the climate change effects by reaching and keeping net zero emissions, further contributing to the NDC (Nationally determined contribution) presented in international commitments. These regulations have a direct relation with the Paris Agreement because Chile ratified this contract, and the internal national way to put into practice the efforts to the climate action plan is this law (EMC, 2022).

The measures contained in this law involves all sector of the country, including transport, thus maritime transportation. For that reason, this statute becomes an important policy for the internal implementation of standards on GHG reduction.

This law aims to transform the country to net zero by 2050, mitigating and stopping GHG emissions and assessing this goal every five years to improve the measures taken if necessary. On the other hand, the regulations consider a budget divided by sector to comply with the objective and support those areas with difficulty achieving ambition. Additionally, this mandate defines several instructions for all governmental institutions to work together on reaching the net zero objective by 2050.

3.5 International experience applying

These days, some countries have developed national action plans to deal with the GHG emissions from vessels under their Flag State Administration, especially from domestic fleets which are not considered under IMO initiatives, and the following paragraph will explain how they manage their policies to contribute to the reduction of pollutant emissions from ships.

3.5.1 Norwegian Government's action plan for green shipping.

Norway has the particular ambition to reduce GHG emissions from domestic shipping and fishing vessels. The level of ambition aims to achieve two objectives: the first is the reduction of emissions by half by 2030, and the second is to promote outcomes in zero and low-emission technologies for maritime transportation (Norwegian Government [NG]. 2019).

Among its domestic fleet, it considers different types of ships, such as passenger vessels, offshore support vessels, aquaculture service vessels, and many other cases. Such a quantity of ships makes this strategy a challenge for the government, which will be tackled with measures and policies. However, they are using an innovative proposal of budget allocation for 25 million Norwegian Crowns to support the change phase for the industry. Equally, cooperation between the private and public sectors is one way to achieve the progress required to reach the ambitions.

Another initiative taken by Norway is to improve its national ship's Register, making it more competitive and attractive for the shipping industry, understanding that this measure can advance the implementation of low-emissions policies in the flagged fleet. Furthermore, this presentation of Norway's action plan allows us to comprehend many alternative solutions and technologies to become traditional vessels in green shipping and how to instrumentalise on board.

Undeniably, the shipping reality of Norway is interesting for this research due to its similarities with the Chilean maritime industry, where the main cabotage sector is concerned with the aquaculture industry on the salmon's production, being an excellent example of how to introduce a change in terms of emissions and fuel consumption.

3.5.2 Implementation of the CII regulation by the French Flag Administration.

In this case, the French Flag Administration presents several requests or questions made by companies during the first step of implementation of the CII and SEEMP according to the last measures taken by IMO related to the reduction of GHG from ships (Intersessional Meeting of the Working Group on Reduction of GHG Emissions from Ships [ISWG-GHG], 2023).

The first resolution taken by the French, for example, was to delegate some specific action to the Recognized Organization (RO), such as validation of SEEMP Part III, verification and validation of DCS data, and CII calculation and CII rating. However, France follows the responsibility as a Flag State.

On the other side, one of the propositions displayed by France is to motivate the use of Biofuels, requiring some change for the calculation of CII because the idea suggested is to uptake a conversion factor equal to zero; henceforth, the result of the CII calculation will improve compared with the use of fossil fuels.

Consequently, the paper submitted by France to the IMO is something to be on the table as an example of how one State is trying to improve IMO measures according to its own national reality and convenience.

3.5.3 Study on the decarbonisation of the Belgian maritime sector for small vessels (< 5000 GT).

Belgium, on the other side, presented to IMO a study explaining how it could improve the outcome of decarbonisation if small vessels of the Belgian domestic fleet were included in the ambitions, in other words, applying some measures of

MARPOL Annex VI in small domestic shipping (Marine Environment Protection Committee [MEPC], 2021).

Belgium's study considers small domestic vessels to all types of ships under 5000 GT (< 5000 GT). This range involves all vessels to which DCS and CII measures do not apply.

In the first part, Belgium starts the report by calculating the emissions from the fleet considered, and in light of the results, the pollutant type of vessel is the tanker with the larger emissions estimated, followed by cargo, sand extractors and fishery.

Although many shipping companies are trying to contribute to the decarbonisation of this sector, there are many technical and operational measures that can support this goal; however, for the small vessels defined by Belgium, the technical ones are the most common at the moment and possible in the future will be developed another kind of operational initiatives for vessels under 5000 GT.

Finally, the report shows and explains the existing options to achieve decarbonisation for the sector analysed and presents the key elements to take into account to decide the implementation of a policy like this.

3.6 Statistical Status of the Chilean Merchant Fleet.

Regarding the Chilean Merchant Fleet, both the international and national fleets are controlled by the General Directorate of the Maritime Territory and Merchant Marine (DIRECTEMAR), which acts as Maritime Administration in the majority of activities that the institution should provide according to the maritime framework. For that reason, when information about ships is required, the DIRECTEMAR homepage can offer all the necessary information or data.

This research is about the Chilean domestic fleets; therefore, it is crucial to obtain data about type, quantity, and every other important data that can support the implementation of decarbonisation measures over this part of vessels. Hence, DIRECTEMAR developed the Maritime Statistical Bulletin of 2023, which include all details and statistic about national maritime trade, cabotage, and vessels, among other material (General Directorate of the Maritime Territory and Merchant Marine [DIRECTEMAR], 2023).

For the purpose of this dissertation, it will be useful to all statistics mainly related to vessels under the Chilean Flag State to analyse and evaluate cases to apply decarbonisation strategy to obtain important outcomes to achieve the objectives established.

3.7 Conclusion

This chapter was divided into seven sections to present the concepts related to the decarbonisation of the shipping industry. The first part explains, using GHG studies from IMO and International agreements, why it is crucial to tackle efforts to reduce the pollutant emissions produced by ships. Then, it presented the current international frameworks available which face climate warnings, showing the strategy followed by the international community. The following section describes the Chilean environmental framework related to GHG emissions and how other countries have established their national contribution to mitigate climate change effects in maritime transport. Finally, the statistical status of the Chilean domestic and inland fleet in order to understand how this fleet is composed of different types and sizes of vessels, with the aim to focus this research on the evaluation of different categories.

Chapter 4. Research Method

4.1 Introduction

In this part of the dissertation it will describe in detail the approach to achieving answering questions and how to reach the objectives established in Chapter 2. To develop this part, the data collection method used will be explained in order to find all information concerning the indexes and indicators, as well as the energy efficiency plan for the reduction of GHG emissions proposed by MARPOL Annex VI. Moreover, we will transit by the characterisation of the Chilean Merchant Domestic Fleet to achieve the information which will be evaluated later, and finally, it will analyse the current technical and operational solutions for vessels to reach the environmental standard established by IMO related to the GHG emissions from ships.

4.2 Data Collection Method.

The data collection method includes primary and secondary sources to obtain the information needed, considering that information was acquired from reports, IMO documents, laws, and statistics, among others.

For the characterisation of the Chilean Merchant Domestic Fleet, it will be used the Maritime Statistical Bulletin 2023 developed by DIRECTEMAR because in this report appears the official information required, which is updated and presented by the National Maritime Administration. This data will be processed to obtain quantitative figures about the types and ages of vessels included in the fleet.

Furthermore, how to address the calculations of EEXI, EEDI and CII for the cases of studies presented in this research will be explicated in accordance with the guidelines developed by IMO to accomplish MARPOL regulations.

Finally, it will examine every possible technical and operational solution for the reduction of GHG emissions from vessels available today and how it can impact vessels and their GHG production.

4.3 Characterization of the Chilean Merchant Domestic Fleet.

Chile has a merchant domestic fleet consisting of vessels to provide different maritime transport between ports of the country. It is important to mention that Chile is a narrow and long strip of land with an extension of more than 4000 km of coasts next to the Pacific Ocean and for its position in South America. Therefore, it is possible to say that Chile is essentially a maritime country because of its dependency on the sea (Martínez, 1993).

Correspondingly, this fleet has different types of vessels operating along the coast, such as General Cargo, TUGs, Fishing Vessels, Wellboats, and Ferries, among others, which participate in the maritime communication routes. In the following paragraph, those sorts of vessels will be described in order to understand how maritime transport is organised and how they will be analysed related to their GHG emissions.

4.3.1 General Cargo Vessels.

General Cargo vessels are interesting for their versatility in maritime transport; they can carry much alternative cargo and move for almost every port; for that reason, they are useful for all industries.

In the case of Chile and its geography, as presented in the Maritime Statistical Bulletin 2023 developed by DIRECTEMAR, 144 General Cargo ships comprise the domestic merchant fleet, almost 15% of the total and operate along the coast connecting the islands and moving cargo 24 hours per day (DIRECTEMAR, 2023).

Considering the percentage of the total fleet, it is possible that their emissions can mean a great amount of pollution; henceforth, it will be part of the analysis in the following section.

4.3.2 Tugboats.

Due to its geographical situation, Chile has more than 15 ports to connect cities and populations; thus, one modal of transport is through ships. Moreover, considering that ports are available to receive ships of different sizes, TUGs are the key element providing facilities and support for each vessel; hence, the TUGs fleet is really relevant at the moment to quantify GHG emissions. In fact, there are 71 TUGs working across the country (DIRECTEMAR, 2023).

4.3.3 Fishing Vessel.

Another important part of the maritime domestic sector is the Fishery industry because, according to the DIRECTEMAR 2023 bulletin, in total, the Fishery fleet has 89 vessels in operations fishing different resources from the sea. Assuming this quantity of ships, GHG emissions should be taken into account to comply with the objectives of the Chilean Climate Change Framework Law that were explained in the last section (DIRECTEMAR, 2023).

4.3.4 Aquaculture Industry.

Furthermore, since 2000, there has been a growing aquaculture industry producing salmon thanks to the great condition of the canals, fiords and internal waters that lead it to be the second in the world, next to Norway (Consejo del Salmón [CS], 2023).

This industry involved in its salmon production considers multiple services, and in the majority of them, maritime transport is the main method to bring this work. In this line of explanation, various services were imported to support this activity; for instance, a new kind of vessel was brought to transport salmon species alive from farms to processing plants on the coast, and these ships are named Wellboats.

Those ships have mainly great tanks onboard to load and carry salmon, avoiding any kind of damage to this product, and then, the fish is unloaded and delivered ashore. Today, because of the expansion of the industry, there are 68 Wellboats under the Chilean flag statement, playing a key role in the economy.

Likewise, another crucial naval platform to support this industry is the marine structures. Those constructions provide several services for salmon farms, such as assistance for people who maintain salmon, normally using those structures to live for a period of time with beds, bathrooms, restaurants and every sort of facility that they need; another kind of assembly used provides space for power generation system that today use fossil fuels to produce energy.

Nevertheless, it should be taken into account that more than 500 marine structures are operatives currently in Chile, and normal use needs energy to work; therefore, consuming fossil fuels and, certainly, GHG production can impact the environment, and this fact should be controlled similarly to vessels. In consequence, for the purpose of this dissertation, it will consider those naval buildings as pollution emitters. Regarding the salmon industry, in Chile in 2021, there were between 130 and 135 farms in operation (Faúndez, 2021), and each one of them uses more than one marine structure to function.

4.3.5 Passenger Transport.

Talking about passenger transport at sea, it can be possible to mention Ro-ro passenger vessels and Ferries. In both cases, one of the most relevant types of cargo is people, and its care is fundamental; henceforth, for the purpose of this research, both types of vessels will be analysed as similar.

One way to connect people between ports and islands in Chile is by Ro-ro Passenger Ships; there are 47 Ro-ro Passenger Ships navigating along the country, but most part is operating in the southern zone, connecting people and delivering cargo. Currently, the number of Ro-ro Passenger Ships working on that service non-stop is 47; in consequence, the amount of GHG emissions can be considerable at the moment to examine the possible reduction measures.

4.3.6 Other Types of Vessels.

Clearly, there are other kinds of vessels navigating in Chile under its flag statement, which can be categorized according to their type and function. Nonetheless, for their quantity in comparison with the ships that were described above, they will not be further detailed, even though they will be present in the following summary.

