SHIP EMISSIONS ASSESSMENT BY AUTOMATIC IDENTIFICATION SYSTEM AIS AND BIG DATA IN LATIN AMERICA

Maricruz Aurelia Fun Sang Cepeda

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Oceânica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Oceânica.

Orientadores: Jean David Job Emmanuel
Marie Caprace
Marcio de Almeida D'Agosto

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Orientadores: Jean David Job Emmanuel Marie Caprace
Marcio de Almeida D'Agosto

Aprovada por: Prof. Jean David Job Emmanuel Marie Caprace
Prof. Marcio de Almeida D'Agosto
Prof. Crístofer Hood Marques
Prof. Magdala Satt Arioli
Prof. Paula Carvalho Pereda
Prof. Luiz Antonio Vaz Pinto

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Dedico este trabalho à minha mãe, embora não parecer, ela sempre acredita em mim.
À minha filha, você é minha vida e minha força.
Às pessoas que estiveram me apoiando cada dia, meu amor, minha familia, colegas e meus amigos.
À minha avó Cruz, † que continua ao meu lado.
Ao meu pai † e minha avó Fanny †, que no céu devem estar orgulhosos e comemorando comigo.
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AVALIAÇÃO DE EMISSÕES DE NAVIOS POR SISTEMA DE IDENTIFICAÇÃO AUTOMÁTICA AIS E BIG DATA NA AMÉRICA LATINA

Maricruz Aurelia Fun Sang Cepeda

Maio/2022

Orientadores: Jean David Job Emmanuel Marie Caprace
Marcio de Almeida D'Agosto

Programa: Engenharia Oceânica

Os dados do Sistema de Identificação Automática (AIS) registram uma grande quantidade de informações sobre a segurança e proteção de navios e instalações portuárias no setor de transporte marítimo internacional. No entanto, os grandes bancos de dados não são úteis apenas para funções de segurança. Também pode ser útil para outras áreas do tráfego marítimo, reduzir os impactos ambientais, melhorar a logística e examinar a conformidade com os regulamentos atuais da Organização Marítima Internacional (OMI). O objetivo desta pesquisa é estimar o inventário de emissões de navios e avaliasse a eficiência de várias opções técnicas para reduzir o impacto dos navios oceânicos na atmosfera e no clima. Em outras palavras, pretende examinar como melhorias tecnológicas e estratégias políticas podem ajudar a reduzir as emissões do transporte marítimo internacional no futuro. Os dados de entrada para as abordagens foram coletados de varias fontes e bancos de dados (BD) marítimos, como o registro mundial da frota de navios e o BD AIS. A presente proposta avalia como possíveis melhorias na tecnologia, energias e combustíveis alternativos impactariam a evolução futura das emissões dos navios. Três estudos de caso (EC) são desenvolvidos para estimar as emissões dos navios baseados no AIS. O último EC adicionou a aplicação de cenários, considerou a combinação de tecnologias e de demanda de tráfego de navios baseados principalmente pelo crescimento econômico. A previsão é para 2050. O resultado mostra como energias e combustíveis alternativos podem impactar até 50% da maioria das emissões de navios menores, junto à implementação das novas regulações internacionais. Por fim, a melhor compreensão quantitativa da eficiência e do impacto das alternativas técnicas para reduzir as emissões dos navios ajudariam os tomadores de decisão a melhorar suas estratégias.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

SHIP EMISSIONS ASSESSMENT BY AUTOMATIC IDENTIFICATION SYSTEM AIS AND BIG DATA IN LATIN AMERICA

Maricruz Aurelia Fun Sang Cepeda

May/2022

Advisors: Jean David Job Emmanuel Marie Caprace
Marcio de Almeida D'Agosto

Department: Ocean Engineering

Automatic Identification System (AIS) data records a high quantity of information regarding the safety and security of ships and port facilities in the international maritime transport sector. However, the big databases are not only useful for these safety functions. It can also be helpful for other areas in maritime traffic, such as reducing environmental impacts, improving logistics, and examining compliance with current International Maritime Organization (IMO) regulations. The purpose of this research is to provide a ship emission inventory and an assessment of the efficiency of several technical options to reduce the impact of ocean-going ships on the atmosphere and climate. In other words, this work aims to examine how technological improvements and policy strategies might help reducing emissions from international shipping in the future. Input data for these approaches were collected from different sources and maritime databases such as the worldwide ship fleet register and AIS database. The present proposal assess how possible improvements in technology or alternative energies and fuels could impact the future evolution of ship emissions. Three cases of studies are developed to estimate ship emissions based on AIS. The last case study added an application of scenarios, and it defined considering a combination of technologies and several future ship traffic demand scenarios mainly determined by the economic growth. The prediction is for 2050. The result shows how alternative energies and fuels could impact almost 50% of most minor ship emissions, concurrently implementing newly introduced international policy measures. In conclusion, a better quantitative understanding of the efficiency and impact of the technical alternative to reduce ship emissions may help the decision-makers to improve their strategies.

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List of Symbols

AS	Actual Speed (knots), p. 49, 54
$EF_{i,j,k}$	Emission factor (g/kWh), p. 54
$E_{i,j,k,l}$	Total emission , p. 54
$LF_{j,l}$	Load factor (%), p. 54
MS	Maximum Speed (knots), p. 49, 54
P_j	Installed power (kW), p. 49, 54
$T_{j,k,l}$	Operating time (h), p. 49, 54
f_w	coefficient for a decrease in speed in a representative sea condition of wave height, wave frequency, and wind speed, p. 25

List of Abbreviations

CO	Carbon monoxide, p. 1
CO_2	Carbon dioxide, p. 1, 2, 24, 25, 38, 49, 55
NO_X	Nitrous oxide, p. 1, 2, 17, 37, 39, 40, 49, 55
O_3	Ozone, p. 38
SO	Sulphur oxide, p. 1
SO_2	Sulphur dioxide, p. 1, 55
SO_X	Sulfur oxide, p. 17, 38–40, 49
SO_X	Sulphur oxide, p. 2, 3
VOS	Volatile Organic Carbon compounds, p. 55
ADS-B	Automatic Dependent Surveillance–Broadcast, p. 9
AIS	Automatic Identification System, p. 9, 10, 12, 44, 46, 48–51, 53, 59–61, 69–71
BC	Black Carbon, p. 1
BOA	Breath Overall, p. 51
B	Breath, p. 51
CC	Climate Change, p. 55
CFC	Chlorofluorocarbon, p. 55
CII	Carbon Intensity Index, p. 5, 19
CII	Carbon Intensity Indicator, p. 7
CLIMA	Climate Action, p. 24
CMOT	Chinese Ministry of Transport, p. 41

CMP	Conference Meeting of the Parties, p. 22
COG	Course over ground, p. 49
COPPE	Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia, p. 48
COP	Conference of the Parties, p. 17, 21, 22
CSR	Continuous Service Rating, p. 50
DALY	Disability-Adjusted Life Year, p. 66, 92, 93, 97
DB	Database, p. 48, 50
DCS	Data Collection System, p. 19
DG CLIMA	Directorate-General for Climate Action, p. 24
DWT	Deadweight Tonnage, p. 2, 51
ECA	Emission Control Area, p. 3, 4, 14
ECAs	Emission Control Areas, p. 17, 37–41
ED	Ecosystem diversity, p. 55, 97
EEDI	Energy Efficiency Design Index, p. 4–6, 18, 19, 24, 25
EEOI	Energy Efficiency Operational Indicator, p. 7
EEXI	/Energy Design Index for existing ships, p. 5, 19
EEXI	Energy Efficiency Design Index for existing ships, p. 6
EIA	Energy Information Administration, p. 43
ERUs	Earn Emission Reduction Units, p. 17
EUETS	European Union Emissions Trading Scheme, p. 24
EU	European Union, p. 24
E	Egalitarian, p. 57
GB	Guanabara Bay, p. 12, 59
GHG	Green House Gas, p. 2, 5, 9, 14, 19–21, 24, 25, 27, 33, 37, 59, 72, 73, 75, 76, 78–80, 91, 99

GHGs	Greenhouse Gases, p. 2, 72, 91
GISIS	Global Integrated Shipping Information System, p. 18
GIS	Geographical Information System, p. 9
GPS	Global Positioning System, p. 9
GT	Gross Tonnage, p. 2, 18, 19, 46, 51
HH	Human health, p. 55, 97
H	Hierarchist, p. 57
IBGE	Institute of Geography and Statistics data, p. 59, 60
IEA	International Energy Agency, p. 43
IMCO	Inter-Governmental Maritime Consultative Organization, p. 15
IMDG Code	International Maritime Dangerous Goods Code, p. 16
IMO	International Maritime Organization, p. 4–7, 9–11, 15, 18–20, 24, 25, 33, 37, 46, 50, 51
INC	Intergovernmental Negotiating Committee, p. 20
IPCC	Intergovernmental Panel on Climate Change, p. 20
I	Individualist, p. 57
LCA	Life-cycle assessment, p. 9, 54, 55, 66, 92, 98
LCIA	Life Cycle Impact Assessment, p. 43, 54, 55, 57, 66, 92, 97
LCI	Life Cycle Impact, p. 55
LDCs	Least Developed Countries, p. 19
LDT	Lightweight displacement, p. 51
LNG	Liquefied Natural Gas, p. 8, 9, 13, 33, 74, 78, 80, 83, 85, 87
LOA	Length Overall, p. 51
LPP	Length between perpendicular, p. 51
MARPOL	International Convention for the Prevention of Pollution from Ships, p. 15–20, 24, 39, 40

MCDA	Multi-criteria decision analysis, p. 99
MEPC	Marine Environment Protection Committee, p. 5, 11, 17–19, 24, 39, 40
MMSI	Maritime Mobile Service Identity, p. 50, 51
MMSI	Maritime Mobile Service Identity, p. 48
NASA	National Aeronautics and Space Administration, p. 20
NDCs	Nationally Determined Contributions, p. 23
NM	Nautical mile, p. 48
NWP	Nairobi Work Programmes, p. 22
NYMEX	New York Mercantile Exchange, p. 11
ODS	ozone depleting substances, p. 17, 39
PMF	Particulate Matter Formation, p. 55
PM	Particulate Matter, p. 17, 39, 40, 66
POM	Particulate Organic Matter, p. 1
RPM	Revolutions per minute, p. 3, 51
SBSTA	Subsidiary Body for Scientific and Technological Advice, p. 22
SECA	Sulphur Emission Control Area, p. 4, 38
SEEMP	Ship Energy Efficiency Management Plan, p. 4, 5, 7, 18, 19, 24, 25
SIDs	Small Island Developing States, p. 19
SOG	Speed over ground, p. 49
SOLAS	International Convention for the Safety of Life at Sea, p. 46
STEO	Short-Term Energy Outlook, p. 11
TA	Terrestrial Acidification, p. 55
UFRJ	Federal University of Rio de Janeiro, p. 48
UNEP	United Nations Environment Programme, p. 20

UNFCCC	United Nations Framework Convention on Climate Change, p. 21, 43
UN	United Nations, p. 20, 21
VOC	Volatile Organic Compounds, p. 1
VOC	Volatile organic compounds, p. 17, 39
WMO	World Meteorological Organization, p. 20
WRF-Chem	Weather Research and Forecasting Chemical, p. 38
WTI	West Texas Intermediate, p. 11

Chapter 1

Introduction

This section first outlines the broad fields of the study, the objectives of the research problem, the boundaries implied in the proposed research, and the description of the work. Finally, the document explains the original contribution to applied science and the outline of the study.

1.1 Contextualization

Emission of exhaust gases and particles from seagoing ships contribute significantly to the total atmospheric emissions from the transportation sector, [14], [15], thereby affecting the chemical composition of the atmosphere, climate and regional air quality and human health. Key compounds emitted are carbon dioxide (CO_2), nitrogen oxide (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), black carbon (BC) and particulate organic matter (POM).

Nitrogen oxides (NO_X) emissions contribute to particles and ozone formation and potentially cause acidification and eutrophication upon deposition on land, lakes, and oceans. Since 2000 studies, [16], [15], suggest that ocean-going ships consumed between 200 and 290 million metric tons of fuel per year. Given nearly 70% of ship emissions occur within 400 km of land, ships have the potential to contribute to significant pollution in coastal communities. The studies mentioned above have estimated around 15% of all global anthropogenic NO_X emissions.

Sulfur in fuel generates sulfur oxide emissions (SO) and contributes to the formation of secondary particulate matter (PM) that is particularly harmful to humans and the environment. These emissions have a significant health impact, causing premature deaths. SO_X emissions also cause environmental problems such as the acidification of soil and water and damage to biodiversity, [17]. Also, 4% to 9% of SO_2 global emissions are attributable to ships, [18], [16], [15].

In 2012, 962 million tonnes were CO_2 emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO_2 emissions of total shipping (international, domestic and fishing). The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018, [19]

One of the challenges for society is to limit or reduce the emissions of greenhouse gases (GHGs), in particular CO_2. Another key challenge is to reduce global anthropogenic NO_X and SO_X emissions as these have health and ecosystem consequences and can be transported large distances from their sources. Shipping contributes an increasing proportion of these emissions. NO_X emissions from shipping are relatively high because most marine engines operate at high temperatures and pressures without effective reduction technologies. SO_2 emissions are high because of high average sulphur content (from 2.4% to 2.7%) in marine heavy fuels used by most ocean-going ships, [20]. It is worth to be mentioned that future scenarios demonstrate that significant reductions are needed to offset increased emissions due to the predicted growth in seaborne trade, [21].

For these reasons, shipping has been given increasing attention over the past decade and has been recognized as a growing problem by both policy-makers and scientists.

In early 2018, the world shipping fleet grew by 2.61%, the slowest growth of the decade, and reached a total of 1.97 billion deadweight tonnage (DWT) that consisted of 95 402 vessels, higher than 500 gross tonnage (GT), including bulk carriers, oil tankers, general cargo ships, container ships and others. Consequently, it produces a major marine traffic, and a growth of fuel consumption and GHG emissions at sea impacting the climate change, [22].

In 2019, the global commercial shipping fleet grew by 4.1%, representing the highest growth rate since 2014, but still below levels observed during the 2004–2012 period, [23]. At the beginning of 2020, the total world fleet amounted to 98140 commercial ships of 100 GT and above, equivalent to a capacity of 2.06 billion DWT.

NO_X and SO_X regulation and targets

Merchant ships in international traffic are subject to International Maritime Organization (IMO) regulations. Emissions from ships in international trade are regulated by ANNEX VI of MARPOL 73/78 (the International Convention for the Prevention of Pollution from Ships). IMO has declared the goal of a 30% NO_X

reduction from internationally operating vessels and introduced a NO_X limiting curve in Annex VI published in 1998, which depends on engine speed. From the 1st January 2000 all new marine diesel engines for new vessels should comply with this regulation (NO_X optimized engines). In MARPOL Annex VI regulation NO_X emission limits are set for diesel engines depending on the engine maximum operating speed (RPM), as shown in Figure 1.1. Tier I and Tier II limits are global, while the Tier III standards apply only in NO_X emission control areas (ECA) [24]. Tier III standards require dedicated NO_X emission control technologies such as diverse forms of water induction into the combustion process (with fuel, in-cylinder, or scavenging air), exhaust re-circulation, or selective catalytic reduction.

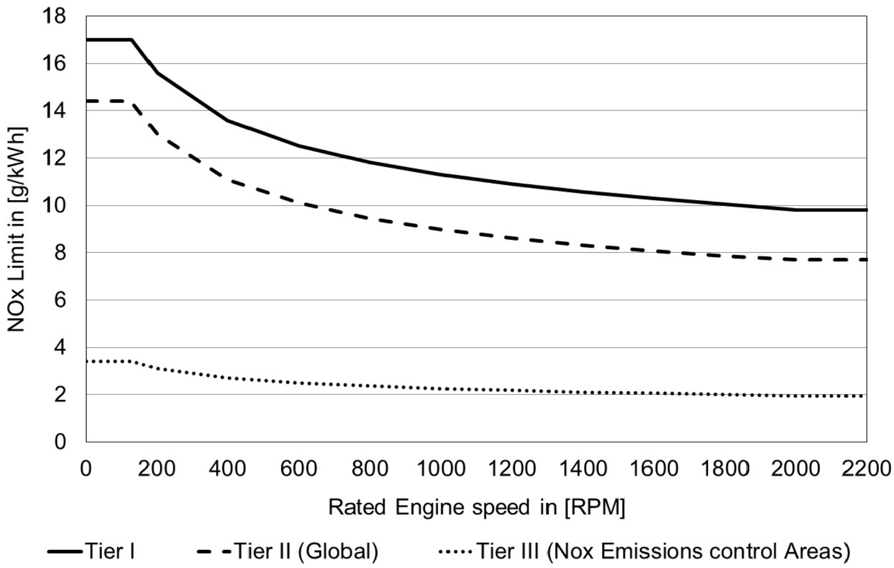

Figure 1.1: MARPOL Annex VI – NO_X emission limits in (g/kWh), [1], and [2].

Annex VI entered into force in May 2005, and sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances. On the same day a global cap of maximum 4.5% on the sulphur content of fuel oil became mandatory for all ships.

In 2012, the legislation of EU adopts the MARPOL Annex VI regulation by Directive 2012/33/EU. This implies especially the introduction of stricter sulphur limits for marine fuel in SO_X ECA (1% from 2010 until 31 December 2014 and 0,1% after 1 January 2015) as well as in sea areas outside SO_X ECA (3,5% since on and after 1 January 2012 and 0,5% on and after 1 January 2020), [25], and [26], see Figure 1.2.

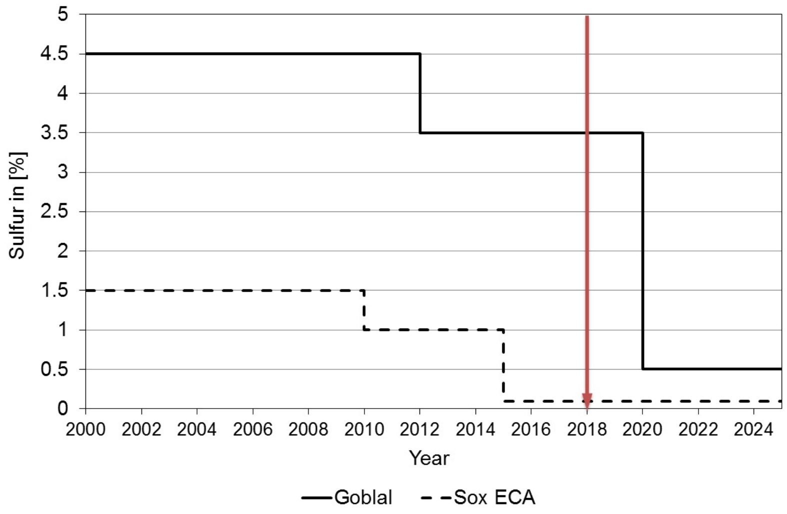

Figure 1.2: MARPOL Annex VI – Content limits of sulphur in marine fuel in (%), year 2018 is in read because is the year of rectification of emission restrictions, [2].

The IMO through the MARPOL Annex VI regulation introduces Emission Control Areas (ECA) and it defines the energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP). These regulations recently amended by Directive 2012/33/EU in Europe aim to reduce emissions and increase ship energy efficiency.

In 2012, limits on global sulphur content were set to 3.5%. The first sulphur emission control area (SO_X ECA, with a maximum fuel sulphur content of only 1.5%) in the Baltic Sea entered into force in May 2006, while the North Sea and English Channel SO_X ECA entered into force in August–November 2007.

Stricter sulphur limits for marine fuel has been introduced in SO_X ECA (1% from 2010 until 31 December 2014 and 0,1% after 1 January 2015) as well as in sea areas outside SO_X ECA (3,5% since 18 June 2014), [25], and [26], see Figure 1.2.

The decision to implement a global sulphur cap of 0.5% in 2020, revising the current 3.5% cap (outside SECAs), was announced by the IMO on October 27^{th}, 2016. This bunker change applies globally and will affect as many as 70 000 ships.

CO_2 regulation and targets

New initial strategy on the reduction of GHG emissions from ships was defined during the 72^{nd} session of the Marine Environment Protection Committee (MEPC) of the IMO organized from 9 to 13 April 2018. The official statement from IMO says the following; *"The vision confirms IMO's commitment to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century. More specifically, under the identified levels of ambition, the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping which should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely"*.

The IMO has made the large-scale development and deployment of carbon-neutral fuels a core part of its long-term strategy. As briefly previously mentioned, the principal objectives are 50% reduction in absolute emissions and 70% reduction in carbon intensity by 2050, see the Figure 1.3 and 1.4.

Figure 1.3: Decarbonization pathway. Timeline for implementing decarbonization measures and achieving targets by IMO, [3].

To reach this goal, the IMO has developed a strategy that has three components as described in Figure 1.4: (i) the design and **technical measures** that include Energy Efficiency Design Index (EEDI) and Energy Design Index for existing ships (EEXI), (ii) the **operational measures** that include the Ship Energy Efficiency Management Plan (SEEMP) as well the Carbon Intensity Index (CII), and finally, (iii) the **innovative measures** including new on-board technologies and alternative fuels.

The MEPC met virtually for its 75^{th} session from 16-20 November 2020, IMO confirmed the initial IMO GHG Strategy, which aims to reduce carbon intensity of international shipping by 40% by 2030, compared to 2008. The Committee also approved the Fourth IMO GHG Study 2020. The study contains an overview of GHG emissions from shipping 2012-2018, developments in carbon intensity and emission projections towards 2050. The study was published by IMO.

Technical measures

The Energy Efficiency Design Index (EEDI) was developed as a technical measure for new vessels. It entered into force for new built vessels in 2013. The objective of the EEDI aims at promoting the use of more energy efficient (less polluting) ships. The EEDI requires a minimum energy efficiency level per capacity × mile, e.g., tonne × mile, for different ship type and size segments. Since 1 January 2013, following an initial two year phase zero, new ship design needs to meet the reference level for their ship type. The level is planned to be tightened incrementally every five years, i.e., in 2020 and in 2025, and so the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase, see Figure 1.4.

More recently, during the MEPC 76 in June 2021, the IMO adopted the amendments to MARPOL Annex VI, entitled Energy Efficiency Design Index for existing ships (EEXI). The EEXI is applicable for all existing vessels, i.e., not only the new builds, above 400 GT falling under MARPOL Annex VI. This rule is a short term measure that will enter into force in 2023 and applied once for all the world ship fleet following technical means to improve the overall energy efficiency. Vessels impacted by EEXI must demonstrate compliance by their next survey – annual, intermediate or renewal – for the International Air Pollution Prevention Certificate (IAPPC), or the initial survey before the ship enters service for the International Energy Efficiency Certificate (IEEC) to be issued, whichever is the first on or after 1 January 2023.

Operational measures

The Ship Energy Efficiency Management Plan (SEEMP) entered into force together with the EEDI for all ships at MEPC 62 in July 2011 with the adoption of amendments to MARPOL Annex VI. The Ship Energy Efficiency Management Plan (SEEMP) is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool. The guidance on the development of the SEEMP for new and existing ships incorporates best practices for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning or more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or a new propeller. The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimise the performance of a ship, see Figure 1.4.

Later, on 1 March 2018, the instrument of the Data collection system for fuel oil consumption of ships entered into force trough an amendments to MARPOL Annex VI. Under the amendments, ships of 5000 GT and above are required to collect consumption data for each type of fuel oil they use, as well as other, additional, specified data including proxies for transport work. The aggregated data is reported to the flag State after the end of each calendar year and the flag State, having determined that the data has been reported in accordance with the requirements, issues a Statement of Compliance to the ship. Flag States are required to subsequently transfer this data to an IMO Ship Fuel Oil Consumption Database. IMO is then required to produce an annual report to MEPC, summarizing the data collected.

Finally, in June 2021, the IMO adopted a new CO_2 regulations applicable to existing ships through the Carbon Intensity Indicator (CII) rating scheme addressing the operational efficiency, and the enhanced Ship Energy Efficiency Management Plan (SEEMP) addressing the management system. The CII measures how efficiently a ship transports goods or passengers and is given in grams of CO2 emitted per cargo-carrying capacity and nautical mile. The actual annual operational CII achieved (attained annual operational CII) would be required to be documented and verified against the required annual operational CII. This would enable the operational carbon intensity rating to be determined. The rating would be given on a scale – operational carbon intensity rating A, B, C, D or E – indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level. The performance level would be recorded in the ship's Ship Energy Efficiency Management Plan (SEEMP). A ship rated D for three consecutive years, or E, would have to submit a corrective action plan, to show how the required index (C or above) would be achieved.

These new IMO goals are going to affect considerably the marine industry in the coming decades. Therefore, a deeper understanding of the consequences of the new policies on the new GHG inventory is required.

1.2 Main Objective

The main objective of this research is to provide an assessment of the efficiency of several technical options to reduce the impact of ocean-going ships on atmosphere

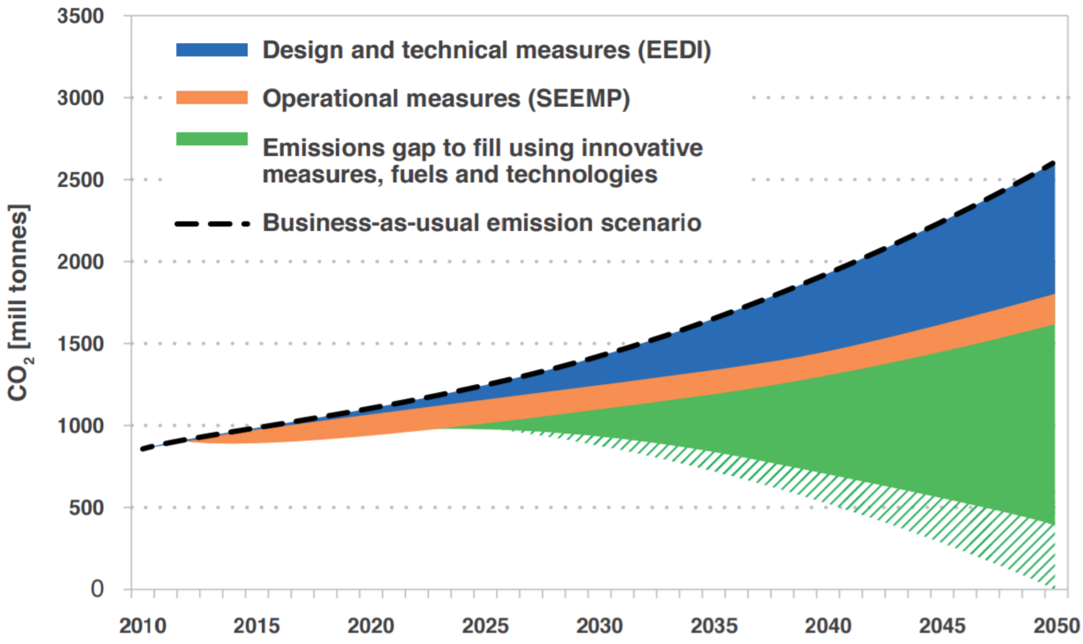

Figure 1.4: How the impacts of IMO actions to reduce GHG emissions from international shipping to achieve goals until 2050, [4].

and climate. In other words, this work examines how technological improvements (slow steaming, sails on-board, enhanced power management, solar panels for auxiliary systems, Liquefied Natural Gas (LNG) implementation, electric propulsion, implementation of marine biofuels) and policy strategies (regulate the life cycle of vessels, zero carbon 2040, fishing incentive policy, port infrastructure projects, production of local biofuel, recycle of batteries of electric motors, and reforestation policy) might help reducing emissions from international shipping in the future.

1.2.1 Specific Objectives

In order to achieve these goals, the following specific objectives should be considered:

- To perform a systematic bibliography review of the research topics.
- To implement a set of big data tools in order to deal with the high quantity of data.
- To develop a methodology to perform a ship emission inventory.
- To study various technical alternatives, such as solar power, slow steaming, wind power (sails), alternative fuels (LNG, and bio-fuels), that allows the shipping companies to comply with the new IMO regulations including an evaluation of Life-cycle assessment (LCA).

- To define several scenarios (reference scenario, low impact scenario, medium impact scenario, and high impact scenario) of world ship fleet and traffic demand.

1.3 Boundaries

1.3.1 Where

This research has been carried out in the Ocean Engineering Program (PEnO) of the Graduate Engineering School (COPPE) of the Federal University of Rio de Janeiro (UFRJ) under the guidance of Professors Jean David J. E. M. Caprace and Marcio de Almeida D'Agosto. The financial support has been provided by the Coordination for the Improvement of Higher Education Personnel (CAPES) through a scholarship.

1.3.2 What

The developments of this study have been applied to the maritime sector. However, it is not restricted to this specific sector. The emission inventory can be applied in others modes of transport such as: air transport and land transport which includes rail, road and off-road transport. Whereas AIS is used in Marine Industry to track the vessels, Automatic Dependent Surveillance–Broadcast (ADS–B) is used for aircraft and other GIS (Geographical Information System) are used in terrestrial transport systems in order to track and process the data collected by the Global Positioning System (GPS) satellites.

1.3.3 How

The methodology that is going to be implemented during this research rely on practical applications. In this context input data are collected from different sources and maritime databases such as worldwide ship fleet register and Automatic Identification System (AIS) repositories. In order to achieve this goal, Big Data tools are going to be used to deal with the high quantity of data, [27], and [28].

1.3.4 Why

The marine industry is going to be considerably affected by the two new IMO goals mentioned in the early section, i.e., the new global limit on sulphur content and the new goal on GHG emissions. Therefore, a deeper understanding of the consequences is required.

The current inventory of emissions and the evaluation of alternative scenarios are tools to understand the consequences of the new IMO regulations. These give the decision-makers a clear vision of the alternatives available to comply with the new rules.

The Fourth IMO GHG Study has been published in 2020. This study is the first iteration since adopting the Initial IMO Strategy on Reduction of GHG Emissions from Ships in 2018. The Fourth IMO GHG Study estimates that total shipping emitted 1 056 million tonnes of CO_2 in 2018, which is about 2.89% of the total global anthropogenic CO_2 emissions for this year. Under a new voyage-based allocation method, the share of international shipping represented 740 million tonnes of CO_2 in 2018. According to estimations in the study, shipping emissions could represent 90-130% of 2008 emissions by 2050, [19].

Also, GEORGE e GHADDAR [29] considers the new IMO regulations will drive up prices of fuel. GEORGE e GHADDAR [29] maintains Gasoil now trades at a premium of about $250 a tonne to fuel oil, but the future curve forecasts that this will balloon to $380 per tonne by early 2020. It is another reason to perform the analysis of alternatives through this thesis.

Energy Information Administration (EIA), Official Energy Statistics from the U.S. Government, predicted that crude oil prices would fall from 2021 levels. However, petroleum consumption returned faster than petroleum production after the COVID-19 pandemic began in 2020. In 2022, EIA expects that petroleum production will increase and consumption growth will slow, leading to an increase in petroleum inventories globally, see Figure 1.5. Although, crude oil prices increased following the further invasion of Ukraine by Russia. Sanctions on Russia and other actions contributed to falling oil production in Russia and created significant market uncertainties about the potential for further oil supply disruptions. These events occurred against a backdrop of low oil inventories and persistent upward oil price pressures, [5].

Nowadays, AIS that collect navigation information on ships are becoming available. However, these data are actually largely underused, or the data is used partially for isolated studies. This thesis develop a mathematical model to assess marine traffic using a AIS database.

Finally we believe that the proposal of different strategic scenarios could help the maritime authorities improve their regulations and propose new public policies.