To summarise, the quantification of the Chilean domestic fleet will be the following:

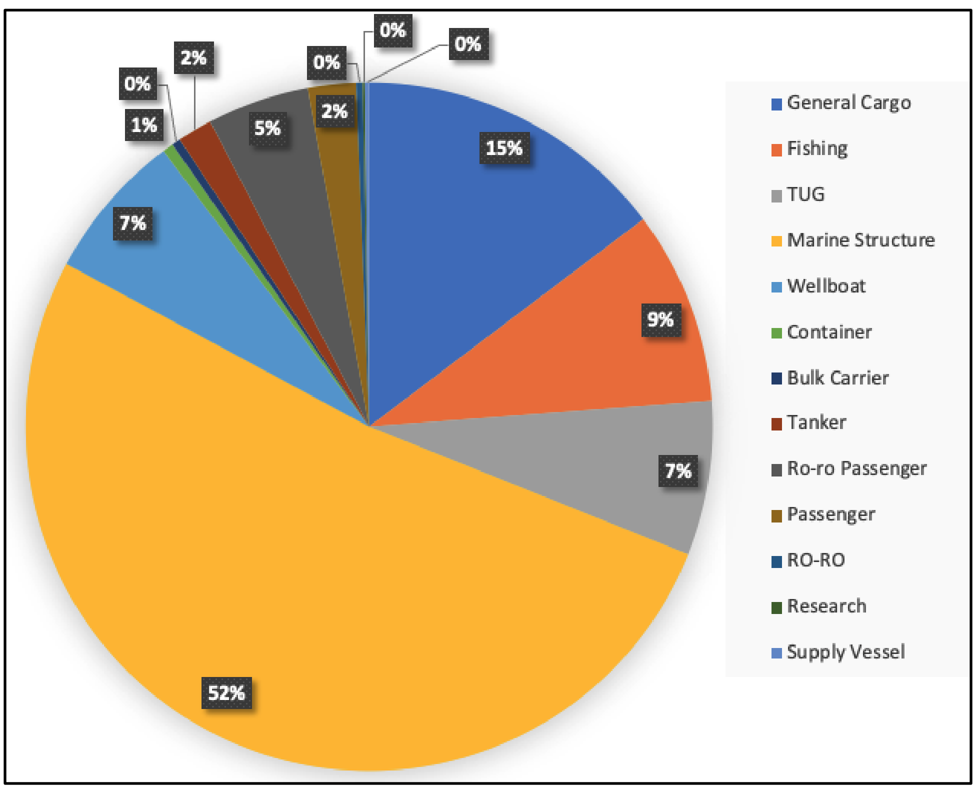
Table 1. Types of Vessels of the Chilean domestic and inland fleet.

Type	Number	%
General Cargo	144	14.71
Fishing	89	9.09
TUG	71	7.25
Marine Structure	507	51.79

Wellboat	68	6.94
Container	5	0.51
Bulk Carrier	4	0.41
Tanker	16	1.63
Ro-ro Passenger	47	4.80
Passenger	22	2.24
RO-ro	3	0.30
Research	1	0.10
Supply Vessel	2	0.20
	979	**100**

Source: Author, 2023.

Figure 4. Pie Chart of the type of vessels.



Source: Author, 2023.

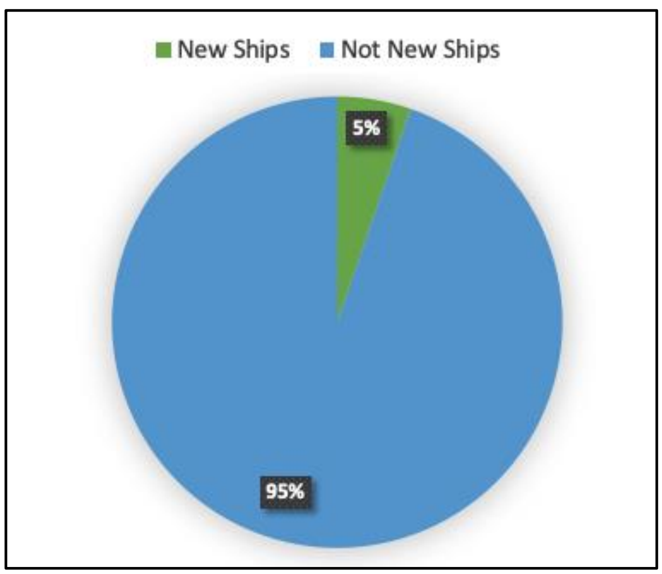
Regardless of the data presented about types of vessels and the quantification of each of them, the subsequent analysis and calculation of EEDI and CII will only include Ro-ro Passenger and Wellboat. This is due to the lack of data about fuel consumption of vessels.

4.3.7 Fleet Age.

Analysing the data available in the DIRECTEMAR bulletin, it is possible to extract information about the year of construction of each vessel registered under the Chilean Ship Register, taking note that the average age of the cabotage fleet is 30 years. Moreover, when it is examined, the number of vessels is new ships according to regulation 2.2.8 of MARPOL Annex VI, it is clear that only 5% of the fleet can be considered as new ships; therefore, EEDI is applicable to that kind of consideration. In contrast, 447 vessels compound the rest of the fleet, and EEXI can be applicable to them over a total of 472.

Figure 5. Pie Chart of the total new and not new ships.

Total:	472
New Ships:	25
Not New Ships:	447



Source: Author, 2023.

4.4 Data about GHG emissions.

Currently, it is not possible to obtain data about GHG emissions from the Chilean domestic fleet directly because there is no database of this information. For that reason, in the first place, this issue will be recorded as a constraint that needs to be reflected in this report due to the importance of maintaining and updating and complete repository about this matter for future decisions and evaluations. And in second place, data will be obtained from the industry on the bases of fuel consumption and operational performance of one ship for every category.

To complete the explanation made in the last paragraph, some shipowners will provide information about the fuel consumption, deadweight (DWG), ships particulars, and power of the main and auxiliary engines, among other details from their vessels, which will be described in the following section.

Nevertheless, because of the difficulty of the data obtention, it will only be considered one ship for some types as a representative figure. Those types examined will be Ro-ro Passenger ships and Wellboats. In the case of Marine Structures, it is not possible to apply the MARPOL Annex VI equations because those standards are developed only for vessels.

The information will be managed as anonymous with the aim of protecting and respecting the rights of the shipowners and their companies, who kindly cooperate with this research.

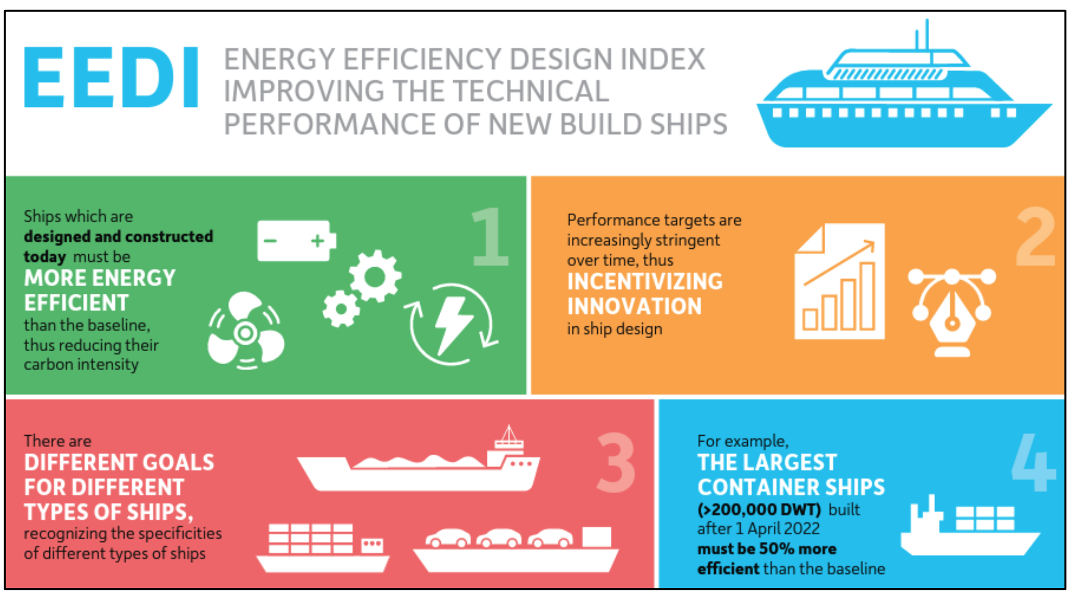
Notwithstanding the importance and high participation in the domestic fleet, Fishing Vessels will not be analysed due to the lack of information available.

4.5 Calculation of the Energy Efficiency Index (EEDI and EEXI).

For the calculation of the EEDI and EEXI of every vessel selected as a representative example of the type analysed, the framework established for IMO and implemented by MARPOL Annex VI, taking into account that those measures are applicable to vessels equal to over 400 GT.

According to the MARPOL regulations, the use of EEDI or EEXI depends on the year of construction of the vessels, and the application in this dissertation will be indicated in Chapter 4 of this Convention. The reckoning of the EEDI will be used for new ships, and its calculations follow the instruction available in regulation 21 of MARPOL Annex VI for the Required EEDI and the procedure described in the 2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index for the Attained (EEDI) (Resolution MEPC.308(73), 2018). The posterior step will be compared to both indexes and define their accomplishment with the regulations of the convention.

Figure 6. EEDI IMO Brochure.



Source: IMO Homepage, 2023.

For the EEXI calculation, the process will be similar; however, the only difference is the reference to calculate the attained EEXI because, in that case, it will use the 2021 Guidelines on the Method of Calculation of the Attained Energy Efficiency Existing Ship Index (Resolution MEPC.333(76), 2021) and the results will be contrasted with the Required EEXI defined in regulation 25 of MARPOL Annex VI.

Figure 7. EEXI IMO Brochure.

Source: IMO Homepage, 2023.

Those indexes will not be applicable to Marine Structure because those naval platforms cannot comply with the variables required in the formula presented by MARPOL Annex VI, such as speed, gross tonnage and many others.

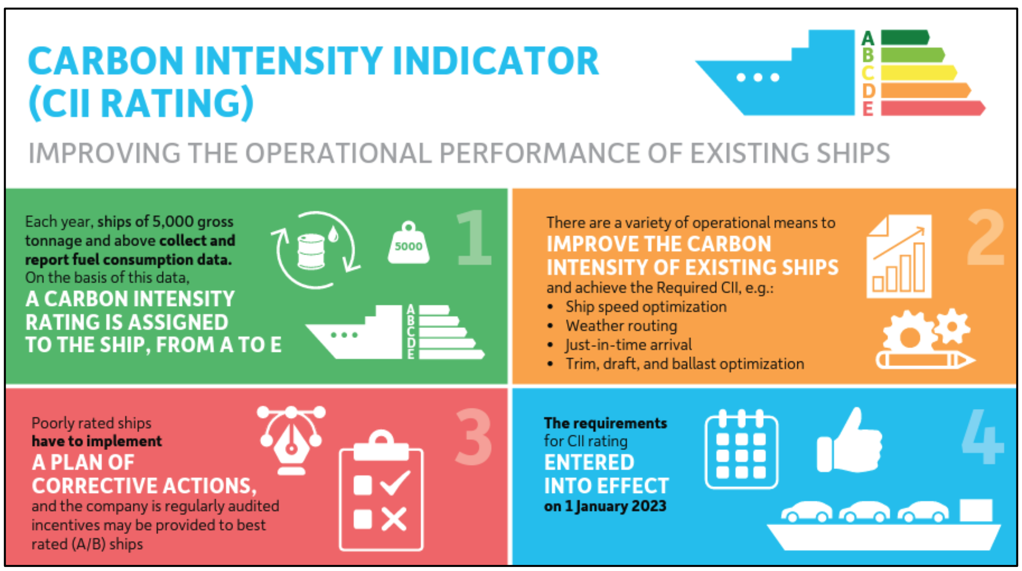
4.6 Calculation of the Carbon Intensity Indicator (CII).

This indicator will be calculated for every ship selected in order to attain a representation of the GHG emission level of every type of vessel. Regardless that

CII is applicable under vessels over 5000 GT, the Chilean domestic fleet is dominated by ships under 5000 GT; for that reason, we will assess how this approach impacts the range of gross tonnage chosen.

To complete the ratio described in the guidelines, it will follow the instructions defined in the Resolution MEPC.352(78), where every variable is well detailed, and formulas are presented accordingly with the objective purpose. All calculations of this indicator applying to vessel samples will be illustrated in Appendix 2.

Figure 8. CII IMO Brochure.



Source: IMO Homepage, 2023.

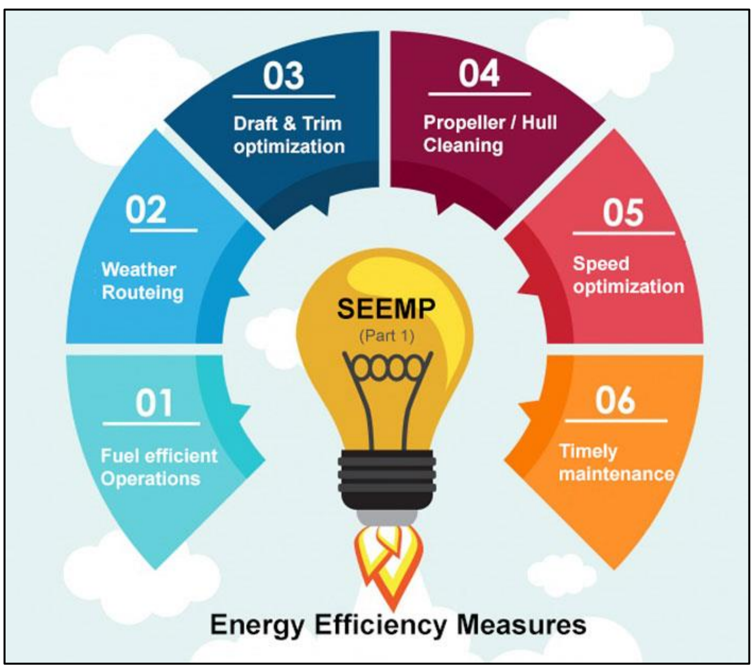
Despite this indicator being created for vessels, for the purpose of this research, it would be applied to salmon farms in order to obtain information about GHG emissions from those kinds of naval constructions, defining a baseline to start implementing energy efficiency measures for the reduction of those emissions. Calculations would be available to be reviewed in Appendix 2.

4.7 Energy-Efficient Plan for Vessels (SEEMP).

Similar to the other IMO measures to obtain data about efficient onboard and carbon emissions produced, the Organisation has developed a framework to establish an Energy Efficient Plan for vessels called Ship Energy Efficiency Management Plan (SEEMP), which is defined by Regulation 26 of MARPOL Annex VI having as objective to elaborate a framework for the best practice and energy efficient operations (Calleya, 2023).

SEEMP was conceived to include each aspect that can reduce pollutant emissions, such as how to make fuel-efficient operation, how to improve the weather routeing, the propeller and hull cleaning, terms of speed optimisation, timely maintenance, among other practice procedures for energy efficiency results.

Figure 9. SEEMP IMO Brochure.



Source: IMO Homepage, 2023.

On the other hand, other chapters of the Guidelines consider instructions for data collection systems for vessels of 5000 GT or above with the methodology of the data collection, and the last chapter is dedicated to the Ship Operational Carbon Intensity plan, which describes CII calculation methodology, energy efficiency measures implementation, plan of correctives actions, among other subjects (Resolution MEPC.346(78), 2022).

Assuredly, SEEMP is a tool that can be applied in all types of vessels regardless of their size or if they sail in international or domestic waters because operational measures for energy-efficient and pollutant emission mitigation are indispensable for all vessels in order to be clean and cost operation cheaper.

It is important to mention that IMO developed SEEMP Guidelines under Resolution MEPC.346(78) “2022 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP)”.

4.8 Interviews with Experts.

For the purpose of this dissertation, the following experts in the Chilean Maritime Industry in order to obtain their opinions and suggestions for the best implementation of regulations to reduce GHG emissions from ships and salmon farms, taking into account the possible barriers and constraints to achieve an effective application and contribution with the climate action efforts.

Experts interviewed come from the following stakeholder segments:

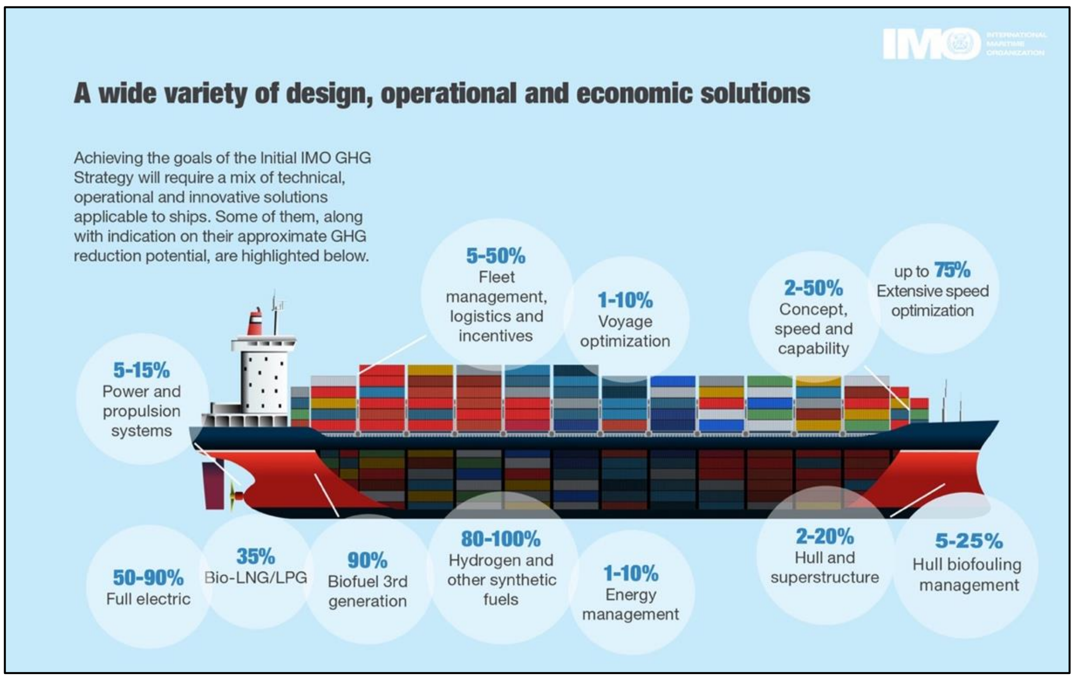
- DNV Surveyor.
- Chilean Flag State Department.
- Chief Engineer.
- Senior Technical Advisor of the Chilean Salmon Industry.

The questions are described in Appendix 5.

4.9 Solutions for the Reduction of GHG Emissions from Ships.

MARPOL has divided into two parameters the measures for GHG emission reduction; one of those is the technical measures, and the second is the operational measures. Besides, technical measures are linked with marine indexes such as EEDI, EEXI, and SEEMP; meanwhile, operational mechanisms are associated with the CII initiative.

Figure 10. IMO Reduction Potential Solutions.



Source: IMO Homepage, 2023.

The following section will describe some mechanisms, technical and operational, to reduce GHG emissions from vessels, which are available currently and others that are in the development phase.

4.9.1 Technical Measures.

Technical measures are directly related to the energy efficiency concept on board. This concept means to be efficient in producing energy; in other words, for our research, it can be described as generating the power needed using a minimal quantity of energy (Patterson, 1996).

One example of this concept could be when one vessel sails from one port to another, using less energy possible to produce the power needed to arrive at the next port without affecting the performance and transportation required for this service, and this improvement can be achieved by decreasing ship resistance.

Currently, there are several options to improve the performance of ships; nonetheless, most of them are considered for the ship design phase and, therefore, applicable to new naval construction even though it is possible to reach some upgrades for the existing vessel, as we will describe in this research. Appendix 1 defines in detail each aspect and characteristic of the technical measures analysed for this study; however, to summarise the Technical Measures available in the market and their results in the reduction of GHG emissions, the following table will present the percentage of GHG reduction achieved for every device or fuel mentioned and analysed.

Table 2. Percentage of GHG reduction.

Technical Measures		GHG Emissions Reduction (%)
Ship Design		3 – 5 (*)
Post-Combustion Devices:		
-	Selective Catalytic Reduction	NOx: 80 - 95
-	Exhaust Gases Recirculation	NOx: 20 - 50
-	Carbon Capture Store	CO_2: 55 – 60
Propulsive Optimisation:		

-	Wake Equalizing and Flow Separation alleviating	0 – 5	
-	Pre-Swirl Devices	2 – 6	
-	Post-Swirl Devices	2 – 6	
-	High-efficiency Propellers	3 – 10	
Alternative Source of Propulsion:			
-	Solar Energy	(**)	
-	Wind Energy	Retrofitting: up to 30 New ship: up to 90	
-	Nuclear Energy	100	
-	Electric Energy	100	
Alternative Fuels:			
-	Methane (LNG)	Diesel Cycle:	CO_2: 23 NOx: 30
		Otto Cycle:	CO_2: 30 NOx: 85
-	Methane (LBG)	65	
-	Biofuels	(***)	
-	Hydrogen	100	
-	Ammonia	100 (****)	

Source: Author, 2023.

(*) It should be compared between the model designs of each vessel.

(**) Depending on the total energy achieved with the area installed of solar panels.

(***) Depending on the type of biofuel analysed.

(****) Depending on the process of production.

Furthermore, it is practicable to combine measures to ensure the best performance for GHG reduction; in that way, there is an example presented by

DNV (2020), where ammonia for the propulsion can obtain zero emission using carbon capture store technology in the post-combustion process.

Certainly, an energy-efficient vessel is also a cheaper operation vessel because using less or, in an efficient way, the fuel can translate into a decrease in the operational cost. As a result, the climate and the ownership win due to GHG emissions reduction and lower operating costs, respectively.

4.9.2 Operational Measures.

For the explanation of those measures, there is a complete and detailed description of those alternatives in Appendix 2. Each part will be described in function of fuel consumption because fuel consumption is directly related to emissions. In other words, if fuel consumption increases, so do the emissions and vice versa.

One of the major benefits of the operational measures is that they can be applied to new and existing ships, being effective in both cases in reducing GHG emissions and improving efficiency.

Taking into account the explication developed in Appendix 2, the following table synthesised the fuel consumption savings with every operational measure proposed.

Table 3. Percentage of Fuel Consumption Savings.

Operational Measures	Fuel Consumption Savings (%)
Speed Reduction:	(*)
Optimal handling of ships and trim optimisation:	2 - 4

Just-in-time arrivals:	(**)
Anti-fouling and coating:	
- Hull	15 – 20
- Propeller	3
Controllable Pitch Propeller (CPP):	0.5
Environmental conditions of the route:	
- Wind Direction	1 – 4
- Speed and Depths	(***)
Ship Maintenance Management	(****)

Source: Author, 2023.

(*) It should be calculated for every vessel according to its engine performance.
(**) Depending on the daily fuel consumption cost of each vessel.
(***) Depending on the speed and the depth analysed.
(****) Depending on each vessel's engine systems and Company planning.

4.10 Conclusions.

To conclude this chapter, the research method included an explanation of the data collection method with the details of the compilation of the information used in the present study. The characterisation of the Chilean Merchant Domestic Fleet allowed us to understand how this industry is composed of more than 400 vessels and more than 500 structures dedicated to salmon production, with the evidence that the majority of ships are General Cargo type, with 14.71% of the total, followed by fishing vessels with 9.09%. TUG also has impacts with a high percentage of 7.25%. Nonetheless, in terms of number, the largest quantity of naval artefacts is the marine structure of the aquaculture industry, with more than 51.79% of the total analysed. Related to the age of the fleet, the average is 30 years, which means that more than 95% of the ships examined can be defined as existing vessels in accordance with MARPOL Annex VI regulations.

Moreover, this chapter explains how will be made calculations for EEXI, EEDI and CII using IMO guidelines and framework. Then, it is possible to read about the interview with expert methods that will be used to attain opinions about barriers and constraints in the MARPOL Annex VI implementation.

Finally, each potential solution for vessels to reduce GHG emissions and improve their energy efficiency performance was described using technical or operational measures currently available in the industry. The interesting fact is that, in some cases, GHG emissions reduction can reach between 80% and 90% or even 100% with the use of alternative sources of propulsion as a technical option. On the other side, operational measures can achieve improvements of up to 20% just by improving their anti-fouling and coating standards.

Chapter 5. Cases of Study

5.1 Introduction

This Chapter will analyse the application of the framework presented before in order to evaluate formulas and calculations for two types of ships to obtain the EEDI or EEXI and CII, taking into account that there is no evidence of those ratios in Chilean Maritime Administration or other institutions due to the lack of regulations for climate action on vessels in the domestic and inland Chilean Fleet. For that reason, the following points will be described: the data attained using the IMO Guidelines and information provided for ownership gathering the EEDI or CII of every ship for further analysis of the potential GHG emitted to the atmosphere.

The Information used in this chapter was provided for a company that developed its business in the South of Chile, supporting the Salmon Industry.

5.2 Ro-ro Passenger Ship.

The first ship analysed is a Ro-ro Passenger Ship with the following main characteristics:

Table 4. **Ro-ro Passenger Ship Particulars.**

Gross Tonnage	:	1424
DWT	:	590 (ton)
Speed of reference	:	11.5 (knot)
Year of Construction	:	2019
Power Main Engine (MCR)	:	4 x 492 (kW)
Power Auxiliary Engine (MCR)	:	2 x 129 (kW) 1 x 75 (kW)

Total Fuel Consumption 2022	:	1800 (ton)
Type of Fuel consumed 2022	:	Diesel
Total Nautical Miles Sail 2022	:	50000

Source: Author, 2023.

Because of the year of construction of the vessel and the data obtained from the year 2022, it was calculated the EEDI and CII. All details of the equations and calculations are available in Appendices 1 and 2, respectively.

5.2.1 Energy Efficiency Index (EEDI) Calculation.

The formula used to calculate this Index is the following:

$$EEDI_{Att} \leq EEDI_{Req} = \left(1 - \frac{x}{100}\right) * EEDI_{ref} \tag{1}$$

In light of the results obtained from the guidelines and calculations used for this evaluation, it is clear that $EEDI_{Att}$ is major in 85%; in other words, it is almost double the index required ($EEDI_{Req}$). Therefore, this ship is not complying with the regulations and guidelines defined in Chapter Four of MARPOL Annex VI.

Table 5. **Ro-ro Passenger Ship EEDI results.**

$EEDI_{Ref}$	:	79.3955
$EEDI_{Req}$	:	72.1969
$EEXI_{Att}$	:	134.2029

Source: Author, 2023.

Definitely, those results are not the best for the vessel, and compared with international shipping, this non-compliance does not mean detention or that the vessel cannot be certified, but the company should take measures to reduce

$EEDI_{Att}$ by applying improvements in the SEEMP to enhance the use of energy onboard in a more efficient way. Operational and technical measures can support solutions for EEDI improvements; however, the company is who should decide which measures are the most powerful without impacting the business operations.

5.2.2 Carbon Intensity Indicator (CII) Calculation.

The formula used to calculate this Index is the following:

$$Required\ annual\ operation\ CII = \left(1 - \frac{z}{100}\right) * CII_{Ref} \tag{2}$$

In this case, CII_{Att} calculated with the data proportionated showed to be 19% more major than the CII_{Req} which means a non-compliance condition as well.

Table 6. **Ro-ro Passenger Ship CII results.**		
CII_{Ref}	:	71.6772
CII_{Req}	:	68.0933
CII_{Att}	:	81.0505
CII_{Att} (16% less Fuel Consumption)	:	68.0824

Source: Author, 2023.