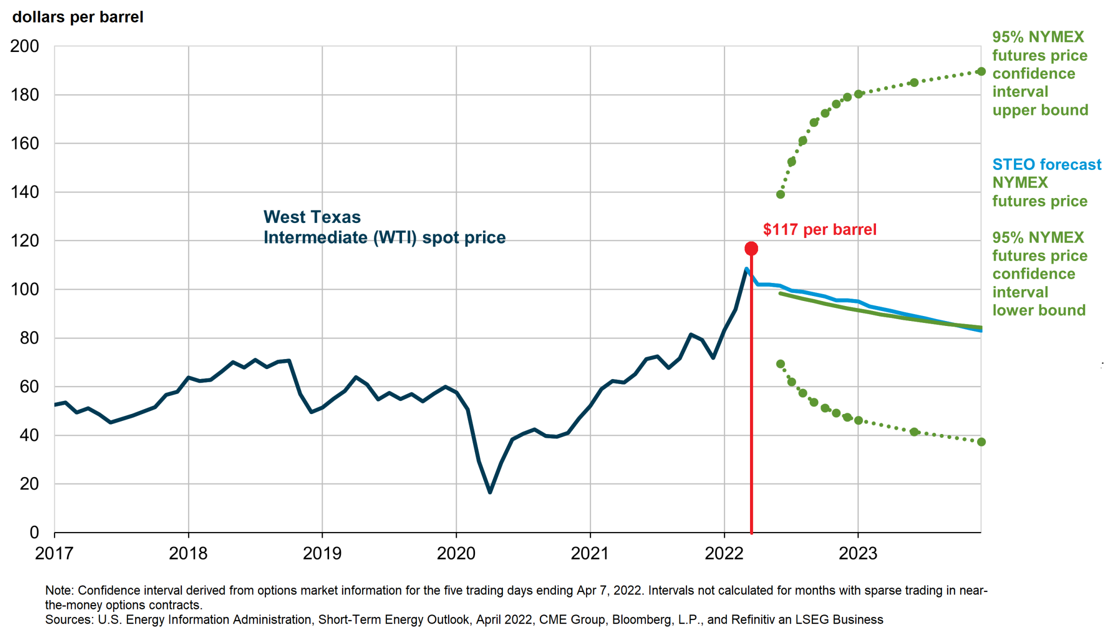

Figure 1.5: West Texas Intermediate (WTI) crude oil price and New York Mercantile Exchange (NYMEX) confidence intervals, with Short-Term Energy Outlook (STEO) forecast NYMEX futures price [5].

1.4 Expected results

The vast majority of marine propulsion and auxiliary plants on-board ocean-going ships are diesel engines. These engines typically have lifetimes of 30 years and more. Because of missing alternative propulsion systems with similar power density, prime costs and fuel efficiency, it is expected that diesel engines will not be replaced in the near future. Therefore, at least for a mid-term period (around 20 years), emission reduction of existing engines will be based on effective emission reduction technologies or changes in the fuel.

On the other hand, it is hard to assess which of the alternative techniques or fuels cited above are likely to be more efficient and in use on the long-term. A shift from a diesel-only fleet to a fleet that partly uses alternative fuels and energies in 2050 is likely to be occur considering the premise declared by IMO during the 72^{nd} session of the Marine Environment Protection Committee (MEPC).

Based on these assumptions, a better understanding (quantitative) of the efficiency and impact of the technical alternative to reduce ship emissions may help the decision makers to improve their strategies.

The expected result of this research work is to show how possible improvements in technology or the use of alternative energies and fuels could impact on the future evolution of ship emissions concurrently to the implementation of newly introduced international policy measures.

1.5 Original contributions

The original contribution of this study relies on the development of a numerical methodology able to simulate and predict the impact of near future technologies on the marine traffic emissions. Moreover, the study places these developments in a logistics strategy where the ship emission objectives are considered simultaneous in order to explore and comply with new regulations.

Other important elements presented in this study are:

- An outstanding state of the art on ship traffic emissions.
- The different strategic scenarios around the world of fuel and technology switching to fulfil the new regulations.
- A simulation tool for decision makers and for the maritime authorities able to provide insights and sensitivity analysis on the consequences to application of new technologies on a specific fleet.
- The structure of a scalable database system to store the world fleet information including the history of the individual ship positions provided by AIS.

1.6 Previous preliminary work

The author of this document worked on various preliminary case studies to develop the skills and framework to deal with a high quantity of AIS data and review alternative fuels.

The first case study deals with the development of a preliminary model to estimate the ship emissions based on AIS Big Data for the Port of Rio de Janeiro. It has been published in the 17^{th} International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT 2018) and presented in Italy in May 2018, [28]. See the first page of the article in the Appendix B.1.

The second case study is about the development of a near-miss ship collision detection model using AIS data for the Port of Rio de Janeiro. It has been published and presented in the 27^{th} International Congress of Waterway Transportation, Shipbuilding and Offshore Construction (SOBENA 2018) in Rio de Janeiro in October 2018, [30]. See the first page of the article in the Appendix B.2.

The third case study focus the development of a preliminary model to estimate the ship emissions and environmental impact based on AIS Big Data for the Port of Rio de Janeiro. It has been published and presented in the XXVI Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering (COPINAVAL 2019) in Colombia in March 2019, [31]. See the first page of the article in the Appendix B.3.

The fourth case study is a near-miss ship collision detection model using AIS data for the Port of Santos. It is published in the 11^{th} International Seminar on Inland Waterways and Waterborne Transportation (SOBENA 2019) and presented in Brasilia in October 2019, [32]. See the first page of the article in the Appendix B.4.

The fifth case study is a review of the use of LNG versus HFO in maritime industry. It is published in the Marine Systems & Ocean Technology journal, volume 14, published on 09 July 2019, [33]. See the first page of the article in the Appendix B.5.

The sixth case study is a dynamic port congestion indicator model using AIS data for the Port of Rio de Janeiro. It is published in the 28^{th} International Congress on Waterborne Transportation, Shipbuilding and Offshore Constructions (SOBENA 2020) in October 2020, [34]. See the first page of the article in the Appendix B.6.

The last case study is the proposal of an Action Plan for the Sustainable Energy Transition of the Galapagos Islands using AIS data. It has been published as an Full Report titled Energy Demand and Supply Scenarios and Energy Policy Options. Galapagos Islands. Republic of Ecuador, in November 2020, [35]. See the first page of the executive summary in the Appendix B.7.

1.7 Outline of the study

This document is organized as follows.

Chapter 1 presents the context of the problem introducing the objectives of the research as well as the boundaries, expected results, and original contribution, and previous preliminary works.

The state of the art is described within Chapter 2. This focus a contextualization about the literature survey about the evolution of emissions regulations around the world, Green House Gas (GHG) emission abatement technologies, and the use of several methodologies about emission inventories, it also introduce the Emission control areas (ECA) around the world.

Chapter 3 deals with the presentation of the methodology explaining the division in various sub-activities. After a general flow chart of the system developed, Section 3.3 presents the system description, including an explanation of inputs, processes, and outputs of them. This chapter describes the Methodology approach, database used, and emission estimation. The methodology used in the life cycle assessment (LCA) is also explained.

Chapter 4 presents the case studies of ship emissions inventory. This include the ports around the two most populated municipalities in Brazil, Guanabara Bay (Rio de Janeiro, Brazil), and Santos Bay (Santos, Brazil). Another case study focuses on the Galapagos Island, an essential region in Ecuador due to the islands' unique ecosystem and endemic animal species that draw wildlife lovers from across the globe. Section 4.3.3 presents the development of models and future scenarios. The results on the comparison of scenarios are discussed in this Chapter.

Finally, Chapter 5 concludes with the key findings and achievements, summary of main contributions, limitations of the study and future works.

Chapter 2

State of the Art

2.1 Introduction

This chapter presents a literature survey about the evolution of emissions regulations worldwide, Greenhouse Gas (GHG) emission abatement technologies, and the use of methodologies about emission inventories.

The literary review of the evolution of regulations at the level of international maritime transport is a guide to know the future steps. The development of emissions regulations headed by the United Nations and the IMO are presented below. There are explained facts in a chronological timeline, see Figure 2.1. It is essential to give the readers a contextualization of the developed regulation to understand the international situation of the maritime industry.

International Maritime Organization (IMO) is an agency of the United Nations formed to promote maritime safety. It was formally established by an international conference in Geneva in 1948 and became active in 1958 when the IMO Convention entered into force. The original name was the Inter-Governmental Maritime Consultative Organization or IMCO, but in 1982 the name changed for IMO. The IMO currently gathers 167 Member States and 3 Associate Members, [36].

2.1.1 MARPOL Adoption and Protocol

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the leading international convention covering the prevention of pollution of the marine environment by ships from operational or accidental causes. The MARPOL Convention was adopted on 2 November 1973 at IMO, [36].

The Protocol of 1978 was adopted in response to a spate of tanker accidents in 1976-1977. As the 1973 MARPOL Convention had not yet entered into force, the 1978 MARPOL Protocol absorbed the parent Convention. The combined instrument entered into force on 2 October 1983, [36].

MARPOL Annex I entered into force on 2 October 1983. This annex deals with the prevention of pollution by oil from operational measures and accidental discharges. The 1992 amendments to Annex I made it mandatory for new oil tankers to have double hulls (double bottom and double side shells) and brought in a phase-in schedule for existing tankers to fit double hulls, which subsequently revised in 2001 and 2003, [36].

MARPOL Annex II entered into force on 2 October 1983. This annex deals with the regulations for the control of pollution by Noxious liquid substances in bulk carriers. Annex II defines the discharge criteria and measures for pollution control by noxious liquid substances carried in bulk. The discharge of these wastes is allowed only in reception facilities within specific concentrations and conditions that vary with substances. In any case, no discharge of residues containing noxious substances is allowed within 12 miles of the nearest land, [36].

MARPOL Annex V entered into force on 31 December 1988. This annex deals with the prevention of pollution by garbage from ships. It deals with different types of garbage and specifies the distances from land and how they are discarded. The most important feature of the Annex is the complete ban imposed on the disposal into the sea of all forms of plastics. Today, more than 150 countries have signed up to MARPOL Annex V, [36].

On 1 July 1992, Annex III enter into force. This annex regulates the prevention of pollution by harmful substances carried by sea. It contains general requirements for the issuing of detailed standards on packing, marking, labeling, documenting, stowage, quantity limitations, excepting, and notifying harmful substances transported by sea, [36]. For this Annex, "harmful substances" are those substances that identified as marine pollutants in the International Maritime Dangerous Goods Code (IMDG Code) or which meet the criteria defined in the Appendix of Annex III, [36].

In 1997, a new annex was added to the MARPOL. The Prevention of Air Pollution from Ships (Annex VI) seek to minimize airborne emissions from ships (SO_X, NO_X, ODS, VOC shipboard incineration) and their contribution to local and global air pollution, and environmental problems. Annex VI entered into force on 19 May 2005 and a revised Annex VI with significantly tightened emissions limits was adopted in October 2008, which entered into force on 1 July 2010, [36].

On December 11, 1997, the third Conference of the Parties (COP 3) achieved a historic milestone with the adoption of the Kyoto Protocol, the world's first GHG emissions reduction treaty, [37].

On February 16, 2005, the Kyoto Protocol Entered into Force. History made when the Russian Federation submitted its instrument of ratification to the Kyoto Protocol, sealing its entry into force, [37].

In January 2006, the Clean Development Mechanism, a key mechanism under the Kyoto Protocol, opens for business, [37].

In January 2008, the Kyoto Protocol mechanism Joint Implementation started. The Protocol allows a country with an emission reduction or limitation commitment under the Protocol to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another country with similar commitments, [37].

The main changes to MARPOL Annex VI are a progressive reduction globally in emissions of SO_X, NO_X, and particulate matter (PM), and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas, [36].

In October 2016, MEPC 70 considered an assessment of fuel oil availability to inform the decision to be taken by the Parties to MARPOL Annex VI and decided that the fuel oil standard (0.50% sulfur limit) shall become effective on 1 January 2020, [36].

The limits applicable in ECAs for SO_X and particulate matter were reduced to 0.10%, from 1 January 2015. Under the revised MARPOL Annex VI, the global sulphur limit will be reduced from current 3.50% to 0.50%, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018, [36].

Amendments to MARPOL Annex VI on Data collection system for fuel oil consumption of ships, adopted by resolution MEPC.278(70), entered into force on 1 March 2018, [36].

Under the amendments, ships of 5 000 gross tonnage (GT) and above required to collect consumption data for each type of fuel oil they use, as well as other, additional, specified data, including proxies for transport work. The aggregated data reported to the flag State after the end of each calendar year, and the flag State, having determined that the data reported under the requirements, issues a Statement of Compliance to the ship. Flag States are required to subsequently transfer this data to an IMO Ship Fuel Oil Consumption Database. IMO will be required to produce an annual report to MEPC, summarizing the data collected, [36].

In addition, on or before 31 December 2018, in the case of a ship of 5,000 gross tonnage and above, the SEEMP shall include a description of the methodology that will use to collect the data and the processes that will use to report the data to the ship's flag State, [36].

IMO Ship Fuel Oil Consumption Database has launched as a new module within the Global Integrated Shipping Information System (GISIS) platform, and that the Member States now have access to the Database (Circular Letter No.3827), [36].

For uniform and effective implementation of the regulations, the following guidelines/circular were developed by MEPC, [36]:

- 2016 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP) (resolution MEPC.282(70)), [38].
- 2017 Guidelines for Administration verification of ship fuel oil consumption data (resolution MEPC.292(71)), [39].
- 2017 Guidelines for the development and management of the IMO Ship Fuel Oil Consumption Database (resolution MEPC.293(71)), [40].
- 2017 MEPC circular on submission of data to the IMO data collection system of fuel oil consumption of ships from a State not party to MARPOL Annex VI (MEPC.1/Circ.871), [41].
- 2018 Sample format for the confirmation of compliance pursuant to regulation 5.4.5 of MARPOL Annex VI (MEPC.1/Circ.876), [42].

In resume, the issue of controlling air pollution from ships was discussed at IMO as early as the 1970s, inter in force in 1988 when the MEPC agreed to include the issue of air pollution in its work programme.

The Kyoto Protocol was a major step in the fight against climate change. In consequence, IMO adopted MARPOL Annex VI on regulations for the prevention of air pollution from ships. The MEPC developed operational and technical measures and IMO agreed to include a new chapter on "energy efficiency" in MARPOL Annex VI.

On 15 July 2011, MARPOL Annex VI Parties adopted mandatory energy efficiency regulations for ships with the Energy Efficiency Design Index (EEDI) for new ships, and Ship Energy Efficiency Management Plan (SEEMP) for all ships. This action represented the first set of mandatory energy efficiency measures for any transport sector. Since their adoption, amendments have been adopted to strengthen the EEDI requirements, particularly for certain ship types.

IMO Data Collection System (DCS) for ships to collect and report fuel oil consumption data from ships over 5 000 GT, was adopted as mandatory in 2016. The first calendar year data collection was completed in 2019.

In April 2018, IMO adopted the Initial Strategy on the reduction of GHG emissions from shipping, a policy framework which sets key ambitions, including annual GHG emissions from international shipping by at least half by 2050, compared with their level in 2008, and working towards phasing out GHG emissions from shipping entirely as soon as possible in this century and reducing the carbon intensity of international shipping (to reduce CO_2 emissions per transport work), as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008, see Figure 2.1.

The Initial Strategy includes a commitment to assess the impacts on States (particularly Least Developed Countries (LDCs) and Small Island Developing States (SIDS)) of any measure proposed for adoption.

In June 2021, IMO adopted key short-term measures aimed at cutting the carbon intensity of all ships by at least 40% by 2030, in line with the ambitions set out in the IMO Initial Strategy.

These measures combine technical and operational approaches to improve the energy efficiency of ships. All ships will have to calculate their EEXI and ships over 5 000 GT will establish their annual operational CII and CII rating, see Figure 2.1.

In other words, ships will get a rating of their energy efficiency - A, B, C, D, E - where A is the best.

This is the first time IMO has established a formal rating system for ships. This sends a strong signal to the market: Administrations, port authorities and other stakeholders as appropriate, are encouraged to provide incentives to ships rated as A or B. A ship rated D for three consecutive years, or E, is required to submit a corrective action plan, to show how the required index (C or above) would be achieved.

MARPOL Annex VI has 100 Parties, representing 96.65% of world merchant shipping by tonnage. The initial GHG Strategy will be revised by 2023, see Figure 2.1.

2.1.2 IPCC

In November 1988, the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC). To this day, IPCC assessments are the scientific underpinning of international negotiations while also providing unique insights into, for example, managing the risk of extreme events and disasters, [37].

In this event, the scientist James Hansen from the National Aeronautics and Space Administration (NASA) attested to the United States Senate that man-made global warming had begun, [37].