According to the regulations, this condition should be improved by reducing the speed of operation, which can be translated into fuel consumption reduction. If the fuel consumption reduction can achieve 16% from 1800 (ton) per year to 1512 (ton) per year, it is possible to reach a CII_{Att} minor than the CII_{Req}, complying with the framework.

Clearly, the final decision of how to comply with the environmental law is part of the company, but each measure proposed in the last chapter can be selected and applied to reach the final objective.

5.3 Wellboat Vessel.

The second case available to be analysed is a Wellboat vessel with the following main characteristics:

Table 7. **Wellboat Vessel Ship Particulars**		
Gross Tonnage	:	1952
DWT	:	2490 (ton)
Speed of reference	:	11 (knot)
Year of Construction	:	2019
Power Main Engine (MCR)	:	2498 (kW)
Power Auxiliary Engine (MCR)	:	3 x 830 (kW) 1 x 195 (kW)
Total Fuel Consumption 2022	:	2760 (ton)
Type of Fuel consumed 2022	:	Diesel
Total Nautical Miles Sail 2022	:	50,000

Source: Author, 2023.

Similarly to the first case, due to the year of construction of the vessel and the data obtained from the year 2022, it was calculated the EEDI and CII. All details of the equations and calculations are available in Appendices 1 and 2, respectively.

5.3.1 Energy Efficiency Index (EEDI) Calculation.

The formula used to calculate this Index is the following:

$$EEDI_{Att} \leq EEDI_{Req} = \left(1 - \frac{x}{100}\right) * EEDI_{ref} \quad (1)$$

Using the same equations presented before, and in light of the results obtained from the guidelines and calculations used for this evaluation, it is clear that $EEDI_{Att}$ is major in 67%; in other words, it is almost double the index required ($EEDI_{Req}$). Therefore, this ship does not comply with the regulations and guidelines defined in Chapter Four of MARPOL Annex VI, despite this type of vessel is not considered in the reference of Annex VI, being used for the calculations of the data presented to the tanker because of the similarity in the operations work.

Table 8. **Wellboat Vessel EEDI results.**

$EEDI_{Ref}$	:	26.8279
$EEDI_{Req}$	:	26.8275
$EEXI_{Att}$	:	45.0442

Source: Author, 2023.

This Index can be improved using the SEEMP alternatives according to IMO guidelines, using a reduction in the power generation or installing any alternative source of propulsion as a complement to the fossil fuel machinery. Besides, it can be applied to any operational measures to generate efficient results.

5.3.2 Carbon Intensity Indicator (CII) Calculation.

Using the same equations presented before for this indicator:

$$Required\ annual\ operation\ CII = \left(1 - \frac{Z}{100}\right) * CII_{Ref} \tag{2}$$

In this case, the outcomes show that CII_{Att} calculated with the data proportionated showed to be 125% more major than the CII_{Req}, which means a non-compliance condition as well.

Table 9. **Wellboat Vessel CII results.**		
CII_{Ref}	:	28.1808
CII_{Req}	:	26.7717
CII_{Att}	:	71.0727
CII_{Att} *(60% less of Fuel Consumption)*	:	28.4291

Source: Author, 2023.

This result is more critical because to produce a reduction required to decrease CII_{Att} will demand a fuel consumption reduction of more than 50%, which can mean an extreme cost for the company in order to retrofit the vessel and introduce operational measures. However, the best option should be a combination of technical and operational measures.

5.5 Conclusions

To finalise this chapter, it is possible to conclude that were calculated EEDI for two types of vessels, Ro-ro Passenger Ship and Wellboat vessels, obtaining in both cases EEDIAtt, which does not comply with the requirement established by the MARPOL ANNEX VI, being necessary to apply technical and operational measures to improve the index with the SEEMP utilisation.

In the case of CII, as well as EEDI, in both cases, the CII_{Att} does not comply with the regulation requirement; however, it was possible to evaluate how much fuel consumption reduction is needed to decrease the indicator attained and accomplish the framework. For instance, in the Ro-ro Passenger Ship, with a reduction of 16% per year, it will be possible to reach the CIIReq; in contrast, the Wellboat needs a reduction of more than 40%, which certainly could impact the business model of the Company.

Finally, there are many technical and operational measures to achieve the index and indicators established in the norm; nevertheless, the Company has the las decision due to any choice involving an impact on the budget.

Chapter 6. Roadmap for the GHG Reduction

6.1 Introduction

Regarding the possibility of implementing Chapter Four of the MARPOL Annex VI over the Chilean domestic fleet, it is fundamental to create a strategy or plan that allows to produce the expected results. According to this idea, this part of the research will provide a proposition of a roadmap to achieving the imposed targets, identifying the barriers and constraints detected during the interviews and the data collection phase, and then it will follow with some solutions for tackling the barriers in a roadmap for the best way to implement the regulations analysed. Finally, it will present some conclusions about this chapter.

6.2 Outcomes of Cases of Studies.

Each case of study analysed in the last chapter shows that vessels cannot comply with Chapter Four of MARPOL Annex VI standard to reduce GHG emissions; nonetheless, in each case, it is possible to apply solutions according to the tables presented in Chapter Four. Besides, Chapter Five of this research showed how it is possible to improve the energy efficiency in vessels with a low performance using any alternative proposed.

Table 10. Outcomes of Cases of Studies.

	EEDI			CII		
	Required	Attained	%	Required	Attained	%
Ro-ro Passenger	72.1969	134.202	↑ 85	68.0933	81.0505	↑ 19
Wellboat	26.8275	45.0442	↑ 67	26.7727	71.0727	↑ 165

Source: Author, 2023

Even though it is not possible to evaluate all vessels included in the Chilean cabotage fleet because of the average age of the vessels, the probability of not complying with the norm is very high; therefore, shipowners and companies should take any efficiency improvements and alternatives to reach the standard implemented by the law.

6.3 Barriers and Constraints.

In the implementation of any policy or regulation, there are some barriers and constraints possible to confront but necessary to overcome in order to reach the application of the law. New environmental frameworks follow the same path because, according to this study, they presented several limitations related to the economic, social and technical restraints that can be translated into obstacles for easy execution.

Nevertheless, the crucial action is to recognise those barriers and constraints and eliminate each one or at least mitigate their effects to avoid problems in the implementation. One example of this work is what the IMO made in creating and strategy for GHG emissions reduction, taking into account the majority of barriers found among the member states and finding consensus and solutions (IMO, 2023). In our case, it will describe the limitations found in Chile to be addressed and managed through the elaboration of a roadmap.

To identify barriers and constraints for the implementation of the environmental regulations proposed over the Chilean domestic fleet, the base of information consulted was the experiences of other countries that applied any framework for GHG emissions reduction in their own national fleet. Those examples were mentioned in chapter three of this research. Moreover, other outcomes were obtained from the interviews with the Chilean experts who have the expertise to recognise those characteristics in the national maritime industry.

6.3.1 International Experience.

Regarding the experiences presented by Norway, France and Belgium in the environmental maritime regulations applied to their cabotage fleets, it is attainable to obtain information about some barriers and constraints that they tackled through the implementation and, in certain cases, is possible to assimilate those impacts in the current Chilean situation. In the following section, it will be described and identified the elements capable of being evaluated for the domestic fleet of Chile.

- Existence of underperforming vessels in the cabotage fleet with the consequent non-compliance of MARPOL Annex VI regulations.
- Lack of sufficient maritime administration staff to control the accomplishment of regulations.
- Lack of a specific framework to cover different vessels according to their sizes, types and routes.
- Lack of knowledge of seafarers and companies about the Annex VI requirements and possible efficiency solutions.
- Lack of offers of alternative green fuels in all ports.
- Lack of Shore Power infrastructure in all Ports.
- Need to elaborate on Public and Private initiatives.
- Cooperation between the Public and Private sectors
- Retrofitting obstacles for Fishing vessels (MEPC, 2021).
- Lack of Space on board to store batteries for the electrical propulsion.
- Research and investigation costs.

6.3.2 Interviews Outcomes.

In total, four experts on the Chilean maritime industry were interviewed in order to understand through their knowledge and experiences which would be the main barriers and constraints in the implementation of the environmental regulations proposed in this research. The findings were the following:

- Stakeholders coordination and technical cooperation.
- Lack of a specific and updated environmental framework for the maritime sector that recognises different realities in the industry.
- The average age of the fleet makes retrofit indispensable in some cases; however, this solution is costly and, in many cases, not feasible.
- Lack of financial incentives and subsidies from the public and private sectors to accomplish the GHG reduction requirements.
- The development and implementation of regulations take a prolonged time.
- The current capacity building of the country is not adequate at all.
- There is a lack of sufficient data to evaluate possible scenarios with this implementation and its impacts on the industry.
- Uncertainty of the benefits and costs of the implementation of environmental regulations.
- Lack of control capacity from the Government sector due to the high number of vessels that compound the national maritime fleet.
- Lack of Port Facilities along the country to receive waste from scrubbers or other devices capable of cleaning air pollution.
- Lack of investment in research and development of new technologies and efficiency solutions.
- Lack of technical cooperation with other similar countries of the region.
- Lack of regulations requirements for aquaculture service vessels.
- Lack of carbon tax for the GHG emissions produced by ships.

Undoubtedly, all opinions are important, and each one should be considered in the roadmap to produce a good policy for the implementation of the regulations analysed in this research. According to the experts and the international experience, one good way should be to apply this framework by adapting to the current Chilean reality in coordination with the public and private sectors.

In order to improve the understanding of the barriers and constraints identified, all the information will be organised in the following classification, taking into account those elements that are duplicated in international experience and interviews:

Table 11. Barriers and Constraints Classification.

Classification	Barriers and Constraints
Economics	Retrofitting Costs.
	Lack of financial incentives and subsidies from the public and private sectors to accomplish the GHG reduction requirements.
	Research and investigation cost.
	Lack of carbon tax for the GHG emissions produced by ships.
Technical	Underperforming vessels in the cabotage fleet.
	Lack of Shore Power infrastructure in all Ports.
	Lack of knowledge of seafarers and companies about the Annex VI requirements and possible efficiency solutions.
	Lack of space for batteries storage.
	Lack of a specific framework to cover different vessels according to their sizes, types and routes.
	The development and implementation of regulations take a prolonged time.
	There is a lack of sufficient data to evaluate possible scenarios with this implementation and its impacts on the industry.

	Uncertainty of the benefits and costs of the implementation of environmental regulations.
	Lack of investment in research and development of new technologies and efficiency solutions.
	Lack of technical cooperation with other similar countries of the region.
Policy	Cooperation between the Public and Private sectors
	Need to elaborate on Public and Private initiatives.
	Lack of sufficient maritime administration staff to control the accomplishment of regulations.
	Stakeholders' coordination and technical cooperation.
	Lack of a specific and updated environmental framework for the maritime sector that recognises different realities in the industry.
Capacity Building	Lack of offers of alternative green fuels in all ports.
	The current capacity building of the country is not adequate at all.

Source: Author, 2023.

6.4 Roadmap Proposed.

With the aim to tackle the barriers and constraints for the implementation of the GHG emissions reduction regulations, taking into account the results obtained in the cases of studies, it is indispensable to promote a roadmap to ensure that the regulations involved in the application will accomplish the objective of GHG emissions reduction.

The roadmap should have some aspects capable of settling the limitations recognised, being feasible and effective in establishing the implementation path for the GHG emissions regulations. Thus, it will propose the following elements to reach the action plan divided into stages according to the recommended work plan presented by Masodzadeh et al. (2022):

6.4.1 Current Diagnosis (1º year): It is fundamental to obtain data from vessels about fuel consumption to evaluate the current diagnosis of the Chilean national domestic vessels' GHG emissions conditions because today, this information is not clear, and it is non-existent. The recommendation is to establish an annual Data Collection System, similar to the IMO DCS, to obtain the information required from ownerships. Another important suggestion is to create a Working Group with stakeholders involved in the implementation to start working on the best way to achieve the application using opinions and consensus of participants.

6.4.2 Action Plan (2º - 4 years)**:** The Action Plan should start including the following key elements for the implementation of the MARPOL Annex VI in the domestic fleet:

- **Policy:** A good policy is crucial to implementing new regulations, and this policy should include inter-sector participation, containing different stakeholders around the industry, making roundtables to find the best way to tackle the implementation, and minimising the negative economic and social impact generated by the new framework.

  One possible policy could be the implementation of green shipping transportation using electricity power produced onshore from any type of clan energy (wind turbines, solar power or tidal energy) and transmitting this energy to vessels, which will be stored in batteries onboard the example presented in Appendix 1 with the Helsingborg and Elsinor Ports is a good illustration of this application.

- **Financial Incentives and subsidies:** Several companies are in the maritime industry, and they cannot invest in new technology to achieve the GHG reduction requirements; however, the Government can incentivise the switch by means of incentives or subsidies that promote more efficient vessels and operations. One example of this concept could be tax exemptions for the use of alternative fuels.

- **Technical assessment:** One of the constraints mentioned by the experts was the uncertainty about the possible scenarios with the introduction of this new environmental framework.

- **Trial Period**: For the implementation of new regulations, it is fundamental to apply a trial period in order to test its function and make the necessary changes to improve its efficacy. This period should take around 1 to 3 years.

- **Capacity Building**: This concept is totally applicable to this implementation due to the lack of current capacities existing in Chile; hence, enhancing capacity building is an important aspect of the policy that this research seeks to propose.

For the improvements of this stage, it could be suggested to discuss all the alternatives and initiatives in the working group to evaluate the feasibilities and requirements. Besides, it is possible to define deadlines for every action selected in order to advance gradually with the implementation.

6.4.3 Impact Assessment of the regulations implemented (5º year)**:** All measures taken will generate an impact in different aspects. For example, in the case of one ship needing to make a retrofit, this change will produce an economic impact on the shipowner; therefore, the company could decide to avoid the retrofitting and sell the ship with the consequent loss for the company. Moreover, impacts can be technical and environmental, among others, and it is crucial to evaluate each of them to introduce changes in the policies defined.

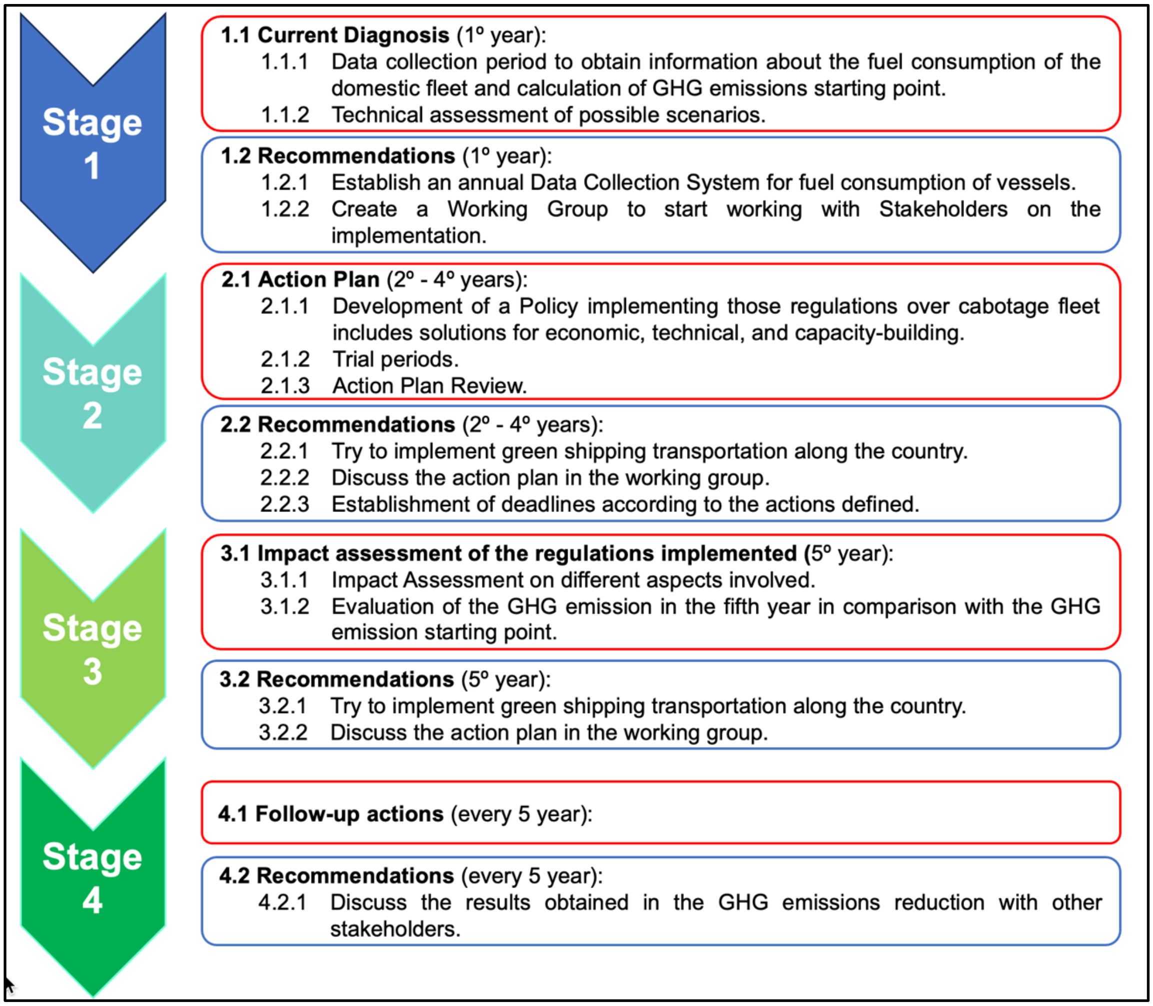
Furthermore, in this stage of the implementation, it should be indispensable to compare the GHG emissions outcomes in the fifth year with the emissions calculated at the starting point.

6.4.4 Follow-up Actions (every 5 years)**:** This stage will be used If the impact assessment shows any need to make changes to improve the implementation in line with the Chilean maritime scenario. It would be relevant if the results obtained with the implementation were discussed with other stakeholders involved to obtain feedback about regulations and how to improve it if it is necessary.

Related to those elements, the following roadmap scheme proposed can be adopted to implement the environmental regulations analysed over the Chilean domestic and inland fleet.

It is important to mention that each stage should be applied in a specific year from the implementation established, and this year is presented next to the title of the phase.

Figure 11. Roadmap Proposed.



Source: Author, 2023.

6.4 Conclusion.

To conclude, this chapter presents several concerns about the barriers and constraints considered by the international experience and experts' opinions regarding the implementation of Chapter 4 of the MARPOL Annex VI in the Chilean domestic and inland fleet. Each barrier was classified as one of the alternatives recognised, such as economics, technical, policy, and capacity building. Then, it was possible to analyse some aspects capable of settling the limitations in order to elaborate a well-planned roadmap, which was presented later.

Chapter 7. Conclusions and Recommendations

7.1 Conclusions.

The research is a review to understand how to address the implementation of regulations for GHG reduction from vessels in a specific domestic and inland fleet, which is the case of Chile. A country that has more than four hundred cabotage vessels to connect cargo and people to every place along its extensive and disseminated coast, where currently is not possible to have an environmental standard of this type. In order to achieve the objectives, the study was divided into 7 chapters to cover all relevant points defined by the author.

The first two Chapters explained the root of the problem of the Chilean Flag State to confront the lack of environmental frameworks to deal with GHG emissions from ships and global warming on this scale; however, it was possible to present the way to tackle the dilemma achieving solutions through the implementation of the Chapter Four of MARPOL Annex VI in the domestic fleet, using parameters such as EEXI, EEDI, CII, and SEEMP, improving maritime energy efficiency and obtaining a reduction in GHG emissions.

The third and fourth chapters considered the literature review and research method, respectively, in order to mention the most important international and national framework for GHG emissions reduction and decarbonisation, as well as the international experience in the implementation of GHG emissions requirements over the different domestic fleet, finalising with the statistical status of the cabotage fleet of Chile to be processed using the methodology defined in Chapter Four, which include interviews and calculations of indexes.

Consequently, two cases of studies analysed were shown in chapter five, where it was possible to apply EEDI and CII indexes over two types of common vessels of the Chilean domestic fleet, such as Ro-ro Passenger Ship and Wellboat. In both cases, EEDI results were negatives in term of comparison between the requirement of the framework and the values obtained; for that reason were necessary to propose some measures to decrease the value and comply with the EEDI required. On the other hand, CII outcomes were out of the range, which means the results did not accomplish the regulations because fuel consumption was much more than the normal range to be lower than the CII required. In that case, a good solution proposed was to decrease the yearly fuel consumption; nonetheless, in the Wellboat circumstance, this measure was not sufficient because the percentage of reduction should be overly to comply. Certainly, in each case, it is possible to combine technical and operational measures to achieve the goal defined by MARPOL; however, the Company has the last decision. The interesting fact was that it is technically feasible to implement the indexes and indicators of MARPOL Annex VI in different types of vessels of the domestic fleet, providing the compulsory adaptation to the current Chilean reality.

In the last chapter, it was shown a proposition of the roadmap discovered in this research, thanks to the identification of the barriers and constraints detected during the investigation and the interviews taken. The chapter includes, in the first part, a description of the barriers and constraints related to the cases of studies. Those barriers were classified into four groups: Economic, Technical, Social, and Capacity Building for a better understanding. Finally, the roadmap elaborated incorporates a current diagnosis of the Chilean Domestic Fleet for the introduction of a new environmental framework, involving all barriers detected to be solved through an Action Plan for the implementation of the regulations, which should be assessed due to their impacts and followed up for the permanent improvement, containing as well, some recommendations for better outcomes.

To conclude, this research proves that it is possible to implement Chapter Four of MARPOL Annex VI taking into account the barriers described and the roadmap proposed which adjust and adapted the international regulations to the national reality, becoming in a national contribution for the maritime decarbonisation.

7.2 Recommendations.

The first recommendation for a successful implementation is to follow the roadmap proposed, elaborating in the first stage a database about fuel consumption, similar to the data collection system, with the aim to obtain all information concerning the use of fuel onboard and analysing how is the performance of vessels related with routes, weather conditions among any other relevant variable. Moreover, the creation of a working group among stakeholders can produce better results thanks to consensus and agreements and public and private cooperation. Their job should be made along the complete process, evaluating each implementation and proposing the improvements required for the Chilean reality.

Before the implementation and as a part of the action plan, it would be important to adapt those regulations to the reality of the Chilean merchant fleet in order to utilise the framework in a homogenous approach, considering all vessels involved in this fleet. This is an example of defining guidelines on the operational carbon intensity rating for ships under 5000 GT because this segment does not approve the current IMO guidelines for vessels.

In terms of economic recommendations, the possibility of creating a fund or budget to support the implementation could help the switch required for the sector, understanding different situations and conditions of the maritime business, promoting incentives for low carbon emissions, research, and many other initiatives.

Defining electricity as the first stage energy switch bringing green energy in ports to vessels with battery propulsion could be a good idea, following the example of Sweden and Denmark with some ferries in Helsingborg and Elsinor straight.

Create regional technical cooperation with countries with similar maritime activities, providing acknowledges and experience about the decarbonisation of the maritime sector.

Finally, change the mindset of the industry and the country to reach decarbonisation and energy efficiency in all sectors can produce the reinforcement required for the country to understand the importance of climate change and its impact in the present and future.

List of Appendices

Appendix 1 – Technical Measures

1. **Ship Design**: During the designing and construction phase of any vessel, it is possible to model an efficient hull form capable of decreasing the resistance and improving its hydrodynamics performance. In other words, with less resistance, we will need less power for the propulsion, and thence, we can achieve less fuel consumption. Besides, it is possible to understand this asseveration thanks to the following formula (Molland et al., 2011):

$$\boldsymbol{P_B} = \frac{R_T * V_S}{\eta_D * \eta_{TR}} \tag{3}$$

Where;

P_B	:	Break power of the main engine
R_T	:	Total Ship resistance
V_S	:	Ship speed
η_D	:	Quasi propulsion Coefficient
η_{TR}	:	Transmission Coefficient

Regarding the equation, power (P_B) is directly proportional to resistance (R_T); basically, if the resistance increases, the vessel will need an increment of power to keep the same speed, and with an addition of power, more fuel is needed. In consequence, with major fuel combustion, the total GHG emission production will grow.

The hull optimisation can be obtained using the technologies available today in designing better hull shapes, for example. Also, the use of computational fluids dynamics software allows for analysis of the hull performance for the sea-making change in order to attain the best option.

The range of improvement depends on the comparison of different hull model designs because it is possible to contrast the results using CFD analyses or towing tank testing.

Nevertheless, this option is mainly used for new constructions because, for existing vessels, it is almost impossible to change the hull shapes despite some options of retrofitting as bulbous bow modification, for example. Bulbous reduction fuel consumption potential can be achieved between 3% to 5% (GV2050, 2022).

In the future, it cannot be ruled out that new technologies will appear to diminish the frictional effects of hull enhancement on the ship's performance at sea.

2. **Post-Combustion devices**:

Undoubtedly, the combustion process of fossil fuel contributes to the generation of GHG emissions due to the chemical reaction between air, fuel and heat. This is the reason why the treatment of the exhaust gases generated in every engine is fundamental for two main objectives, such as the reduction of pollutant emissions, energy optimisation, or both. The following paragraphs, will describe those current devices that can lead to procuring the objectives mentioned, making the fuel consumption of vessels more efficient.

a. **Selective Catalytic Reduction (SCR):**

The Selective Catalytic Reduction device is a post-combustion equipment used to convert back the Nitrogen oxide (NOx) emission produced during the combustion into the molecular form of Nitrogen to be released into the air, with the result of avoiding the pollutant condition of the NOx.

Its function works by catalysing the exhaust gases through a catalyst agent, normally ammonia or urea, which converts the NOx into N_2, reducing emissions up to 95% (Calleya, 2023).

Usually, the Installation includes other equipment to provide the catalyst and system control and piping to connect those elements. Its location is in any place along the exhaust gas chimney. Moreover, its utilisation onboard is regulated by IMO frameworks in order to attain the NOx emissions level allowed with the respective certification, testing, surveys, etc.

b. Exhaust Gas Recirculation (EGR):

This implement uses the temperatures kept in the exhaust gases of the engine to activate the turbocharger, making the combustion process more efficient. Besides, the EGR can reduce NOx emissions by recirculating the exhaust gases back into the engine cylinder.

The potential NOx reduction is around 20% to 50%, and its use is regulated by IMO frameworks, including testing, surveys, and certification, among other requirements (Calleya, 2023).