In November 1990, IPCC released the first assessment report saying that emissions resulting from human activities are substantially increasing the atmospheric concentrations of GHG, leading to calls by the IPCC and the second World Climate Conference for a global treaty, [37].

2.1.3 United Nations General Assembly Negotiations on a Framework Convention

On 11 December 1990, the United Nations (UN) General Assembly establishes the Intergovernmental Negotiating Committee (INC) for a Framework Convention on Climate Change. The INC held five sessions where more than 150 states discussed binding commitments, targets, and timetables for emissions reductions, financial mechanisms, technology transfer, and "common but differentiated" responsibilities of developed and developing countries, [37].

In May 1992, the text of the United Nations Framework Convention on Climate Change (UNFCCC) adopted at the United Nations Headquarters in New York, [37].

In June 1992, the United Nations Framework Convention on Climate Change (UNFCCC) opened for signature at the Earth Summit in Rio de Janeiro, joining efforts to reduce GHG emissions and fight against climate change. The UNFCCC has two sister Conventions in Rio, the UN Convention on Biological Diversity and the Convention to Combat Desertification, [37].

On March 21, 1994, the UNFCCC, spawned two years earlier in Rio, enters into force. Countries that sign the treaty are known as 'Parties.' With 196 Parties, the UNFCCC has near-universal membership. Parties meet annually at the Conference of the Parties (COP) to negotiate multilateral responses to climate change, [37].

2.1.4 Conference of the Parties (COP)

The first Conference of the Parties (COP 1) hold in Berlin in April 1995. The German environment minister, Angela Merkel, presides the event, where Parties agreed that commitments in the Convention were 'inadequate' to meet the convention objectives. The Berlin Mandate establishes a process to negotiate strengthened commitments for developed countries, thus laying the groundwork for the Kyoto Protocol, [37].

On that occasion, experts said that "4.1 billion people have been injured, lost their homes, or required emergency relief because of climate-related disasters".

In July 2001, the sixth Conference of the Parties (COP 6) meeting is held in Bonn. A breakthrough was achieved in the second part of COP 6, with governments reaching a broad political agreement on the operational rulebook for the 1997 Kyoto Protocol, [37].

In November 2001, the seventh Conference of the Parties (COP 7) happened in Marrakesh. The results in the Marrakesh Accords, setting the stage for ratification of the Kyoto Protocol. The Protocol would formalize an agreement on operational rules for International Emissions Trading, the Clean Development Mechanism and Joint Implementation along with a compliance regime and accounting procedures, [37].

Following the Kyoto Protocol's entry earlier in the year, the eleventh Conference of the Parties (COP 11) happens in December 2005 in Montreal. The first time held in conjunction with the First Conference of the Parties serving as the Meeting of the Parties (CMP 1), [37].

In November 2006, at the twelfth Conference of the Parties held in Kenya (Nairobi). The Subsidiary Body for Scientific and Technological Advice (SBSTA) was mandated to undertake a program to address impacts, vulnerability, and adaptation to climate change. The Nairobi Work Programme (NWP) activities are ongoing, [37].

Also the Science journal published a paper warning of the collapse of fish stocks by 2048 due to over fishing and pollution, [37].

In December 2007, at Bali, the thirteenth Conference of the Parties adopted the Bali Road Map, including the Bali Action Plan, charting the course for a new negotiating process to address climate change. The Plan has five main categories: shared vision, mitigation, adaptation, technology, and financing, [37].

In December 2008, the fourteenth Conference of the Parties in Poznan, Poland, delivers important steps towards assisting developing countries, including the launch of the Adaptation Fund under the Kyoto Protocol and the Poznan Strategic Program on Technology Transfer, [37].

In December 2009, World leaders gathered for the fifteenth Conference of the Parties in Copenhagen, Denmark, which produced the Copenhagen Accord. Developed countries pledge up to USD 30 billion in fast-start finance for the period 2010-2012, [37], and [43].

The Convention aims to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. We shall recognize the scientific view that the increase in global temperature should be below 2 degrees Celsius, based on equity and in the context of sustainable development, enhancing our long-term cooperative action to combat climate change. The COP 15 recognizes the critical impacts of climate change and the potential consequences of response measures on countries particularly vulnerable to its adverse effects. It stresses the need to establish a comprehensive adaptation program, including international support, [43].

On 12 December 2015, 195 nations agreed to combat climate change and unleash actions and investment towards a low-carbon, resilient and sustainable future. The Paris Agreement, for the first time, brings all nations into a common cause based on their historical, current, and future responsibilities, [37].

The Paris Agreement builds upon the Convention and, for the first time, brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort, [44].

The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius, above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. To reach these ambitious goals, appropriate financial flows, a new technology framework, and an enhanced capacity-building framework will be put in place, supporting action by developing countries and the most vulnerable countries in line with their national objectives. The Agreement also provides for enhanced transparency of action and support through a more robust transparency framework, [44].

The Paris Agreement requires all Parties to put forward their best efforts through nationally determined contributions (NDCs) and to strengthen these efforts in the years ahead. The Agreement includes requirements that all Parties regularly report on their emissions and their implementation efforts, [44].

In 2018, Parties will take stock of the collective efforts concerning progress towards the goal set in the Paris Agreement and inform the preparation of NDCs, [44].

There will also be a global stocktake every five years to assess the collective progress towards achieving the purpose of the Agreement and informing further individual actions by Parties, [44].

The Paris Agreement entered into force on 4 November 2016, thirty days after the date on which at least 55 Parties to the Convention accounting in total for at least an estimated 55% of the total global greenhouse gas emissions have deposited their instruments of ratification, acceptance, approval or accession with the Depositary, [44].

2.1.5 EU Emissions Trading Launches

In January 2005, the European Union Emissions Trading Scheme (EUETS), the first and largest emissions trading scheme globally, launches as a significant pillar of EU climate policy. Installations regulated by the method are collectively responsible for close to half of the EU's emissions of CO_2, [37].

The Directorate-General for Climate Action (DG CLIMA) leads the European Commission's efforts to fight climate change at EU and international levels. The Climate Action (CLIMA) formulates and implements cost-effective policies for the EU to meet its climate targets for 2020, 2030, and beyond, especially on greenhouse gas emissions and the ozone layer, [37].

CLIMA also ensures climate changed is taken into account in all other EU policies and that adaptation measures will reduce the EU's vulnerability to the impacts of climate change, [37].

2.1.6 Energy Efficiency

In 2011, IMO adopted mandatory technical and operational energy efficiency measures, which are expected to reduce CO_2 emissions from international shipping. These mandatory measures Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) entered into force on 1 January 2013, [36].

IMO has adopted important guidelines aimed at supporting the implementation of the mandatory measures to increase energy efficiency and reduce GHG emissions from international shipping, paving the way for the regulations on EEDI and SEEMP to be smoothly implemented by Administrations and industry, [36].

The expected growth of world trade represents a challenge to meeting a future target for emissions required to achieve stabilization in global temperatures, and so IMO has begun consideration of further technical and operational measures to enhance the energy efficiency of ships, [36].

Since 2012, Marine Environment Protection Committee (MEPC) adopted/approved or amended following important guidelines aimed at assisting the implementation of the mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI, [36]:

- 2012 Interim Guidelines for the calculation of the coefficient f_w for a decrease in ship speed in a representative sea condition for trial use. f_w is a non-dimensional coefficient indicating the decrease in speed in a representative sea conditions of wave height, wave frequency and wind speed, [45].
- 2014 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI), as amended, [46].
- 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI), [47].
- 2013 Guidelines for calculating reference lines for use with the Energy Efficiency Design Index (EEDI) for cruise passenger ships having non-conventional propulsion, [48].
- 2013 Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, as amended, [49].
- 2013 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI, [50].
- 2014 Guidelines on the method of calculation of the attained Energy Efficiency Design Index for new ships, as amended, [46].
- 2016 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP), [38].
- 2021 Guidelines for Exhaust Gas Cleaning Systems, [51]

2.1.7 Reduction of GHG Emissions from Ships

In 2012, the estimated international shipping contributed about 2.2% to the global emissions of carbon dioxide (CO_2). Although international shipping is the most energy-efficient mode of mass transport and only a modest contributor to overall CO_2 emissions, a global approach to improve its energy efficiency further and effective emission control is needed as sea transport will continue growing apace with world trade, [36].

As already acknowledged by the Kyoto Protocol, CO_2 emissions from international shipping cannot be attributed to any particular national economy due to its global nature and complex operation. Therefore, IMO has been energetically pursuing the limitation and reduction of greenhouse gas (GHG) emissions from international shipping to recognize the magnitude of the climate change challenge and the intense focus on this topic.

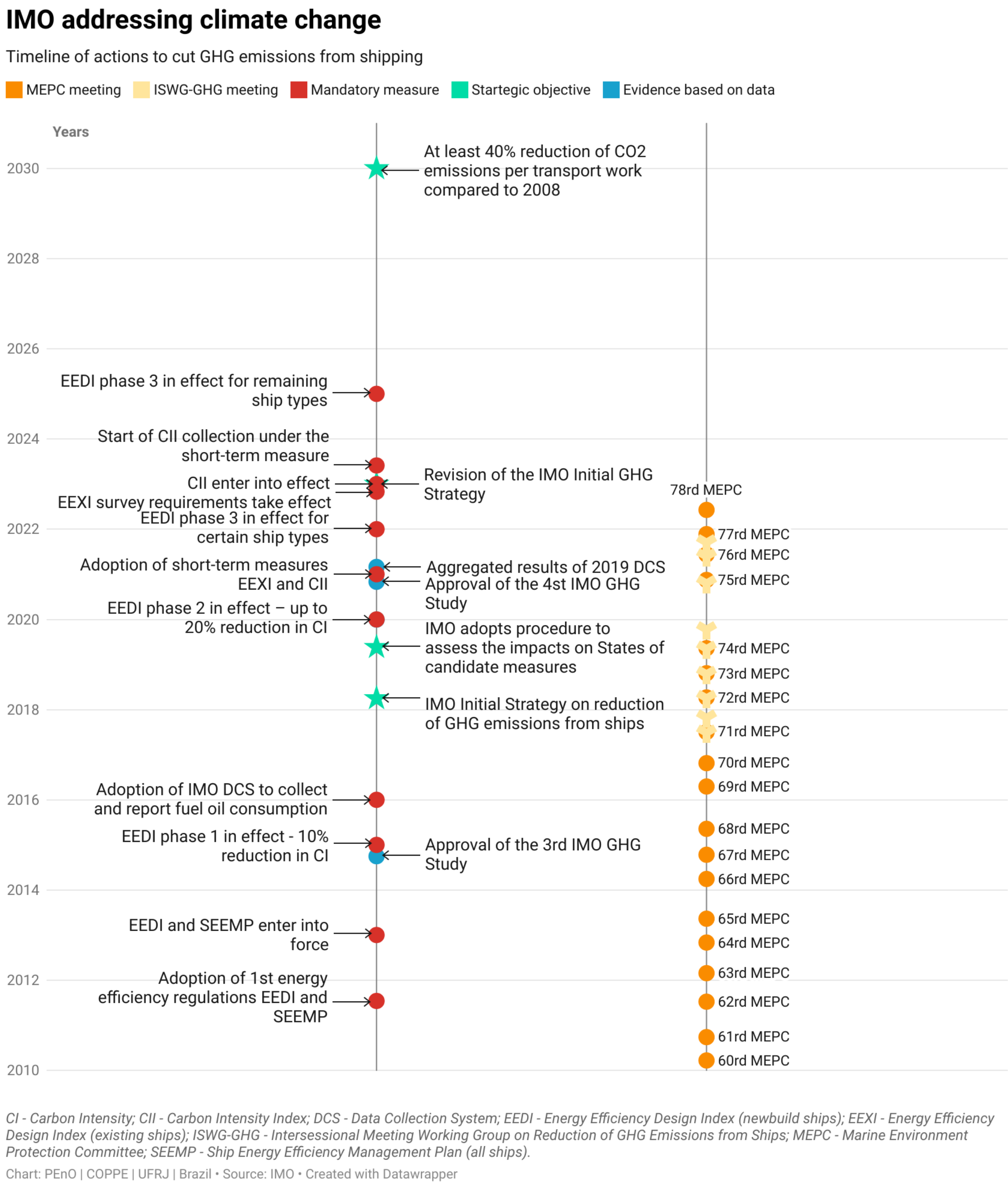

Figure 2.1: IMO addressing climate change timeline

2.2 GHG Emission Abatement Technologies

Most countries around the world are looking for ways to reduce their greenhouse gas (GHG) emissions. Reducing emissions and increasing the use of renewable energy have been identified as priorities and targets towards international shipping. In general, this section intended to show the GHG Emission Abatement Technologies available for maritime transportation, see Figures 2.2 and 2.3.

A non-exhaustive list of Greenhouse Gas (GHG) emission abatement technologies is bellow:

1. Overall vessel design options

   (a) Efficiency of scale: This measure refers to the transition to ships with greater cargo capacities, as they tend to have greater energy efficiency per unit of cargo. When the load-carrying capacity doubled, the energy and fuel consumption required could increases by about two-thirds, resulting in a reduction in fuel consumption per unit of load, [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64].

   (b) Design for reduced ballast operation (ballast free): The traditional ballast tanks could be replaced by longitudinal, structural ballast trunks that extend beneath the cargo region of the ship below the ballast draft, [52], [62], [65], [56], [57].

   (c) Lightweight construction and scantling optimization: The target is practical techniques for using lightweight materials for ship construction, [52], [66], [54], [65], [67], [56], [57], [68], [69], [70].

   (d) Hull, dimensions optimization and opening hydrodynamic optimization: The optimization of the hull to reduce hull resistance to achieve the desired speed with less power, [52], [62], [53], [71], [66], [55], [65], [54], [67], [56], [57], [72].

   (e) Interceptor trim plates: The interceptors are very useful in trim control and resistance reduction, [73], [74], [75], [76].

   (f) Aft waterline extension: It is considered a retrofit measure to improve hydrodynamic performance. [77], [54], [78].

   (g) Skeg shape – Trailing edge: Reducing noise by controlling turbulence, [77], [79], [80], [81].

   (h) Air bubble hull lubrication: It is a method to reduce the resistance between the ship's hull and seawater using air bubbles. It helps ships to improve their efficiency and reducing energy losses, [52], [66], [54], [65], [67], [56], [57]

(i) Bulbous bow shape optimization: It is an appendage that is known to reduce drag, thanks to its influence on the bow wave system, [82], [83], [84], [85].

2. Engine design options (EDO)

   (a) Engine derating: De-rating the engine offers the possibility to lower the vessel's maximum speed. It results in higher efficiency with reduced specific fuel oil consumption (SFOC) at the new optimum design point, [77], [86], [66], [87], [88], [89].

   (b) Diesel electric drives: Some options to convert an inboard diesel engine with an electric drive propulsion system as shaft-drive, sail-drive, Pod-drive, and electric outboard, [52], [62], [54], [65], [67], [57], [90], [71].

   (c) Combined diesel-electric and diesel-mechanical drives: This action can improve the total efficiency in ships with an operational profile containing modes with varying loads, [52], [62], [54], [65], [67], [57], [90], [71].

   (d) Waste heat recovery: It attempts to regain some of the 50% or so lost thermal efficiency from the fuel used in the engine, [52], [62], [54], [55], [91], [65], [92], [93], [67], [57], [72], [78], [94], [95], [96].

   (e) Enhanced engine tuning and part-load operation: Tuning options facilitate specific needs to be met, such as IMO Tier II compliance and optimal performance for multiple operational profiles, like slow steaming, low load, partial load, and steam requirements, [77], [88], [78], [92], [54], [56].

   (f) Common rail engine: Common rail is a fuel injection system found in modern diesel engines. These systems provide flexibility that can be exploited for class-leading emission control, power, and fuel consumption, [56], [78], [92], [54], [97], [98], [99], [100], [101].

3. Other technology strategies (OTS)

   (a) Low-loss electric drive: These are based on the principle of speed-controlled DC or AC motors driving the propeller directly or via gears. The most reliable and low-noise design is the direct drive. A power distribution system comprises higher efficiency, lower weight and volume, and increased system redundancy. The primary motive for the design is to reduce and eliminate the need for supply (pulse) transformers to the frequency converters, especially those supplying electric propulsion, [54], [102], [77], [103].