These devices allow vessels to accomplish both objectives, GHG reduction and energy optimisation, with the reutilization of the exhaust gas heat.

c. Onboard Carbon Capture Store (OCCS):

The use of Carbon Capture Store Onboard devices is one of the last technological improvements by the maritime industry to mitigate GHG emissions and now, is now under development for different companies. Its potential outcomes are so relevant and promising that it can generate a new way to obtain the IMO objectives of keeping the use of fossil fuel oils.

Its function works as equipment that can separate CO_2 from the exhaust gases through the absorption of any specific chemical component and then is carried to a storage tank onboard to be posteriorly discharged in any facilities onshore.

Some cases of studies presented by Maersk Mc-Kinney Moller Center (2022), showed that it could be possible to reduce GHG emissions between 55% to 60%. Nonetheless, the fuel consumption of those results describes an increase of up to 45% of the total fuel consumption as additional. energy requirements. On the other side, this option can be installed in new builds as retrofits.

Furthermore, Carbon capture will be both costly and space-demanding on ships and furthermore requires a new infrastructure to store CO_2. (DNV, 2021). Moreover, ports will require facilities to receive the CO2 and processes according to the frameworks available for these services.

Clearly, this option is not mature enough; however, different industries are working on its development to provide a well-prepared solution for climate change in the medium term.

3. **Propulsion Optimisation**: Propulsion optimisation can include many different options due to the vast alternatives that currently can be used for new and existing ships. Between the technologies and devices produced today, it is feasible to seek retrofitting elements that can save between 2 to 10% of fuel consumption (Insel, 2023); therefore, the energy efficiency improvement is considerable. In the following paragraph, we will analyse the devices available for vessel improvements:

a. Wake Equalizing and Flow Separation alleviating:

Those devices allow for the improvement of the sea flow that is used for the propeller, correcting possible hydrodynamic alterations. Those components can prevent or mitigate the vortex phenomenon in the propeller, obtaining better performance and, henceforth, a reduction in propulsion fuel consumption with a saving rating of up to 5%.

To achieve the objectives of those gadgets, there are four options that can be selected for ownership as follows: ducts, Grothues spoilers, Schneekluth duct, and vortex generators.

b. Pre–Swirl Devices:

Those kinds of devices are usually evaluated in conjunction with the propeller to reach better performance; for that reason, their uses should be calculated as a system adding the propeller comportment in the equations because some variables can be enhanced in the results obtained, such as hull, rotative and propeller coefficients,

The function of those gadgets is to improve the propeller hydrodynamic flow before entering the swirl generated by the blades, saving fuel consumption in the range of 2-10% (Insel, 2023). Besides, it can be applicable to any type of vessel.

In the market, it can be possible to find several alternative pre-swirl devices, for instance, Fines, Mewis duct, Stators, and Twisted fin, with offbeat efficiencies and results.

c. Post–Swirl Devices:

In the same way as the pre-devices, post-swirl devices can achieve improvements in the energy efficiency path, saving fuel consumption between 2-6%; notwithstanding, its function can be beneficial if it is used in combination with the propeller performance and pre-swirl device.

The pro-swirl device works by correcting the flow after the propeller, mitigating some anomalies generated when water trespasses the propeller blade's effects.

Examples of those devices proposed by the market are different, but it is possible to improve the objectives when calculations for its selection include the system compound by pre-swirl device, propeller and post-swirl component. Some types of post-swirl are Stators, Fin, Bos cap, Conrarotating propellers, Rudder bulbs, Costa bulbs, and Twister rudders. Furthermore, all sorts of devices can be installed on any type of ship.

d. High–Efficiency Propellers:

The efficiency of the propeller is part of the equation used to calculate the power propulsion; for that reason, it is important to consider the best option at the moment to assess the fuel consumption parameters.

Nowadays, high-efficiency propellers are taking relevance because of their suitability to the operational characteristic of the vessels and their properties on the fuel consumption for propulsion reduction, which can be among 3-10%. Equally important is their uncomplicated implementation for any type of ship, including new or existing vessels in the design phase or retrofitting, respectively.

Some types of high-efficiency propellers are Kappel propellers, CLT propellers, and Controllable Pitch Propellers (CPP), among others.

Regarding any device described, the cost can be an important issue at the moment to select any alternative; however, it is crucial to assess saving cost over fuel consumption to compare the benefits and useful utilities of every component.

4. **Alternative Source of Propulsion**:

From the last change in the source of ship energy propulsion, fossil fuels have had primacy among any other; however, GHG emissions reduction requires a less pollutant alternative. Such alternatives should be different, but renewals are taking the lead of the options. The following paragraph will describe the existing alternatives for the maritime industry and to leave the pollutant fossil fuels.

a. **Solar Energy**:

To generate solar power for the propulsion of any vessel, it is necessary to install photovoltaic panels because the total solar panel area is directly proportional to the power produced.

In this order, it is feasible to generate propulsion with solar power, but there are some constraints important to take into account. Basically, the first limitation is related to the solar-to-electricity conversion efficiency, which is around 25% with the current technology of panels (Schönborn, 2023). An example of irradiation and its conversion into electricity is presented in Appendix 3.

Therefore, following the example presented, it is necessary to install 400 (m^2) of photovoltaic panels on board to generate 1 (MW) of power, and not all types of vessels have this available area. A typical example is the Container Ship, where decks are designed to carry containers and loading and unloading constantly, making it impossible to keep an area available for photovoltaic panels; however, in vessels such as car carriers, it could be possible to use a zone for this purpose.

The second constraint is sun irradiation availability because it is only for some hours per day and depends on the region in which the vessel is sailing (Lan et al., 2015).

On the other side, when solar panels obtain energy from the sun, this energy is converted into electric energy that is possible to store in batteries, but to store a huge amount of energy, the vessel needs a lot of space to put the batteries, and normally vessels use space for cargo (Jossen et al., 2004).

Finally, the possibility of fuel consumption savings depends on the installation of photovoltaic panels in every vessel and how ships use this energy on board.

b. **Wind Energy**:

The case of wind energy is different because it has been used from the beginning of sailing history, and today, it is returning as a clean option for new and existing vessels.

Currently, it is possible to find different devices such as Rig Wing Sails, Flettner Rotors, Turbosails, Dynaring, and Kites, among other options, which can be installed on board or designed for new vessels, reaching fuel consumption saving up to 30% and 60% for existing and new vessels, respectively (Schönborn, 2023).

Another example of potential energy savings shows that rigid sails can obtain between 55 and 60% working together with the conventional fossil fuel engine (Chou et al, 2021).

c. **Nuclear Energy**:

Nuclear power is an interesting option to produce power on board and is currently used for Large Naval Vessels such as aircraft carriers and Ballistics Submarines. Nevertheless, there are some applications in the Russian Merchant fleet that can be studied (Freire et al., 2015).

Nuclear energy generated on board is totally zero GHG emission and is converted into electricity usable in different equipment, being clean and not pollutant. However, there are some other constraints with the use of this power source because nuclear management is another chapter that needs to be developed in the case of choosing this energy option (Calleya, 2014).

In the case of Chile, Nuclear Power is not a possibility due to political and societal barriers that prohibit its utilisation; nonetheless, it can be evaluated for some interested in this matter.

d. **Electric Power:**

Electricity can be an exceptional source of energy because of its availability and possibility to be stored on board. Indeed, there are many vessels that use electricity for propulsion, charging batteries in every stayed at berth. This is the case of some Ferries that connect the ports of Helsingborg and Elsinore between Sweden and Denmark, an example that can reproduce in other countries.

The theory of this source of energy is to obtain electricity from any source and store this energy in any sort of battery or supercapacitors on board. There are two important issues to solve at the moment to select this option. First is the way to obtain energy because the concept is to reduce GHG emissions; therefore, that way should be clean or almost net zero emission. The second issue is the volume of batteries to complete the journey of the vessel (Schönborn, 2023).

According to the explanation made before, if we have a Ferry using electrical power in batteries that connects two ports by crossing a strait of 4 nautical miles sailing at 10 (kn) for 24 minutes, it should need 800 (kWh) for every trip between ports (calculations can be checked in Appendix 4). Then, the total volume needed for electricity storage is 4 (m^3), assuming the use of lithium-ion batteries of 4.2 (V). The evaluation reveals that only one journey vessel needs huge space for batteries; thus, if the trip is larger than this example, the volume can increase considerably. Nevertheless, it is a good application for the short-sea shipping concept.

5. **Alternative Fuels**: From the last change in the source of ship energy propulsion, fossil fuels have had primacy in use onboard; nonetheless, due to the need to reduce GHG emissions, some alternative fuels have clean or at least less pollutant than the current tendency for the use of fossil fuels.

   Those alternatives which are applicable to marine engines will be described in the following section.

   a. **Methane:**

      It is possible to find methane as Liquified Natural Gas (LNG) and Liquid Biogas (LBG), and both types can be used in Diesel cycle and Otto cycle engines.

With the use of this fuel, it is realisable a reduction of CO_2 emissions of 23% in Diesel engines and 30% in Otto engines, and NOx reduction between 20% to 30% for the Diesel cycle and 85% for the Otto cycle. In the case of Biogas, it is attainable up to 65% GHG reduction compared with Diesel fuel (Schönborn, 2023).

Despite every advantage of methane in pollution reduction terms, it is important to take into account that methane is the second GHG in percentage in the atmosphere and has a global warming potential of 28 with respect to CO_2; thus, its uses should be evaluated before deciding its implementation due to the eventual pollution with the unburned gas release to the air (Boucher et al., 2009).

b. Biofuels:

Biofuels today appear as a clean option for the transition from fossil fuels to other less pollutants. Besides, its chemical components make it simple for implementation onboard (Korberg et al., 2021).

As mentioned by the U.S. Department of Energy (2007), GHG emissions of fuels vary, achieving, in the case of cellulosic ethanol, an 86% reduction compared with gasoline. Moreover, ethanol is biodegradable without harm to the environment.

In the case of biodiesel, it is possible to use this fuel onboard without engine modification, and it also has the potential to reduce pollutant emissions by around 78% in contrast with normal diesel oil. The problem is that emissions of NOx can increase by 10% compared with petroleum (Mohd Noor et al., 2018).

For the application in Chile, currently, there is no availability for ships; therefore, the feasibility is uncertain, as well as the cost. Nevertheless, with the growing interest in the development of this fuel, some companies make it viable for its use in the future.

c. Hydrogen:

Unquestionably, hydrogen is the most promising fuel for the future onboard, thanks to its zero GHG emission. But its price, development, availability, storage and transportation are issues important to note (Riera et al., 2023).

The electrolysis for the production of hydrogen needs a great amount of energy that can be obtained from green sources such as wind or solar energy. In the case of Chile, a public strategy established the production of hydrogen from solar power in the North of the country meanwhile, it will be used wind power in the South. Therefore, in the short term, it will be hydrogen available for use in vessels (Energy Minister of Chile [ENC]. 2019). However, technology is a limitation nowadays because ships in Chile are old, and they will need retrofit engines to the utilisation of this kind of fuel.

Another limitation is the storage due to the difficult properties of this chemical element to be managed; they need special tanks with a high level of compression and very low temperatures that, today, are not possible to find easily onboard (Van Hoecke et al., 2021).

Price can be another constraint because of the lack of availability in the market and the cost of producing, added to the fact that the engine should be retrofitted. However, it is estimated that the price of production will decrease in the future (Alkhaledi et al., 2022).

Notwithstanding all limitations explained, the industry is working briskly in the development of technologies to mitigate the constraint in the use of hydrogen for maritime transport; for that reason, its implementation onboard seems not far.

d. Ammonia:

Ammonia is the other potential zero-emission fuel that pledges for GHG emission reduction. One of the relevant points of this compound is that for the same amount of energy, the volume required to store ammonia is less than hydrogen. Another positive asset of ammonia is the current level of international trade as fertiliser, showing experience and capability of transportation in comparison with hydrogen. Because of the direct relation between the production of ammonia and electricity, the prices have varied during the last 20 years but are expected to decrease in the future. Regarding the feasibility of use as fuel propulsion, it is possible to modify internal combustion engines for its utilisation (Det Norske Veritas [DNV], 2020).

Similarly to hydrogen, its production and availability for maritime propulsion purposes have not been totally developed yet (Mallouppas et al., 2022); however, the industry is working on it because of its excellent properties to reduce GHG emissions, according to the IMO ambition. Additionally, there is a close relationship between the production of hydrogen and ammonia and their transportation, thanks to their properties that make ammonia one of the methods to carry hydrogen (Sun et all., 2022).

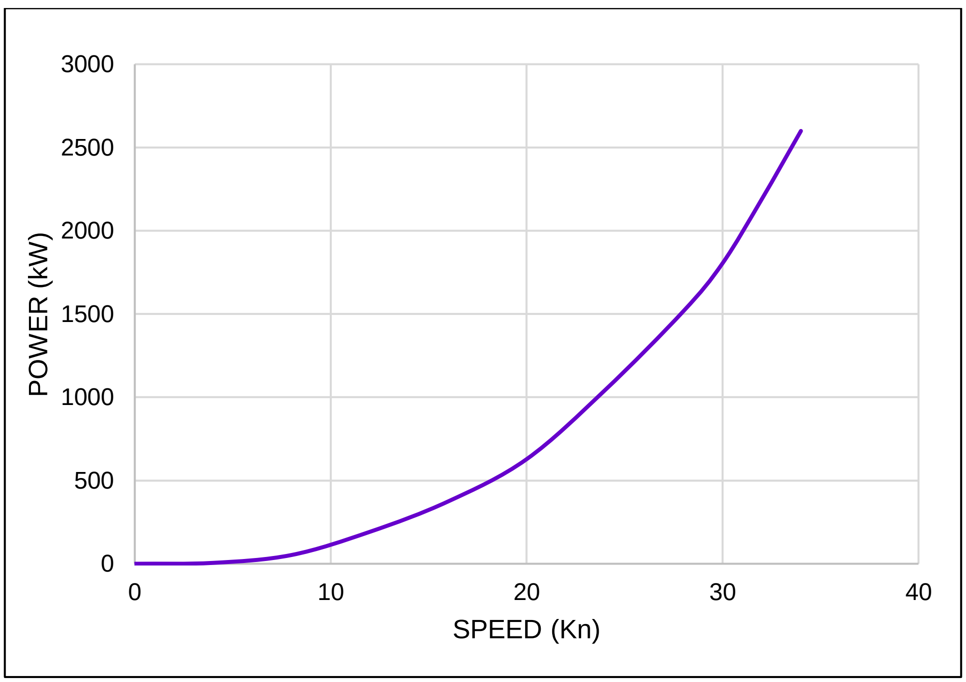
Even though it is beneficial in terms of emissions, ammonia is really dangerous and toxic for people and corrosive for materials; for that reason, its use should be analysed and regulated by the IMO before applying it on board.

Appendix 2 – Operational Measures

1. Speed Reduction:

Speed Reduction or Slow Steaming is one of the primary measures to reduce GHG emissions, thanks to the exponential relation between power and speed existing in marine vessels. In fact, the importance of speed reduction is so clear that it is one of the short-term measures implemented by MARPOL Annex VI with the installation of a device that limitate the power propulsion in engines or the shaft; those gadgets are Engine Power Limitation (EPL) and Shaft Power Limitation (SHaPoLi).

Figure 27. Typical power graph showing the exponential relation between power and speed.



Source: Elaborated by Jorge de la Fuente for the Trimaran propulsion analysis.

According to IMO, EPL and SHaPoLi are used to comply with EEXI requirements about speed reduction; however, this mechanism can be applied as well in domestic vessels (Resolution MEPC.335(76), 2021).

Regarding domestic vessels and operative measures, there is no obligation to install EPL or SHaPoLi to achieve the emission reduction benefits because companies or ownerships can plan their ship's operations by reducing the speed with the aim of decreasing the fuel consumption and, therefore, lower emissions.

The total amount of emission reduction depends on several variables such as route, cargo, type of vessel, environmental condition, and engine performance, among many others; thus, the results are independent for every ship or company, being necessary to optimise the speed granting the objectives established by the ownerships which should include climate action. Nonetheless, IMO has established in its Fourth IMO Greenhouse Gas Study (2020) a potential CO_2 reduction of 7.5%.

2. Optimal handling of ships and trim optimisation:

Optimal handling as an operational is directly linked with trim optimisation, and those measures take relevancy due to the option of saving fuel consumption and decreasing emissions. Optimisation of cargo can impact the trim of the ship and, therefore, it can improve or deteriorate sailing conditions, including an increase in fuel consumption because of a large wet surface under the water, which produces major frictional, wave resistance, and transom submergence, in consequence, the need of more power to advance. In the IMO Train the Trainer Course on Energy Efficient Ship Operation (2015), they indicated that it is feasible to save between 2% and 4% of fuel consumption with an optimal trim related to the draft and speed of the ship.

Ballast condition plays a crucial role in improving the trim condition, being essential to use this system as an instrument for better sailing condition and regulating weight distribution refining stabilities parameters. Nonetheless, ballast water and sediments are regulated by an international framework that should be applied onboard at every moment.

This optimisation should be planned to use operational programs for loading planning; however, during the designing phase, it is important to generate a model with the best cargo performance, avoiding any mistake of trim and draft, allowing the vessel to sail with the best efficiency possible, according to its characteristics, trim tables, etcetera.

3. **Just-in-time arrivals:**

The concept of just-in-time arrivals can be described as the evasion of excessive and non-required time for operations in ports or routes. For instance, when a vessel arrives two days early at any port, it should wait to start unloading. This event produces 48 hours of inactivity and auxiliary engine use, which means more fuel consumption and more pollutant emissions.

There are some ideas to improve the planning voyage, making it optimal and avoiding those losses. For example, operation management is crucial and virtual arrivals is another notion feasible to introduce in the execution of voyage and itinerary with the currently available resources. All parties involved in the ship arrivals should participate in this optimisation because each one is a link in the logistic chain, making the interaction among them the key element of coordination. This process may be the most difficult barrier due to each part having its own coordination system that should be adapted completely for the new system.

The percentage of fuel consumption savings can be calculated taking into account all variables of the equation, and each company have the data to develop this improvement.

4. Anti-fouling and coating:

Basically, frictional resistance is made by the hull, and its regular cleaning can avoid increments in fuel consumption. It has been estimated that a good plan of drydocking and hull cleaning to eliminate fouling can decrease up to 40% in drag resistance (Insel, 2023).

This result of drag increments can be translated into saving for fuel consumption levels that are around 15% to 20% in typical vessels, which can be exemplified by the fact that the undermining of the propeller and hull efficiency caused by fouling effects produced between 9% and 12% of the world fleet GHG emissions in 2011 (MEPC, 2011). This example was taken from a study presented by the Clean Shipping Coalition (CSC) in the 63º session of the Marine Environmental Protection Committee in the IMO.

The propeller is another device that can increase the drag if it does not perform proper maintenance, generating roughness in blades due to fouling. In that case, fuel consumption potential can be up to 3%, according to IMO Train the Trainer Course on Energy Efficient Ship Operation (2015).

5. Controllable Pitch Propeller (CPP):

The pitch of the propeller can be optimised by using a propeller with controllable blade positions in order to improve efficiency even during its rotating work. Its function allows for enhancing propeller performance with the thrust force generated; thus, the propeller efficiency is improved as well.

Despite those devices being more expensive than a fixed propeller because they need a system to control the movements of the blades and their construction needs more components, if it is used effectively, it is feasible to reach up to 0.5% efficiency, which is equal to fuel consumption saving (IMO, 2015).

6. Environmental conditions of the route:

Environmental conditions include weather analysis, wave conditions of the route, water depths, and several other environmental factors that can impact the ship's performance during the travel. For example, if a vessel is sailing under bad weather conditions on the Beaufort scale of eight, it is clear that fuel consumption will increase because of the need to keep the safety of people and cargo, making a major effort with the engine to follow the schedule planned. In that case, using the weather forecast available today, it is possible to take alternative routes that are less expensive in terms of fuel consumption, avoiding bad weather, abnormal wave situation or any other problem in the route.

IMO has developed an approximation relation between increased wind strength, direction, and increment of fuel consumption for each Beaufort unit as follows:

Table 12. Relation between Wind direction and Fuel Consumption.

Wind direction	Type	Increase Fuel Consumption (%)
315º - 360º; 0º - 45º	Head Wind	4
45º - 135º; 225º - 315ª	Side Wind	2
135º - 225º	Tail wind	1

Source: Dr. A. I. Ölçer Lectures, 2023.

Squad effects are another issue that should be taken into account during route planning because shallow waters can form an increment in the resistance of the vessel; therefore, trying to keep a high speed could increase the fuel consumption level with the consequent effect on the GHG emissions. In that case, the relation between fuel consumption, depths and speed is the following:

Table 13. Relation between Speed, Depth and Fuel Consumption.

Speed (Kn)	Depth (m)	Increase Fuel Consumption (%)
10	8	5
	10	3
	100	0
17	8	20
	15	10
	100	0
20	8	30
	15	20
	100	0

Source: Dr. A. I. Ölçer Lectures, 2023.

With those approximations, it is possible to understand how much energy is feasible to save in planning and improving the route, which is especially interesting and applicable in those cases where vessels sail for fiords and canals of the South Chilean routes.

7. Ship Maintenance Management:

Ship Maintenance Management seems to be normal behaviour of the Company; nevertheless, guaranteeing a good ship maintenance system can be the key element for the energy-efficient management of the engines and equipment onboard, marking the difference between good and bad performance.

For example, depending on the types of maintenance options, shipowners could prevent engine failures by following the instructions for maintenance developed by the engine manufacturer; therefore, it could avoid injector failures that produce low-quality combustion and more GHG emissions.

To achieve this concept, it is crucial to keep a link between the company and the vessel, informing every event and complying with the maintenance plan.

Appendix 3 – EEDI Calculations

According to the EEDI framework analysed in this research, Resolution MEPC.308(73), the following section will describe the formulas and calculations in use for the study cases:

Corrections factors were not included because of the lack of more data and details about ship operations.

- **Ro-ro Passenger Ship**:

DWT	:	590 (ton)
P_{ME} 1 Starboard (MCR)	:	492 (kW)
P_{ME} 2 Starboard (MCR)	:	492 (kW)
P_{ME} 1 Port (MCR)	:	492 (kW)
P_{ME} 2 Port (MCR)	:	492 (kW)
P_{AE} 1 (MCR)	:	129 (kW)
P_{AE} 2 (MCR)	:	129 (kW)
P_{AE} 3 (MCR)	:	75 (kW)
$C_{F\,ME}$	:	$3.206 \left[{(t * CO_2)}/{(t * Fuel)}\right]$
$C_{F\,AE}$	:	$3.206 \left[{(t * CO_2)}/{(t * Fuel)}\right]$
SFC_{ME}	:	$190\ ({g}/{kWh})$
SFC_{AE}	:	$215\ ({g}/{kWh})$
V_{ref}	:	11.5 (Knots)

Formulas:

To obtain the $\boldsymbol{EEDI_{Req}}$:

$$EEDI_{Att} \leq EEDI_{Req} = \left(1 - \frac{x}{100}\right) * EEDI_{ref} \tag{2}$$

a. ***Reference line value ($\boldsymbol{EEDI_{ref}}$)***:

$$EEDI_{ref} = a * b^{-c} \tag{4}$$

$$a = 902.59$$
$$b = 590$$
$$c = 0.381$$

$$EEDI_{ref} = 902.59 * 590^{-0.381}$$

$$\boldsymbol{EEDI_{ref} = 79.3955}$$

b. Reduction Factor ($\boldsymbol{x}$), by interpolation:

$$x = \frac{(20 - 0)}{(1000 - 250)} * (590 - 250)$$

$$\boldsymbol{x = 9.067}$$

Then;

$$EEDI_{Req} = \left(1 - \frac{9.067}{100}\right) * 79.3955$$

$$\boldsymbol{EEDI_{Req} = 72.1967}$$

To obtain $\boldsymbol{EEDI_{Att}}$:

$$EEDI_{Att} = \frac{(P_{ME} * C_{F\,ME} * SFOC_{ME}) + (P_{AE} * C_{F\,AE} * SFOC_{AE})}{Capacity * \, V_{Ref,app}} \tag{5}$$

c. Power of the Main Engine ($\boldsymbol{P_{ME}}$):

$$P_{ME} = 0.75 * MCR \tag{6}$$

$$P_{ME} = 0.75 * 492 \; (kW)$$

$$\boldsymbol{P_{ME} = 369 \; (kW)}$$

d. Power of Auxiliary Engine ($\boldsymbol{P_{AE}}$):

$$P_{AE} = 0.05 * MCR \tag{7}$$

$$P_{AE\_1} = 0.05 * 129 \; (kW)$$

$$\boldsymbol{P_{AE\_1} = 6.45 (kW)}$$

$$P_{AE\_2} = 0.05 * 75 \; (kW)$$

$$\boldsymbol{P_{AE\_2} = 3.75 (kW)}$$

e. Certified Specific Fuel Consumption ($\boldsymbol{SFC}$):

$$\boldsymbol{SFC_{ME} = 190 \left({}^{g}/_{kWh} \right)}$$

$$\boldsymbol{SFC_{AE} = 215 \left({}^{g}/_{kWh}\right)}$$

f. **EEXI**$_{Att}$:

$$EEDI_{Att} = \frac{(4(369 * 3.206 * 190) + 2(6.45 * 3.206 * 215) + (3.75 * 3.206 * 215)}{11.5 * 590}$$

$$\boldsymbol{EEDI_{Att} = 134.203 \left({}^{gCO_2}/_{tnm}\right)}$$

g. Comparison between $EEDI_{Req}$ and $EEDI_{Att}$:

$$EEDI_{Req} = 72.1967 < EEDI_{Att} = 134.203$$

$$\boxed{\therefore \boldsymbol{EEDI_{Req} < EEDI_{Att}}}$$

Certainly, in this case, the vessel does not comply with the established reference where $\boldsymbol{EEDI_{Att}}$ should be minor than $\boldsymbol{EEDI_{Req}}$.

- **Wellboat Vessel**:

A Wellboat vessel is a kind of ship that has the operational profile to carry alive fish using tanks totally full of water or totally empty for sailing conditions; for that reason, in terms of operational performance is similar to a small tanker. For the purpose of this research, due to a lack of specific information about this type of vessel, it will be using the tanker data available in Chapter Four of MARPOL Annex VI.