(b) Hybrid auxiliary power generation: These systems offer significant efficiency improvement by running the engine on optimal load and absorbing many load fluctuations through batteries. Increasing the power redundancy allows the engine to operate closer to its optimum design point, where it has the highest efficiency and most minor emissions. This will result in reduced maintenance needs and increased systems performance. Rapid response from the battery system is also among the benefits offered, [52], [62], [54], [65], [67], [57], [71],[60], [90].

(c) Variable-speed electric power generation: Variable speed power generation can provide significant fuel savings with diesel-electric propulsion when the vessel's operational profile has a high degree of variation in speed and power demand, [52], [66], [54], [65], [92], [67], [56], [57], [72], [78], [94].

(d) Energy-saving lighting and heating: Retrofitting can provide a fast and cost-effective way to upgrade existing lighting and heating systems to increase energy efficiency and carbon savings and reduce energy costs, [52], [62], [104], [65], [54], [57], [72], [78].

(e) Enhanced power management: Power is quickly becoming a first-class resource management concern in High-Performance Computing (HPC). Upcoming HPC systems will likely be hardware over-provisioned, which will require enhanced power management subsystems to prevent service interruption, [105], [106], [107], [108].

(f) Solar power: It is a way to reduce fuel consumption onboard ships. Recent advances in solar cell and photovoltaic (PV) module technologies have led to solar power becoming a cost-effective fuel reduction option on pleasure boats, ferries, and tourist's vessels. However, on large ships, the amount of fuel saved through solar power alone is relatively small. So the idea of a commercially viable solar ship seems impractical at the moment, [52], [62], [66], [54], [55], [109], [57], [72].

(g) Fuel cells for auxiliary power: The potential reduction of local emissions during operation is a significant incentive to apply fuel cell systems in ships. It happens due to the efficiency gain with this type of system, [52], [62], [54], [55], [110].

(h) Variable speed pumps: The internal energy of the storage tank can be removed via a chiller. The energy savings in the main engine cooling system significantly reduce electrical power consumption in slow steaming operations, [54], [78], [52].

(i) Automation: Automation play a significant role in the shipping industry is having great success. Artificial Intelligence is blending well with machine-human interaction and logistics collaboration, [111], [112], [113], [114], [115], [116].

4. Operational strategies (OS)

   (a) Fuel additives: The use of additives can improve the performance of diesel after-treatment systems, [78], [92], [38].

   (b) Port turn-around time (slow steaming – Just in Time Arrivals): The adoption of slow steaming is seeking to reduce the time in the waiting time arrivals at the port, [57], [38] [117], [65], [118].

   (c) Cold Ironing: The ability to better utilize shore-based power allows a ship in port to switch off its main engines and run offshore sourced electricity, [52], [62], [119], [56], [120], [121].

   (d) Propeller surface maintenance: The propeller surface maintenance helps to eliminate the presence of fouling. The fouling increases the frictional resistance by increasing roughness and wall shear stress, [104], [92], [54].

   (e) Hull coating: The maintenance of the hull coating is essential to avoid the increased roughness at the hull during the vessel's operation might increase by 1% of the total hull resistance, [52], [66], [104], [92], [54], [56], [57], [72], [78].

   (f) Hull cleaning: The accumulation of marine growth, biofouling, and other matter from ship hulls create performance problems. For the ship, slowing down its passage adversely impacts vessels' maneuverability, operability, and durability, [78], [72], [54], [57], [38].

   (g) Ship speed reduction (slow steaming – new ship construction): It refers to the use of slow steaming or speed reduction to saving on fuel costs and emissions, [52], [122], [60], [53], [117], [66], [104], [123], [54] [119], [124], [65], [92], [67], [109], [56], [57], [62], [72], [78], [120], [125], [126], [127], [128].

   (h) Voyage planning and weather routing: Voyage planning and weather routing services help to save fuel and increase safety and schedule reliability, [52], [104], [123], [54], [56], [57], [129], [117], [62], [53], [91], [65], [92], [67], [72], [78], [130], [131], [132], [133], [134], [135], [136], [137].

   (i) Optimised vessel trim: The trim and draft of the ship influence the hull resistance and, therefore, the fuel consumption. Monitoring trim gives a more evident vessel performance and can also reduce costs [78], [92], [67], [54], [65], [57].

(j) Optimized autopilot: It is the use of an automatic system to control the rudder on the ship. Autopilot use can decrease fuel consumption by smoothing out the large-angle rudder movements to maintain a steady course, [104], [54], [38], [111], [72], [65].

(k) Overall energy awareness: An overall energy efficiency awareness program supports and reinforces the team's overall energy efficiency objectives, [118], [112], [94], [138], [104].

(l) Condition-based maintenance: Condition-based maintenance is a management philosophy that bases the decision to repair or substitute assets on current and future conditions, [57], [139], [140], [141].

5. Propulsion system options (PSO)

(a) Wing thrusters: Installing wing thrusters can achieve significant power savings, mainly due to lower resistance from the hull appendages, [78], [54], [57].

(b) Counter-rotating propellers: Its propulsion systems have the hydrodynamic advantage of recovering part of the slipstream rotational energy, which would otherwise be lost to a conventional single-screw system, [67], [54], [57], [78], [119].

(c) Optimised propeller-hull interface: It optimizes the interface to the control system, and easier serviceability, [54], [65].

(d) Propeller-rudder unit: It combines maximum maneuverability, high propulsion power, and precise dynamic positioning, [142], [143], [144], [145].

(e) Optimised propeller blade sections: The objective of this optimization is to obtain higher efficiency of the system, [54], [78], [146], [57].

(f) Propeller tip winglets: Improved propeller efficiency of up to 4%, [57], [54], [78].

(g) Propeller nozzle: The propeller nozzle is specifically designed to increase the thrust of marine propellers and performs significantly better the system[57], [54], [38], [78].

(h) Propeller efficiency monitoring: An efficient monitoring system and flow meters onboard your vessels will help make your project a success because the hull and propeller efficiency monitoring influences your fuel consumption. Potential efficiency gains up around to 5%, [54], [78], [104], [117], [56], [57].

(i) Efficient propeller speed modulation: Potential efficiency gains up around to 5%, [147], [148], [94], [57].

(j) Pulling thruster: It is a highly efficient pulling thruster with reduced building height. It has an ease of installation compared with conventional geared azimuth thrusters with separate electric motors in the thruster room, [78], [54], [57].

(k) Wind power - Flettner rotor: Flettner rotors are vertical cylinders that spin and develop lift due to the Magnus effect as the wind blows across them. It must be mechanically driven to create lift and propulsion power and restrict maneuverability by wind speed and direction. This working on a ship, the force created will generate thrust. It may reduce a ship's energy consumption, but it cannot be used as the main propulsion, [104], [117], [89], [54], [65], [57], [119], [53], [50].

(l) Wind power – Kites and sails: Kites and sails are lightweight and highly efficient. Kites fly much higher than traditional sails, where the wind can be as much as 2x the strength, [52], [62], [66], [104], [119], [91], [65], [54], [109], [57], [72], [149], [150], [151].

6. Alternative fuels (AF)

(a) Liquefied Natural Gas (LNG): LNG helps to mitigate climate change by offering a cleaner alternative to conventional fuels used in maritime transport. Using LNG removes all SO_X emissions and particles and reduces NO_X emissions by up to 85%. LNG reduces CO_2 emissions by at least 20%, [52], [62], [66], [54], [119], [91], [152], [109], [94], [153], [154], [155].

(b) Biofuels: Biofuels represent a significant option to simultaneously reduce fossil fuel dependence and GHG and air pollutants emissions. Biofuels of second and third-generation have significant potential to reduce GHG emissions, comparable to conventional fuels because feedstocks can be produced using marginal land, [156]. In addition, given the sector's well-established operational structure and long lifespan of ships, drop-in fuels are the most feasible alternatives, at least in the mid-term, [52], [62], [54], [119], [153], [154], [157], [158], [87].

(c) Methanol: In operation, conventional Methanol offers significantly lower CO_2 emissions compared to traditional marine fuel. If it originated from one of the numerous renewable pathways, such as biomass or renewable electricity combined with recycled carbon dioxide, Methanol has the potential to reduce CO_2 emissions significantly, [138], [3], [1], [159], [160], [161], [162].

(d) Hydrogen: Hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water. You can produce hydrogen from various domestic resources, such as natural gas, nuclear power, biomass, and renewable power like solar and wind. However, to produce hydrogen, you need energy. The hydrogen-fuel-cell-powered generators are an alternative to diesel generators to provide clean power.

(e) Ammonia: Green ammonia, it produced by electrolysis powered by renewables or nuclear, is an excellent source of zero-emission fuel, provided that associated NO_X emissions are managed appropriately, [163], [138], [52], [89], [104], [87], [164].

The Figures 2.2 and 2.3 show the potential of GHG emission abatement technologies for the shipping industry. The Figures are divided into vessel design, engine design, other technology, operational strategies, propulsion systems, and alternative fuels.

Techniques involving speed reduction require a travel time analysis considering the power speed function of vessels. Example: slow steaming, speed reduction (virtual arrival), etc.

Techniques involving a reduced volume of cargo carried require analysis of fleet increase (number of vessels) to compensate for lost volume. Example: slow steaming, LNG fuel, ballast-free, etc.

Techniques involving port logistics efficiency require analysis of average port queue time and average berth occupancy rate.

A recent study of LONGVA [6] modeled GHG-reduction since today until 2050, see Figure 2.4.

The primary energy source of methane varies between fossil, biomass, and other renewables. Ammonia is the most promising carbon-neutral fuel option for newbuilds. Another alternative would be a gradual shift of existing ships relying on drop-in fuels compatible with current fuel converters, such as bio/electro-diesel replacing liquid fuels or bio/electro-methane replacing LNG. The preference for ammonia is due to the lower cost of the converter, storage, and the fuel itself compared with H_2 and liquefied biogas (LBG)/synthetic methane. Carbon-neutral combustibles have to supply 30 to 40 percent of the total energy for international shipping by mid-century if IMO GHG ambitions are to be achieved, [6].