DWT	:	2490 (ton)
P_{ME} (MCR)	:	2498 (kW)
$P_{AE}1$ (MCR)	:	830 (kW)

P_{AE} 2 (MCR)	:	830 (kW)
P_{AE} 3 (MCR)	:	830 (kW)
P_{AE} 3 (MCR)	:	830 (kW)
$C_{F\,ME}$	:	$3.206\ \left[{}^{(t * CO_2)}/_{(t * Fuel)}\right]$
$C_{F\,AE}$	:	$3.206\ \left[{}^{(t * CO_2)}/_{(t * Fuel)}\right]$
SFC_{ME}	:	$190\ ({}^{g}/_{kWh})$
SFC_{AE}	:	$215\ ({}^{g}/_{kWh})$
V_{ref}	:	11 (Knots)

Formulas:

To obtain the ***EEDI**$_{Req}$*:

$$EEDI_{Att} \le EEDI_{Req} = \left(1 - \frac{x}{100}\right) * EEDI_{ref} \qquad (2)$$

a. ***Reference line value ($EEDI_{ref}$)***:

$$EEDI_{ref} = a * b^{-c} \qquad (4)$$

$$a = 1218.8$$
$$b = 2490$$
$$c = 0.488$$

$$EEDI_{ref} = 1218.8 * 2490^{-0.488}$$

$$\boldsymbol{EEDI_{ref} = 26.8279}$$

b. Reduction Factor (***x***), by interpolation:

$$x = \frac{(20-0)}{(20000-4000)} * (2490-4000)$$

$$\boldsymbol{x = -1.8875}$$

Due to the number obtained as a Reduction Factor, it will be used as the minor number that can be interpolated for tanker vessels equal to 4,001 GT.

$$x = \frac{(20-0)}{(20000-4000)} * (4001-4000)$$

$$\boldsymbol{x = 0.00125}$$

Then;

$$EEDI_{Req} = \left(1 - \frac{0.00125}{100}\right) * 26.8279$$

$$\boldsymbol{EEDI_{Req} = 26.8276}$$

To obtain $\boldsymbol{EEDI_{Att}}$:

$$EEDI_{Att} = \frac{(P_{ME} * C_{F\ ME} * SFOC_{ME}) + (P_{AE} * C_{F\ AE} * SFOC_{AE})}{Capacity * V_{Ref,app}} \tag{5}$$

c. Power of the Main Engine ($\boldsymbol{P_{ME}}$):

$$P_{ME} = 0.75 * MCR \tag{6}$$

$$P_{ME} = 0.75 * 2498\ (kW)$$

$$\boldsymbol{P_{ME} = 1873.5\ (kW)}$$

d. Power of Auxiliary Engine (P_{AE}):

$$P_{AE} = 0.05 * MCR \tag{7}$$

$$P_{AE\_1} = 0.05 * 830\ (kW)$$

$$\boldsymbol{P_{AE\_1} = 41.5\ (kW)}$$

$$P_{AE\_2} = 0.05 * 195\ (kW)$$

$$\boldsymbol{P_{AE\_2} = 9.75 (kW)}$$

e. Certified Specific Fuel Consumption (SFC):

$$\boldsymbol{SFC_{ME} = 190\ \left({}^{g}/_{kWh}\right)}$$

$$\boldsymbol{SFC_{AE} = 215\ \left({}^{g}/_{kWh}\right)}$$

f. **EEXI**$_{\mathrm{Att}}$:

$$EEDI_{Att} = \frac{(1873.5 * 3.206 * 190) + 3(41.5 * 3.206 * 215) + (9.75 * 3.206 * 215)}{11 * 2490}$$

$$\boldsymbol{EEDI_{Att} = 45.0442\ \left({}^{gCO_2}/_{tnm}\right)}$$

g. Comparison between $EEDI_{Req}$ and $EEDI_{Att}$:

$$EEDI_{Req} = 26.8276 < EEDI_{Att} = 45.0442$$

$$\boxed{\therefore \boldsymbol{EEDI_{Req} < EEDI_{Att}}}$$

Certainly, in this case, the vessel does not comply with the established reference where $EEDI_{Att}$ should be minor than $EEDI_{Req}$.

- **Salmon Farm**:

Despite the data obtained from the industry, Salmon Farms cannot be supported by EEDI or EEXI equations because the information needed for the calculations, according to the MARPOL regulation, cannot be adapted to marine structures if it is not possible to use any reference to compare EEDI/EEXI reference with EEDI/EEXI required. This problem will be considered as a limitation for further analysis of this research.

- **Data Summary**:

Table 14. EEDI Calculations Summary.

EEDI	Ro-ro Passenger Ship	Wellboat
$EEDI_{Ref}$	79.3955	26.8279
x	9.067	0.00125
$EEDI_{Req}$	72.1969	26.8275
P_{ME} (kW)	4*(369)	1873.5
P_{AE} (kW)	2*(6.45) + 3.75	3*(41.5) + 9.75
$SFOC_{ME}$	190	

$\boldsymbol{SFOC_{AE}}$	125	
$\boldsymbol{V_{Ref}(kn)}$	11.5	11
$\boldsymbol{EEXI_{Att}}$	134.2029	45.0442

Appendix 4 – CII Calculations

According to the CII framework, Resolution MEPC.352(78), analysed in this research, the following section will describe the formulas and calculations in use for the study cases:

- **Ro-ro Passenger Ship**:

Data about the vessel:

Gross Tonnage	:	1424
DWT	:	590
Fuel Consumption (FC)	:	$1800\ ton$
$C_{F\,ME}$ *Diesel*	:	$3.206\ \left[{}^{(t * CO_2)}/_{t * Fuel}\right]$
Distance traveled (Dt)	:	$50000\ NM$
Annual Reduction Factor (z) for 2023	:	5%

Formulas:

To calculate the CII_{Req}:

$$Required\ annual\ operation\ CII = \left(1 - \frac{z}{100}\right) * CII_{Ref} \quad (3)$$

a. CII_{Ref}:

$$CII_{Ref} = a * Capacity^{-c} \quad (8)$$

$$a = 2023$$

$$Capacity = 1424$$

$$c = 0.46$$

$$CII_{Ref} = 2023 * 1424^{-0.46}$$

$$\boldsymbol{CII_{Ref} = 71.6772}$$

b. $\boldsymbol{CII_{Req}}$:

$$Required\ annual\ operation\ CII = \left(1 - \frac{Z}{100}\right) * CII_{Ref}$$

$$Required\ annual\ operation\ CII = \left(1 - \frac{5}{100}\right) * 71.6772$$

$$Required\ annual\ operation\ CII = 68.0933$$

$$\boldsymbol{CII_{Req} = 68.0933}$$

To obtain the $\boldsymbol{CII_{Att}}$:

c. $\boldsymbol{CII_{Att}}$:

$$CII_{Att} = \frac{FC * C_F}{C * D_t} \tag{9}$$

$$CII_{Att} = \frac{(1800 * 10^6) * 3.206}{1424 * 50000}$$

$$\boldsymbol{CII_{Att} = 81.0505}$$

d. Comparison between $\boldsymbol{CII_{Req}}$ and $\boldsymbol{CII_{Att}}$

$$CII_{Req} = 68.0933 < CII_{Att} = 81.0505$$

$$\boxed{\therefore \boldsymbol{CII_{Req}} < \boldsymbol{CII_{Att}}}$$

Certainly, in this case, the vessel does not comply with the established reference where CII_{Att} should be minor than CII_{Req}.

- **Wellboat**:

For the case of this study and in the absence of reference values for this type of vessel, it will be used the data specified for general cargo vessel available in Table 1 of Resolutions MEPC.353(78) 2022 guidelines on the reference lines for use with operational Carbon intensity indicators (CII reference lines guidelines, g2)

Data about the vessel:

Gross Tonnage	:	1952
DWT	:	2490
Fuel Consumption (FC)	:	$2760\ ton$
$C_{F\ ME}\ Diesel$	:	$3.206\ \left[{(t * CO_2)}/{t * Fuel}\right]$
Distance traveled (Dt)	:	$50000\ NM$
Annual Reduction Factor (z) for 2023	:	5%

Formulas:

To calculate the CII_{Req}:

$$Required\ annual\ operation\ CII = \left(1 - \frac{z}{100}\right) * CII_{Ref} \tag{3}$$

e. CII_{Ref}:

$$CII_{Ref} = a * Capacity^{-c} \tag{8}$$

$$a = 588$$
$$Capacity = 2490$$
$$c = 0.3885$$

$$CII_{Ref} = 588 * 2490^{-0.3885}$$

$$\boldsymbol{CII_{Ref} = 28.1808}$$

f. ***CII***

CII_{Req}:

$$Required\ annual\ operation\ CII = \left(1 - \frac{z}{100}\right) * CII_{Ref}$$

$$Required\ annual\ operation\ CII = \left(1 - \frac{5}{100}\right) * 28.1808$$

$$Required\ annual\ operation\ CII = 28.7718$$

$$\boldsymbol{CII_{Req} = 28.7718}$$

To obtain the CII_{Att}:

g. CII_{Att}:

$$CII_{Att} = \frac{FC * C_F}{C * D_t} \tag{9}$$

$$CII_{Att} = \frac{(2760 * 10^6) * 3.206}{2490 * 50000}$$

$$\boldsymbol{CII_{Att} = 71.0728}$$

h. Comparison between CII_{Req} and CII_{Att}

$$CII_{Req} = 28.7718 < CII_{Att} = 71.0728$$

$$\boxed{\therefore \boldsymbol{CII_{Req} < CII_{Att}}}$$

Certainly, in this case, the vessel does not comply with the established reference where CII_{Att} should be minor than CII_{Req}.

- **Salmon Farm:**

Despite the data obtained from the industry, Salmon Farms cannot be supported by CII equations because the information needed for the calculations, according to the MARPOL regulation, cannot be adapted to marine structures if it is not possible to use any reference to compare CII reference with CII required. This problem will be considered as a limitation for further analysis of this research.

- **Data Summary**:

The following table summarises the CII results obtained.

Table 15. CII Calculations Summary.

CII	Ro-ro Passenger Ship	Wellboat
CII_{Ref}	71.6772	28.1808
CII_{Req}	68.9033	28.1667
CII_{Att}	81.0505	71.0727
$CII_{Req} > CII_{Att}$	NO	NO

Appendix 5 – Solar Energy Calculations

This appendix describes how the example of the solar energy conversion was calculated at point 4.9.1 of the chapter 4.

For instance, if we assumed solar irradiation equal to 1000 (W/m^2), the area needed to produce 1 (MW) is:

$$P_{Solar} = \emptyset * \eta_{Solar} * A \qquad (10)$$

Where;

P_{Solar}	:	Solar Power generated (W)
$\emptyset$	:	Solar irradiation
η_{Solar}	:	Solar to electricity conversion efficiency
A	:	Area (m^2)

Then;

$$1000000\ (W) = 1000 \left({}^{W}/_{m^2}\right) * 0.25 * A\ (m^2)$$

$$A = 400\ (m^2)$$

Therefore, it is necessary to install 400 (m^2) of photovoltaic panels on board to generate 1 (MW) of power.

Appendix 6 – Electricity Source of Energy

1. The journey of 4 (NM) will take 0.4 hours (24 minutes) at 10 (Kn); therefore, the energy required to sail the strait once is:

$$Energy_{Required} = Power\ (kW) * time\ (h) \tag{11}$$

$$Energy_{Required} = 2000\ (kW) * 0.4\ (h) = \mathbf{800\ (kWh)}$$

2. The total volume necessary to store lithium-ion batteries capable of supplying energy for one trip of 4 (NM) is:

$$V_{Store} = \frac{Energy\ (kWh)}{\frac{Energy}{volume}\ (\frac{kWh}{m^3})} \tag{12}$$

$$V_{Store} = \frac{800\ (kWh)}{200\ (\frac{kWh}{m^3})} = \mathbf{4\ m^3}$$

One 20 (ft) container had a cubic capacity of 33.2 m^3; therefore, using only one container full of batteries (8 modules of 4 m^3 every each) will be possible to keep sufficient energy for 8 strait crosses without charging.

3. The total volume necessary to store lithium-ion batteries capable of supplying power of 2 (MW) is:

$$V_{Store} = \frac{2000\ (kW)}{1500\ (\frac{kW}{m^3})} = \mathbf{1.33\ m^3}$$

4. The mass of the lithium-ion battery will be:

$$m_{battery} = \frac{Energy\ (kWh)}{ENergy/Mass\ (\frac{kWh}{ton})} \tag{13}$$

$$m_{battery} = \frac{800\ (kWh)}{200\ (\frac{kWh}{ton})} = \boldsymbol{4\ m^3}$$

Appendix 7 – Interview Questionary

The questions for the interview are related to the obtention of their points of view about the possible limitations in the implementation process of the environmental frameworks according to their background and experience in the industry. Therefore, those questions will be the hereunder:

1. Do you believe that in Chile, some legal body applies to larger cabotage vessels that are in line with the Framework Law on Climate Change and allow for reduced GHG emissions from ships?

2. Do you believe Chapter 4 of MARPOL Annex VI could be applied to larger cabotage vessels to reduce GHG emissions from vessels in order to comply with the environmental framework mentioned before?

3. What would be the constraints and barriers that exist in the application of the existing regulations in that chapter on cabotage vessels? Considering the fleet's average age, it is equivalent to 30 years.

4. How do you think these constraints and barriers could be overcome to achieve a reduction of the GHG emissions from ships?

5. In line with the reduction of GHG from ships, is it possible to meet the net-zero goal in the maritime sector by the year 2050?

The consequent outcomes will be presented in Chapter Six during the discussion of the proposal roadmap for the upcoming GHG emissions reduction regulations.

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