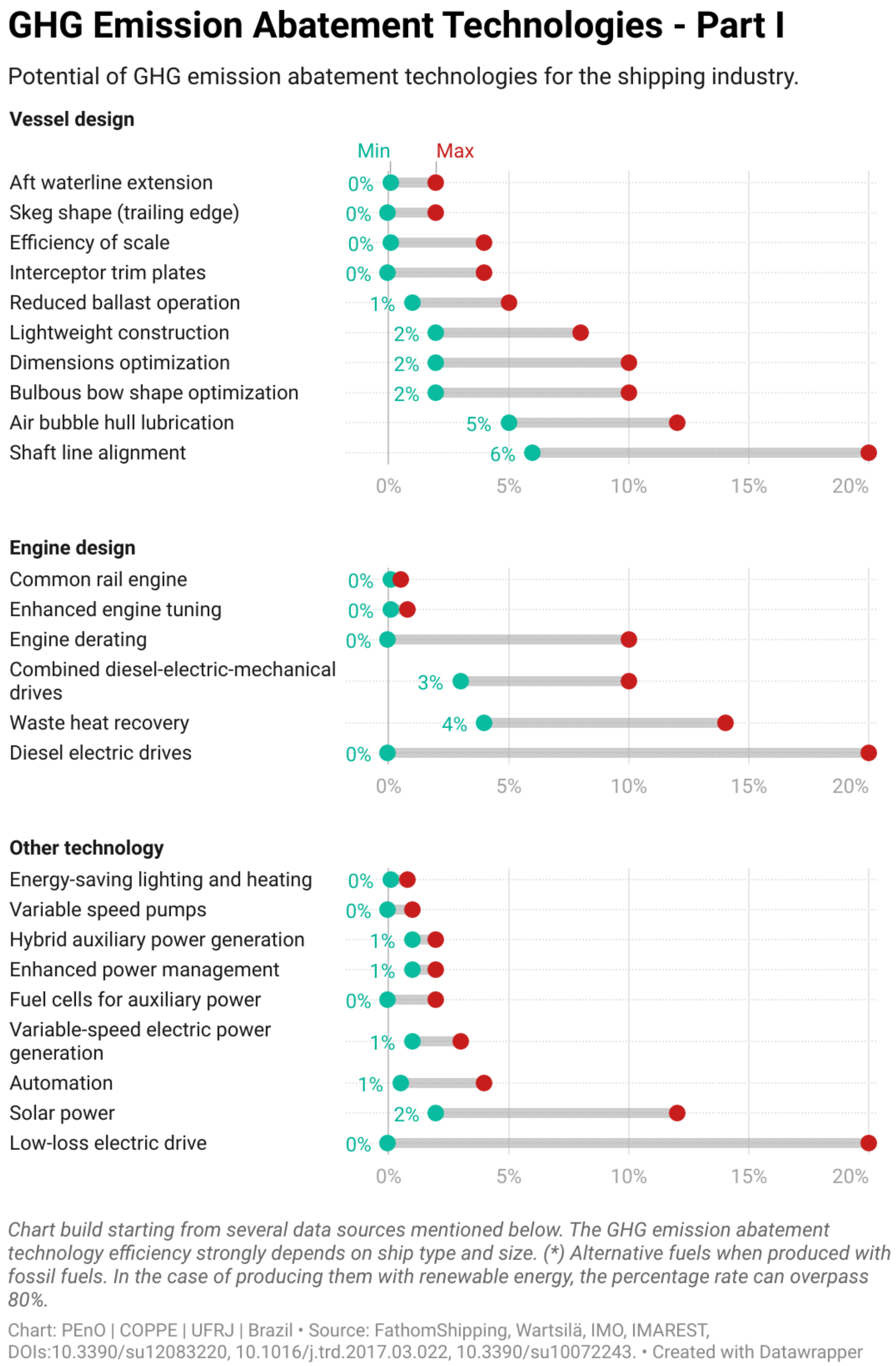

Figure 2.2: GHG Emission Abatement Technologies – Part I

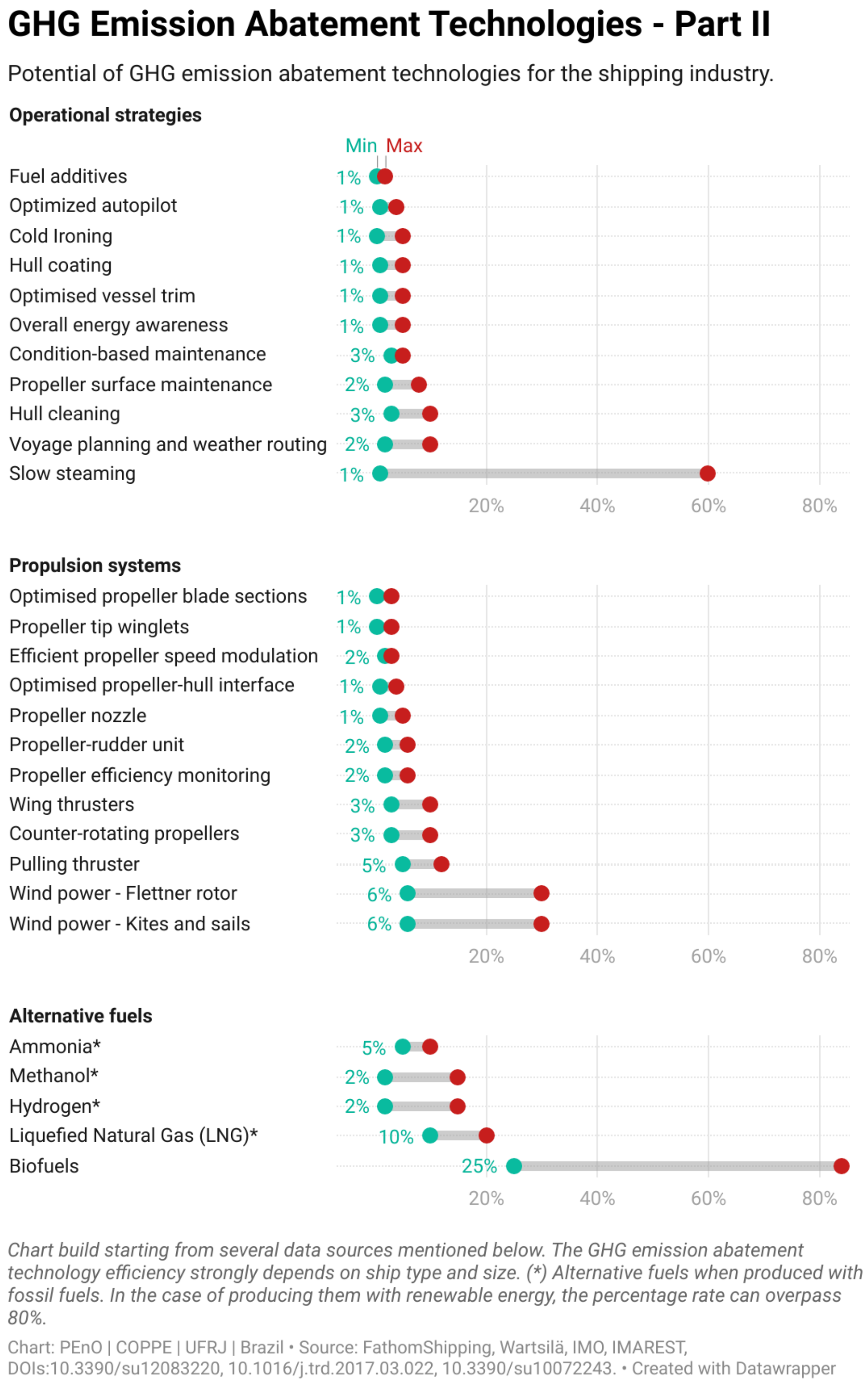

Figure 2.3: GHG Emission Abatement Technologies – Part II

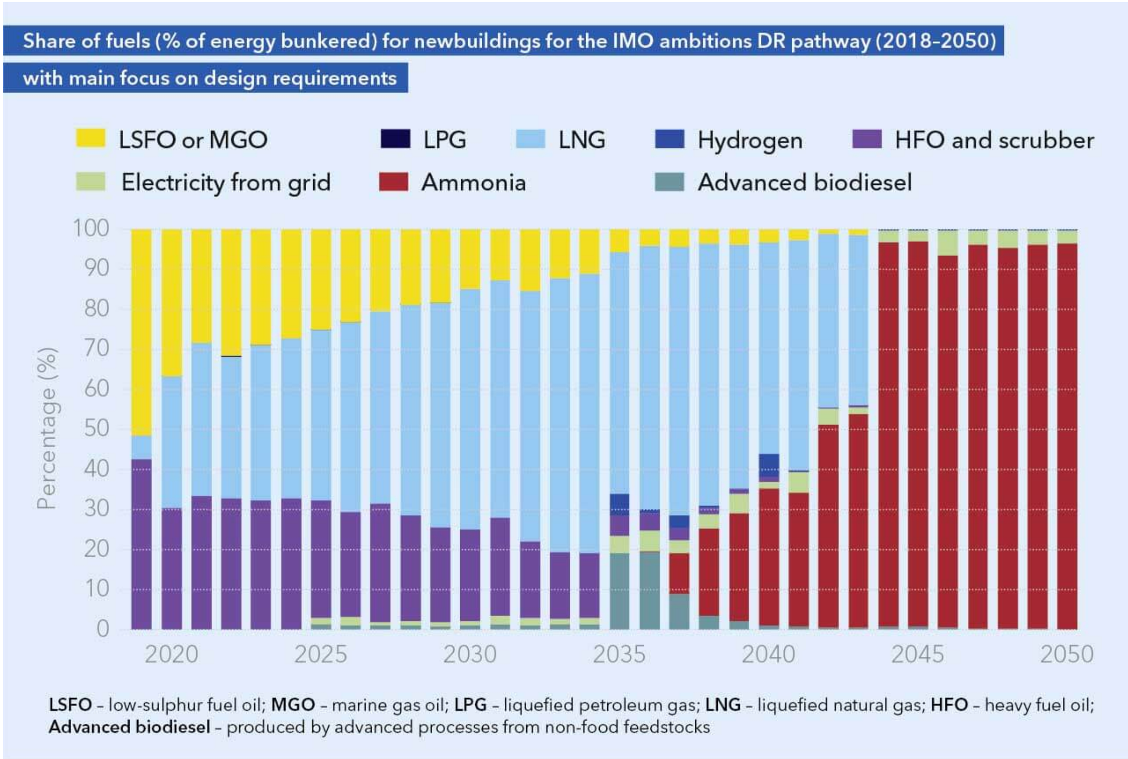

Figure 2.4: Predicting the future energy mix of the world fleet, [6]

2.3 Studies about Emission Inventories

Since 2009 studies about emissions are presented in the literature, the first developments are in Turkey by the same group of researchers, [165], and [166]. These studies are about the estimation of shipping emissions in Candarli Gulf, Izmit Gulf, and the region of Ambarli Port. The emission amounts from ships can be calculated with the activity-based emission model.

Some authors focused their research only on emissions calculation in various regions around the world. The latest studies are based on AIS data. However, the emissions studies in the literature are mainly focusing on Europe and Asia. Figure 2.5, developed by NUNES *et al.* [7], shows the geographical location of the studies from 2010 until 2017 about ship emissions. As can be seen, 14 studies were performed in Europe, 9 in Asia, 2 in Oceania, and 1 in the Arctic region.

In Europe, the implementation of new rules imposed by the European Union and IMO, such as creating new Emission Control Areas (ECAs) and more restrictive legislation for NO_X emissions, has motivated the number of studies concerning ship emissions. On the other hand, nine of the ten largest container ports globally are located in Asia. The major activity of Asian ports has emphasized the necessity of performing studies concerning emissions from ships, since some of these ports are established near cities with high population density, such as the case of Busan and Hong Kong, [7].

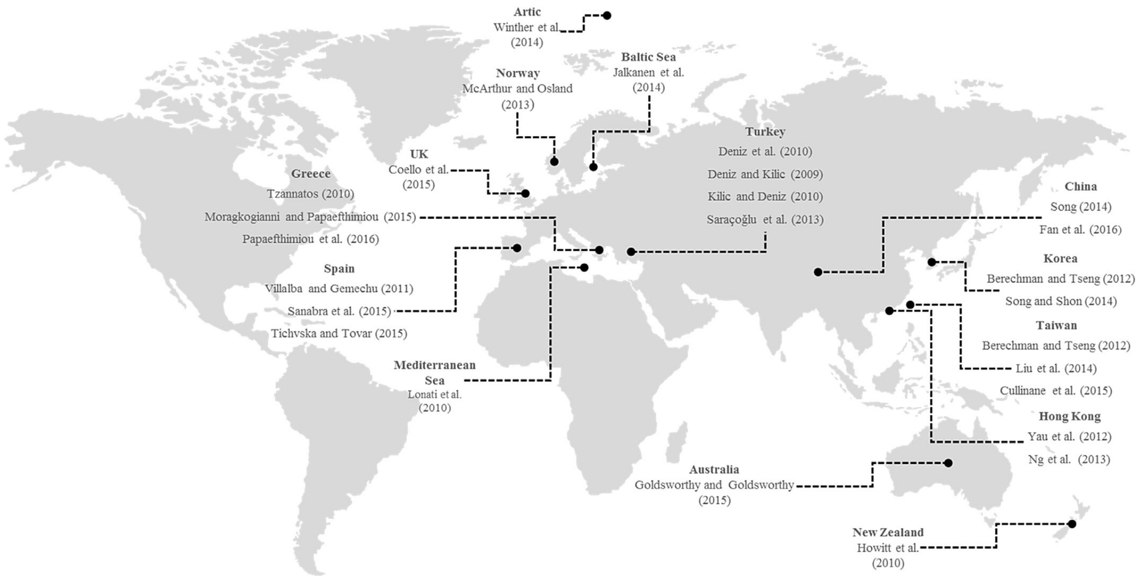

Figure 2.5: The geographical location of the reviewed studies using a bottom-up approach to assess ship emissions from 2010 until 2017, [7]

In the literature, studies on ship emission inventories have been published more frequently since 2009. Such as CEPEDA *et al.* [31] that reviewed approximately forty papers about emissions calculations since 2009. Most of the studies make emission inventories that focus on ports in Europe and Asia. This study is among the first studies that assessed the environmental impact and the life cycle assessment, reviewed studies until early 2019, [31].

The study area for calculating ship emissions has grown considerably in recent years. Researchers are conducting studies from different perspectives and for various purposes, [31]. Bellow, it shows some additional studies not included by the author in the reference CEPEDA *et al.* [31].

A specific study with passenger ship used for pleasure voyages to model the amount of GHG emitted at sea and in port in Norwegian waters are development by SIMONSEN *et al.* [167]. This study uses information about 81 cruise ships of various sizes that sailed Norwegian waters in 2017. The results confirm the differences in the environmental performance of cruise ships.

Some studies are not calculating the emission inventory because of the complexity involved, rather than understanding the airborne pollutant emissions. The research by WAN *et al.* [168] is one example of that analysis. It identifies the major types of ocean-going vessels visiting the ECAs and the emissions associated with these types of ships.

As well, the inventory of CO_2 emitted from ships to support a practical environmental performance management framework for the maritime industry studied by RONY *et al.* [169]. The issues relating to shipping operations and compliance, institutional, and management matters are relevant. The authors also identify the industry's preparedness for this new policy framework of environmental performance management and the impact on existing energy efficiency practices.

Some advances related to the effect of ship emissions developed by WANG *et al.* [170] are also presented. This study aims to identify the contribution of ship emissions to ozone O_3 pollution and the impact of mixing emissions on O_3 pollution in the Yangtze River Delta. The study used the Weather Research and Forecasting Chemical (WRF-Chem) model.

Another study that estimates the impact of atmospheric pollution, specifically in coastal cities, is the work conducted by MERICO *et al.* [171]. One of the purposes of the study is the development of a system based on the integration of measurements collected. It is using a network of low-cost online sensors with local-scale dispersion modeling. It can operate in near-real-time, and it tested studying the impact of the Bari harbor for the year 2018. The relative impact of maritime activities was evaluated and could use for planning timely mitigation actions.

The research, according to LÄHTEENMÄKI-UUTELA *et al.* [172] seeks to provide empirical evidence on how the Baltic Sea Sulphur Emission Control Area (SECA) has impacted the technological innovation system within the Baltic Sea Region maritime sectors.

New studies to minimize emissions appear as alternatives. An example of that is the study done by CHEAITOU e CARIOU [173] as an alternative between economic and environmental optimal solutions and that policies considering imposing a tax on CO_2 or SO_X to reduce the negative externalities from international shipping.

However, there is a calculation gap because the existing emissions inventories are generally developed locally and the methodologies are not standardized. This gap causes an opportunity to define a precise method of the emissions inventories, especially with large databases that can give us more efficient results.

2.4 Emission control areas (ECAs)

In 1997 MARPOL Annex VI was first adopted. It limits the primary air pollutants contained in ships exhaust gas, including sulfur oxides (SO_X) and nitrous oxides (NO_X), and prohibits deliberate emissions of ozone-depleting substances (ODS). MARPOL Annex VI also regulates shipboard incineration and the emissions of volatile organic compounds (VOC) from tankers, [36].

On 19 May 2005, following the entry into force of MARPOL Annex VI, the MEPC, in July 2005 at its 53rd Session, agreed to revise MARPOL Annex VI to significantly strengthen the emission limits in light of technological improvements and implementation experience, [36]. As a result of three years examination, in October 2008, MEPC 58 adopted the revised MARPOL Annex VI and the associated NO_X Technical Code 2008, which entered into force on 1 July 2010, [36].

The main changes are a progressive reduction globally in emissions of SO_X, NO_X and PM, and the introduction of emission control areas (ECAs), see Figure 2.6, [36].

Figure 2.6: Geographical location of the Emission Control Areas

According to the revised MARPOL Annex VI, the global sulfur limit reduced from 3.50% to 0.50%, in force from 1 January 2020. It subject to a feasibility review completed at the latest 2018, [36].

In October 2016, MEPC 70 considered an assessment of fuel oil availability to inform the decision to be taken by the Parties to MARPOL Annex VI, and decided that the fuel oil standard (0.50% sulfur limit), happened on 1 January 2020, [36].

The limits applicable in ECAs for SO_X and PM were reduced to 0.10%, from 1 January 2015, [36].

Progressive reductions in NO_X emissions from marine diesel engines installed on ships are included, with a “Tier II" emission limit for the engines installed on a ship constructed on or after 1 January 2011. A more stringent “Tier III" emission limit for machines installed on a vessel built on or after 1 January 2016 operating in ECAs (North American Emission Control Area and the U.S. Caribbean Sea Emission Control Area). Marine diesel engines installed on a ship constructed on or after 1 January 1990, but before 1 January 2000, are required to comply with “Tier I" emission limits, if an approved method for that engine has been certified by an Administration, [36].

The revised NO_X Technical Code 2008 includes a new chapter based on the agreed strategy for the regulation of existing (pre-2000) engines established in MARPOL Annex VI, provisions for a direct measurement and monitoring method, a certification procedure for existing the engines and test cycles to be applied to Tier II and Tier III engines, [36].

In April 2014, MEPC 66 adopted amendments to regulation 13 of MARPOL Annex VI regarding the effective date of NO_X Tier III standards, [36].

The amendments provide for the Tier III NO_X standards. It applied to a marine diesel engine installed on a ship constructed on or after 1 January 2016. Which operates in the North American Emission Control Area or the U.S. Caribbean Sea Emission Control Area that is designated for the control of NO_X emissions, [36].

Furthermore, Tier III requirements would apply to installed marine diesel engines when operated in other emission control areas, which might be designated in the future for Tier III NO_X control. Tier III would apply to ships constructed on or after the date of adoption by the Marine Environment Protection Committee of such an emission control area, or a later date, as may be specified in the amendment designating the NO_X Tier III emission control area, [36].

Moreover, the Tier III requirements do not apply to a marine diesel engine installed on a ship constructed before 1 January 2021 of less than 500 gross tonnages, of 24 meters or over in length, which has been specifically designed and is used exclusively for recreational purposes, [36].

The revised measures are expected to have a significant beneficial impact on the atmospheric environment and human health, particularly for those people living in port cities and coastal communities, [36].

An example of the countries that have given continuity to the ECAs is China. From 1 January 2019, vessels must switch to fuel with a sulfur content not exceeding 0.50% before entering China's territorial sea, [174].

On 8 November 2018, China notifies Members and clients of regional sulfur emission control requirements taking effect on 1 January 2019 in Hong Kong, Taiwan, and Mainland China's domestic ECA, [174].

According to Gard's correspondent Huatai Insurance Agency & Consultant Service Ltd., the Chinese Ministry of Transport (CMOT) has now issued a new regulation that expands the geographic scope of China's sulfur ECAs. As a result, a new Coastal ECA was designated. The ECA includes all sea areas and ports within China's territorial sea. Another specially designated ECA in China's southernmost province Hainan, the Hainan Coastal ECA. In addition, two Inland ECAs have been established, which include parts of the Yangtze River and the Xi Jiang River, see Figure 2.7, [174].

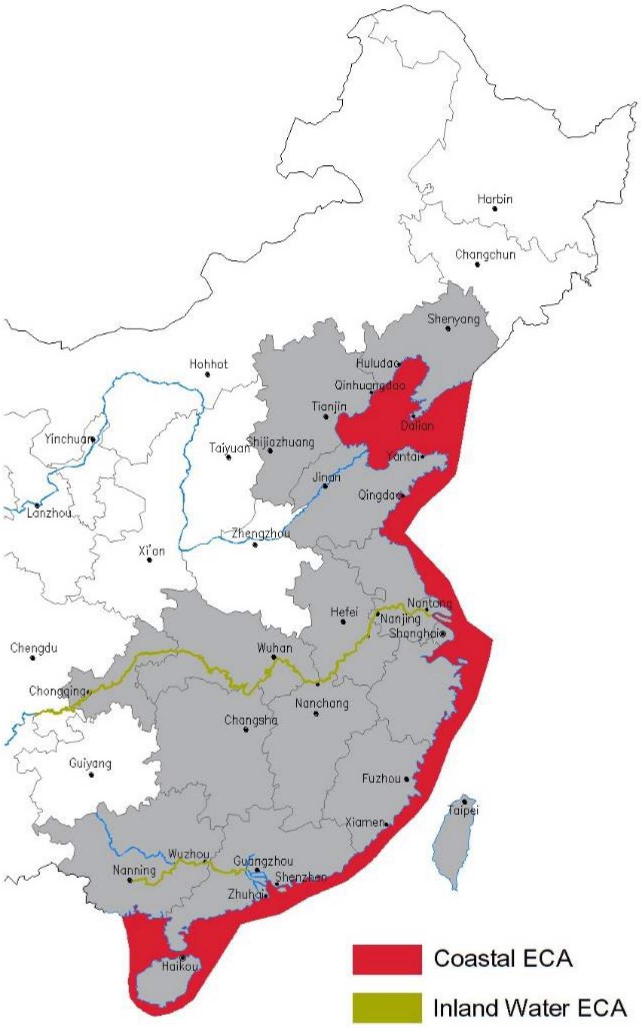

Figure 2.7: Geographical location of the China Emission Control Areas

Chapter 3

Methodology

3.1 Introduction

This chapter presents a detailed bottom-up methodology developed to calculate the ship emission inventory, dis-aggregated by ships and operation modes.

It includes the main approach, the system description, the emission estimation, and the life cycle impact assessment (LCIA).

3.2 Methodology Approach

Generally, two main methods are used in emission inventories so called "Bottom-up" and "Top-down".

The "top-down" method, also called the fuel-based method, is based on marine fuel sales to estimate emissions. The advantage of this method is the availability of the data. This data is from energy databases of marine bunker supply published by the Energy Information Administration (EIA), the International Energy Agency (IEA), and the United Nations Framework Convention on Climate Change (UNFCCC). The disadvantage is the reliability of estimating total fuel consumption and emissions based on the number of marine bunker fuel sales reported. The main reason is that bunker fuel statistics in some countries are unreliable from the fuel suppliers. Such as the miss-allocations or incorrect fuel type descriptions provided by the suppliers may disturb the fuel balance, [175].

The "bottom-up" method, also called the "activity-based" method, is based on fleet activity to estimate ship emissions. The advantage is that emissions are calculated based on all ship movements and characteristics. The disadvantage is the availability of the data because this method needs information on ship characteristics, ship movements, fuel consumption, and emission factors, [175].

The methodology approach has many variants, mainly depending on the available inputs and the modeling or other assumptions. The use of this methodology is heavily dependent on the availability of both quantitative and qualitative data.

During the past years, Industry 4.0, based on the rise of industrial digital technology, provides researchers with big data and the analysis of ever-larger volumes of data as a present-day tool.

Here the "bottom-up" approach is selected due to the accessibility to the AIS, IHS, and Marine Traffic databases. The methodology of which described in the following sections. See Figure 3.1.

The general flow chart of the system to make the emission inventory has three parts, *Inputs*, *Processes*, and *Outputs*.

The input data from this system deals with the information of different databases of ships. The AIS database have Dynamic, Static, and Voyage Data. The study used AIS Database with all data of the operation and movements of the analyzed vessels. Other databases such as the IHS Markit World Sea Ship database, the Maritime Authority databases, and the Classification Society databases having static ship data information may be used to complement the data of each individual ships, e.g., with ship propulsion information.

The second part of the system relies on processing the input data. It performs some operations to improve the data reliability including the filtration of outliers and treatment of the missing values. The methodology used two steps, *(i)* the AIS result processing and the *(ii)* Estimate the ship emissions. These steps includes the definition of the zone of the geographical study, and the classification of the zone depending on the the ship operation: ship in harbor, under maritime voyage, or in the port entrance. The second step applied the specific methodology to calculate the fuel consumption and made the emission estimation. Finally, the application of the Life cycle impact assessment occurs.

The last part of the system relate to outputs. It consists of the result generated after the processing of data. The output files show the total emissions of each air emission gas and the environmental impact. Additional information in the output is the Judgment of Maritime Transportation Stakeholders. This last part of the system is a detailed analysis with some proposed strategies based on the study of the zone and the obtained results. In this case the KNIME platform was used.

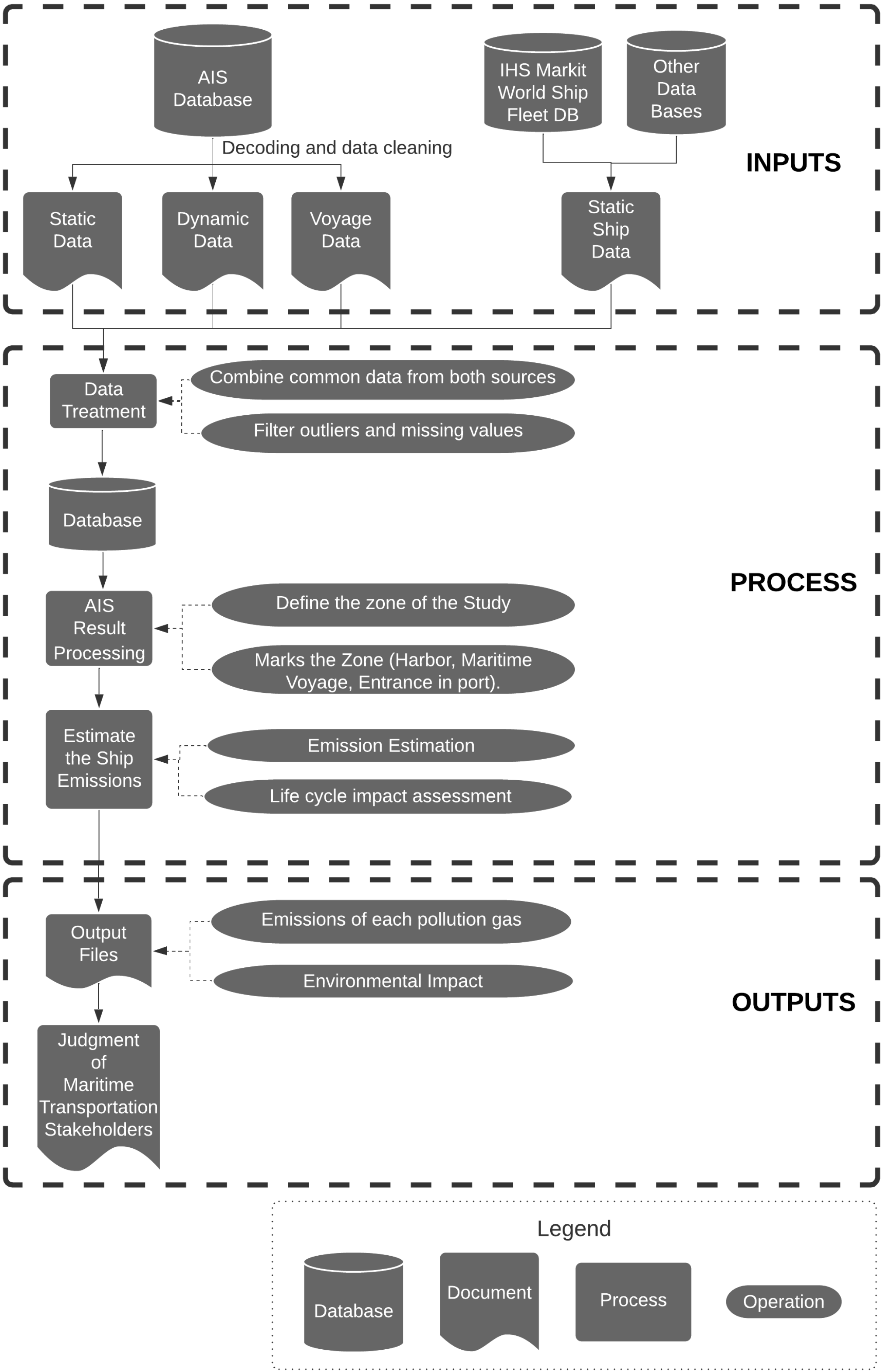

Figure 3.1: General Flow chart of the system to make the emission inventory

3.2.1 Automatic Identification System

The Automatic Identification System (AIS) is a mandatory collision-avoidance system required to be installed on ships by the IMO and the Maritime Safety Administration of several countries. The AIS system makes it possible to locate the majority of vessels throughout the world. The ships that require AIS are the follows:

- International voyaging ships with a Gross Tonnage (GT) of 300 or more,
- Passenger ships of all sizes,
- Domestic vessels with GT of 200 or more traveling in coastal waters,
- Inland ships with a GT of 100 or more.

Special purpose vessels such as military ships, fishing ships, small yachts, and public service ships are exceptions, [11], and [176].

There are, in fact, two types of AIS, [177]:

- Class A: transponders are mandatory on board merchant ships exceeding 300 tonnages and all passenger ships meeting International Convention for the Safety of Life at Sea (SOLAS) standards (merchant navy, ferries, etc.).
- Class B: transponders concern small ships that are not required to comply with SOLAS conventions (recreational vessels, fishing vessels of less than 15 meters, etc.) to enable them to adapt voluntarily to the AIS system.

The objectives of IMO implementing the AIS system are to enhance the safety and efficiency of navigation, the safety of life at sea, and the protection of the maritime environment. AIS facilitates communication between vessels and assist vessel traffic control functions in congested ports, locks, and waterways, [177].

The reported AIS data are divided into static, dynamic, and voyage-related data categories, [176].

- Static information includes:
  1. Maritime Mobile Service Identity number (MMSI) - a unique identification number for each vessel station (the vessel's flag can also be deducted from it)

2. International Maritime Organisation number (IMO) - note that this number remains the same upon transfer of the subject vessel's registration to another country (flag)
3. Call Sign - international radio call sign assigned to the vessel by her country of registry
4. Name - up to 20 characters
5. Type (or cargo type) - the AIS ID of the subject vessel's ship type
6. Dimensions - based on the position of the AIS GPS antenna on the vessel
7. Location of the positioning system's antenna onboard the vessel
8. Type of positioning system (GPS, DGPS, Loran-C)
9. Design draught - 0.1 to 25.5 metres
10. Destination - up to 20 characters
11. ETA (estimated time of arrival) based on UTC with month, date, hours and minutes

- Dynamic data includes:

1. Navigational status, e.g., under way using engine, at anchor, moored, etc.
2. Rate of Turn (ROT) - right or left (0 to 720 degrees per minute)
3. Speed over Ground (SOG) - 0 to 102 knots (0.1-knot resolution)
4. Position coordinates (latitude and longitude - up to 0.0001 minutes accuracy)
5. Course over Ground (COG) - up to 0.1 degrees relative to true north
6. Heading (HDG) - 0 to 359 degrees
7. Bearing at own position - 0 to 359 degrees
8. UTC seconds - the seconds' field of the UTC when the subject data-packet is generated.

- Voyage-related data includes current draught, description of cargo, and destination.

3.2.2 Data acquisition

One of the database considered in this study relies on a AIS base station (hardware and software) that has been installed and maintained by our research group. The base station is named UFRJ-COPPE, and is located at the Technology Centre of the Federal University of Rio de Janeiro. The area covered up to 2 091 Km^2, the average range of the signal reception is 7.21 Nautical mile (NM) with a maximum of 56.23 NM. The average of records received in one hour is around 32 distinct vessels and 15 958 ship positions. The station cover 100% of the Guanabara bay in Rio the Janeiro including the port entrance channel and the anchorage area outside of the bay.

The hardware consists of one omnidirectional Sirio GP6E antenna of 2x5/8λ (162 Mhz), one AIS receiver COMAR SLR350N and one Raspberry Pi3 to provide Ethernet connectivity and to host an NMEA multiplexer server. An NMEA message decoder, as well as a Microsoft SQL server, compose the data warehouse configuration. The main table in the database contains 196 different fields extracted from the messages. The average AIS message quantity is about 395 per minute.

The AIS data provides efficiency to assist ships in collision avoidance ports and maritime authorities in traffic monitoring, ensuring better surveillance of the sea. However, it also has other potential utilization, such as estimating emissions with accurate data, as proved in this thesis.

Other databases used are the IHS and Marine Traffic databases that provide detailed data for ships.

3.2.3 Input data

In this work, emission inventory is obtained through the assessment of various input data. There is two types of data. Input data used in the AIS processing and input data used in the emissions assessment applied.

Input data of AIS processing are the data used to define the zone of the study and to evaluate the behavior of the ship (harbor, maritime, entrance in port).

The data used for AIS processing are presented below:

1. MMSI number - Maritime Mobile Service. Identity (MMSI) identification number.
2. Ship name - Name of the ship.
3. Service Speed - Service speed of the ship in knots.
4. Latitude - Latitude in degrees, minutes, seconds.
5. Longitude - Longitude in degrees, minutes, seconds.

6. Ship Type - Type of the ship.
7. Navigational status - Status of the ship (underway using the engine, at anchor, not under command, restricted maneuverability, constrained by her draught, moored, aground, engaged in fishing, underway sailing, etc.).
8. Speed over ground (SOG) - Speed over ground is the speed of the ship concerning the ground or any other fixed object in knots (based on GPS).
9. Course over ground (COG) - Cardinal direction in which the craft is to steered, relative to true north.

Input data of the emission assessment methodology are the data used to estimate the ship emission inventory.

The input data of the methodology are presented below:

1. Engines power P_j – Installed power for the engine j in kW
2. Service speed MS – Service Speed of the ship in knots
3. Speed over ground AS – Speed over ground (SOG) is the speed of the ship concerning the ground or any other fixed object in knots
4. Time of operation $T_{j,k,l}$ – Operating time for engine j, using fuel type k during navigational status l in hours
5. Fuel type k – Type of fuel used by the ship
6. Navigational status l – Status of the ship (underway using the engine, at anchor, not under command, restricted maneuverability, constrained by her draught, moored, aground, engaged in fishing, underway sailing, etc.)
7. Emission type i – Emission type considering CO_2, SO_X and NO_X, PM_{10}, and $PM_{2.5}$

3.3 System description

This section explains each part of the general flow chart of the system presented in Figure 3.1 including the three steps: Inputs, Processes, and Outputs.

3.3.1 Inputs of the System

Inputs are all the information entering into the system to operate. There are static, dynamic, and voyage information, and all are about the fleet activity.

In the inventory emissions system, inputs are from various databases as their own AIS database as principal Database (DB). The primary DB is explaining in Section 3.2.1. IHS Markit World Ship Fleet Database and MarineTraffic are secondary DB.

The most important fields in the DB at route point level are:

1. IMO number - IMO identification number.
2. MMSI number - Maritime Mobile Service Identity (MMSI) identification number.
3. Ship name - Name of the ship.
4. Fuel consumption of the main engines - Fuel consumption from main engines in tonnes per day running at Continuous Service Rating (CSR).
5. Engines Number - Number of engines in the ship.
6. Service Speed - Service Speed of the ship in knots.
7. Latitude - Latitude in degrees, minutes, seconds.
8. Longitude - Longitude in degrees, minutes, seconds.
9. Ship type - Type of the ship.
10. Engines RPM - Revolutions per minute of the engine.
11. Fuel type - Type of fuel used by the ship for main propulsion.
12. Navigational status - Status of the ship (underway using the engine, at anchor, not under command, restricted maneuverability, constrained by her draught, moored, aground, engaged in fishing, underway sailing, etc.).
13. Maritime call signs - Call signs assigned as unique identifiers to ships and boats.
14. Speed over ground (SOG) - Speed over ground is the ship's speed concerning the ground or any other fixed object in knots.
15. Course over ground (COG) - Cardinal direction in which the craft steered, relative to true north.

IHS Markit Sea-Web – World Ship Fleet Database (2018) The IHS Markit Sea-Web service is one of the largest maritime databases available, covering ship characteristics, movements, owners and managers, ship and company sanctions compliance, casualty and risk events, ports, terminals, and berths.

In this study, the maritime world fleet product of the IHS Markit Sea-Web service has been used to export the fields relating to vessel particulars of the world seagoing ship fleet. It corresponds to approximately 77198 ships. Figure 3.2 shows the quantity of available data for the fields that have been used:

- Identification: IMO ship number (primary key); MMSI; ship name
- Classification: ship type; ship group; classification society; flag; ship status [in service, lay out, etc.]
- Dimensions: length overall (LOA); length between perpendicular (LPP); draught; breadth overall (BOA); molded breadth (B)
- Capacity: gross tonnage (GT); deadweight tonnage (DWT); lightweight displacement (LDT); gas capacity; grain capacity; liquid capacity; TEU capacity
- Propulsion: service speed; fuel consumption of the main engines; total KW (installed power) of the main engines; the number of main engines; RPM of main engines; total KW (installed power) of generators; the number of generators
- Total fuel consumption including main engines, generators, and auxiliaries
- Age: the year of the ship launch

3.3.2 Process of the system

In order to perform the emission inventory several processes are developed. The process has a series of actions, operations, or functions that lead to the result.

The process is divided into three parts: Data treatment, AIS processing results, and Estimate ship emissions.

Data treatment is essential to make use of the data in the proper form. Raw data collection is only one aspect. The organization of data is equally crucial so that relevant conclusions can be drawn. This step is what data treatment is all about.

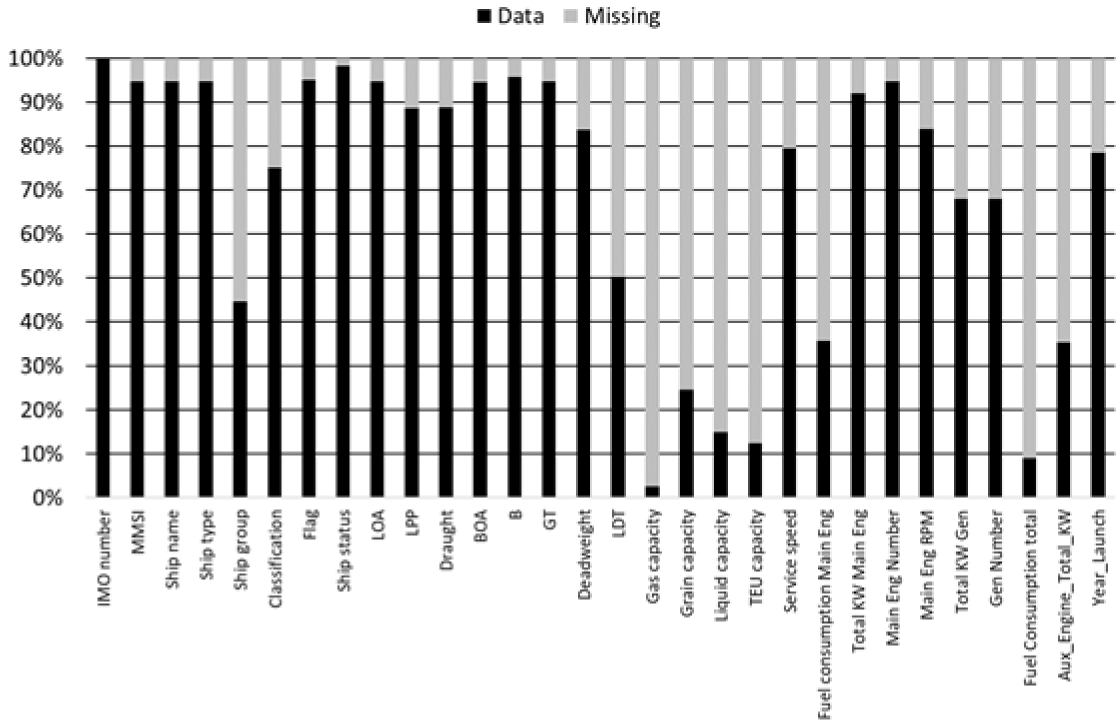

Figure 3.2: Available and missing data for the IHS database

The combination of the data of the DB sources happens in this part of the process. This action is necessary to build a database with all the information. The main primary key that is used to undertake this process is the IMO ship number and the second primary key is the Maritime Mobile Service Identity (MMSI) identification number.

An essential aspect of data treatment is the handling of errors. All experiments or simulations invariably produce errors and noise. Both systematic and random errors need to be considered.

Data treatment consists of defining the records that be considered or not for the process. The outliers and the missing values are excluded.

Records not considered in the process are associated with the accuracy of the information, for example, the verification of the ships speed. The ships speed, in some cases, have wrong values due to the transponders' errors. Then, a filter can be established to detect vessels that present a speed over ground above the design speed of the ship.

Another critical action is removing the AIS records that relates to inland, lock/bridge/terminal messages, and the records of aids to navigation (buoys and lighthouses). These are not associated with emission inventory.

AIS processing results consist of two parts. First, it defines the zone of the study. Second, it marks the area where you want to assess the ship's behavior (harbor, maritime voyage, entrance in port).

The zone depends on the scope of the research. It can be defined worldwide or in a particular area. It also depends on the capacity of your hardware and software to process the records.

Inside the zone of the study are defined three subdivisions of operation of ships. These divisions are the harbor zone, maritime voyage zone, and entrance in the port zone. Each division depends on the characteristics of each type of ship, it focus on speed and status.

Estimate ship emissions are part of the process where the methodology is applied. More details on the emissions assessment are presented in the next section.

3.3.3 Outputs of the system

The main output of the study relies on the assessment of the inventory of the emissions of each gas (in tons) and the impact on the environment. An interesting point to highlight is that the emissions can be geo-localized. This can be of a great value to recommend maritime authorities, port administrations, vessel operators, and other stakeholders to support emission decisions.

3.4 Emission assessment

The methodology of ship emissions assessment is adapted from Equation 3.1. The CO_2, SO_2 and NO_X, PM_{10}, and $PM_{2.5}$ emissions has been calculated between two AIS report positions of a vessel using the equation proposed by LIMITED [12], and GOLDSWORTHY e GOLDSWORTHY [178]. This formulation depends mainly on the installed power of the ship engines, the type of fuel used, as well as the load factor of the engine, see Equation 3.2.

$$E_{i,j,k,l} = (P_j \times LF_{j,l} \times T_{j,k,l} \times EF_{i,j,k})/10^6 \quad (3.1)$$

where $E_{i,j,k,l}$ Total emission of pollute i from engine j using fuel type k during operation mode l tons),
P_j Installed power for engines j (kW),
$LF_{j,l}$ Load factor for engine j during operation mode l (%),
$T_{j,k,l}$ Operating time for engine type j, using fuel type k during operation mode l (hours),
$EF_{i,j,k}$ Emission factor for pollute i from engine j using fuel type k (g/kWh).

$$LF_{j,l} = (AS/MS)^3 \tag{3.2}$$

where $LF_{j,l}$ Load factor for engine j during operation mode l (%),
AS Actual speed (knots),
MS Maximum speed (knots).

The emission factors used in this study are taken from [11] considering the the main engine (ME) and the fuel oil type as residual oil (RO) for all the ships. All auxiliary engine (AE) are considering to burn marine diesel (MD). For each engine, the corresponding emission factors apply, as described in Table 3.1. Other emission factors tables are in the Appendix A.

Table 3.1: Emission factors (CO_2, SO_2 and NO_X, PM_{10}, and $PM_{2.5}$) for pollute and fuel type for each engine type (g/kWh), [11]

Machine Type	Engine Type	Oil Type	CO_2	SO_2	NO_X	PM_{10}	$PM_{2.5}$
ME	SSD	RO	622	10.3	18.10	1.38	1.22
ME	MSD	RO	686	11.31	14	1.19	1.22
ME	HSD	RO	686	11.31	12.7	0.65	0.5
AE	MSD	MD	692	2.12	13.9	0.33	0.3

where SSD means Slow Speed Diesel (SSD), MSD means Medium Speed Diesel, HSD means High Speed Diesel, RO means Residual Oil, MD means Marine Distillate, ME means Main Engine and AE means Alternative Engine

3.5 Life cycle impact assessment (LCIA)

Life-cycle assessment (LCA) is an environmental management tool that helps to evaluate the effects of a product on the environment over the entire period of its life, [179]. Emissions and consumption of resources are evaluated at every stage of the life cycle. The emergence of Big Data Analytics is a tool that helps us to better understanding the LCA, [179].

LCA is classified in different levels, such as the development of mid-point-oriented and end-point-oriented methods for life cycle impact assessment (LCIA). The method ReCiPe 2008 for LCIA has been used, [180]. ReCiPe is a method for the impact assessment (LCIA) in a LCA. ReCiPe provides a procedure to calculate the life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to this project, National Institute for Public Health and the Environment (RIVM), CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. ReCiPe can be seen as a fusion of the two methodologies, taking the midpoint indicators from CML and the endpoint indicators from Ecoindicator, [180].

The idea of ReCiPe is that the user can choose the level of the results:

- Eighteen midpoint indicators; low uncertainty but difficult to interpret. The midpoint indicators are similar to what is used in the CML methodology: Climate change, acidification, eutrophication etc.

- Three endpoint indicators; easy to understand but more uncertain. The endpoint indicators are similar to what is used in the Ecoindicator 99 methodology: Damage to Human health, ecosystems, and resource availability

ReCiPe 2008 comprises two sets of impact categories with associated settings of characterization factors. Eighteen impact categories were discussed in the midpoint level and the end-point level. Most of these midpoint impact categories further converted and aggregated into the following three end-point categories. Figure 3.3 sketches the relations between the life cycle impact (LCI) parameter (left), midpoint indicator (middle), and end-point indicator (right), [8].

CO_2 is in the climate change (CC) midpoint level, SO_2 and NO_X are in the terrestrial acidification (TA) midpoint level, PM_{10}, and $PM_{2.5}$ are in particulate matter formation (PMF) midpoint level. At the endpoint level, most of these midpoint impact categories further converted and aggregated into the following two endpoint categories: damage to human health (HH) and damage to ecosystem diversity (ED), [8]. The normalisation is developed both for the midpoint and endpoint indicators.

Weighting is not developed for the mid-point indicators by the ReCiPe authors. The midpoint values can be weighted using the thinkstep LCIA Survey 2012. Using this only makes sense combined with a normalisation hereby bringing the impacts to the same unit of person-equivalents. The endpoint indicators can be weighted

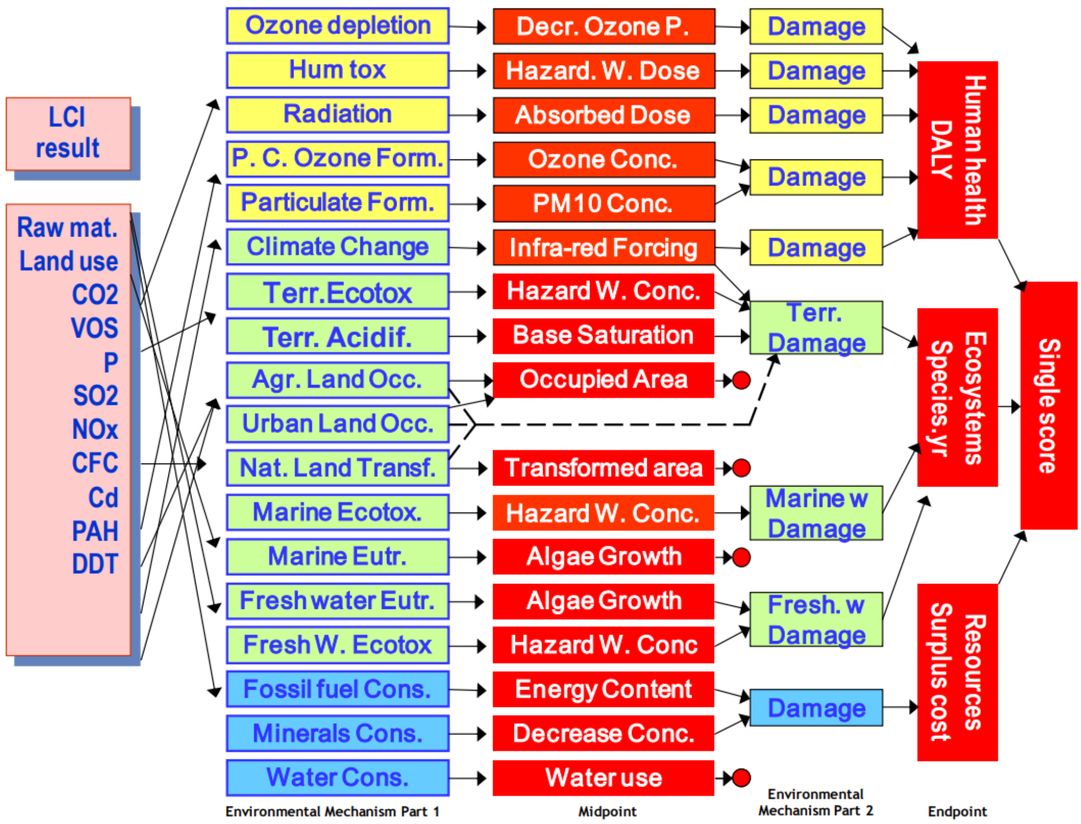

Figure 3.3: Relationship between LCI in the different levels of impact (environmental impact, midpoint, and endpoint), [8]

using the ReCiPe weighting factors developed by the authors or using the weighting factors developed in the thinkstep LCIA Survey 2012.

ReCiPe presents three value perspectives: individualist (I), hierarchist (H), and egalitarian (E), which differ from each other in terms of magnitude and time scales of environmental issues. The individualist (I) perspective assumes a short-term interest (e.g., for climate change, the time horizon is 20 years) and optimistic technological breakthroughs in the future. Hierarchist (H) perspective takes an intermediate time frame (e.g., 100 years time horizon for climate change) and common policy principles. Egalitarian (E) perspective is more prudent as it assumes the most prolonged period (e.g., 500 years time horizon for Climate change) and pessimistic development scenarios, [8].

In other words, all mid- and endpoint indicators are available in three versions taking into account three different cultural perspectives:

- Individualist (I) is based on the short-term interest, impact types that are undisputed, technological optimism as regards to human adaptation. Uses the shortest time frame e.g. a 20 year timeframe for global warming, GWP20.
- Hierarchist (H) is based on the most common policy principles with regards to time-frame and other issues. Uses the medium time frame e.g. a 100 year timeframe for global warming, GWP100.
- Egalitarian (E) is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc. Uses the longest time frame e.g. a 1000 year timeframe for global warming, (GWP1000) and infinite time for ozone depletion (ODPInf).

Chapter 4

Case Study

4.1 Introduction

This chapter presents different areas of study where the methodology is applied to make emission inventory. There are in the ports around the two most populated municipalities in Brazil (Rio de Janeiro Area, and Santos Area), and Galápagos Island Area (Ecuador).

Case Study 1: Brazil represented by Rio de Janeiro and Santos, was chosen due to the availability of an extensive collection of data, including the static data of the ships. Also, the diversity of vessel types in this zone is essential to classify what are the ships polluting more than others. This classification provides a tool to make better decisions with alternative fuels or new technologies selection. Furthermore, these regions in Brazil have a significant influence on the economy, and the pollution generated causes a substantial impact on the population's health.

Case Study 2: Ecuador represented by Galápagos Island, it is a vulnerable natural zone of the world, with environmental importance in the biodiversity and also an economic significance in a small country. The data available allows the evaluation of a fleet with minor dimensions, and it provides an excellent example to make better decisions with alternative fuels or new technologies selection. Also, this is a case that the author applied within a project developed in partnership with the Maritime Authority and the country's tourism ministry. Furthermore, these data provide a tool to compare the methodology developed and the statistical calculus of fuel consumption. The information available and the results found give more robustness to the case. Moreover, the Galapagos region in Ecuador has a significant influence on the economy, and it is an area that needs special attention because of its worldwide environmental importance.

The GHG emission abatement technologies applied in Galápagos Island Area (Ecuador) is presented in study case 2, this is part of the action plan for the sustainable energy transition of the Galapagos Islands.

4.2 Case Study 1: Brazil, the ports of Rio de Janeiro and Santos

The Case Study 1: Brazil area includes the ports around the two most populated municipalities in Brazil: The ports of Rio de Janeiro and Santos.

The author developed various academics articles, CEPEDA *et al.* [28], CEPEDA *et al.* [30], CEPEDA *et al.* [31], RAMOS *et al.* [32], and MARTINS *et al.* [34] based on the methodology presented in this dissertation with Rio de Janeiro and Santos Port separately.

4.2.1 Rio de Janeiro Area

Rio de Janeiro Area in Brazil is the principal city involved in the petroleum industry. The area of the study is an oceanic bay called Guanabara Bay (GB), located in Southeast Brazil in the state of Rio de Janeiro, between 22°40'S and 23°00'S latitude and between 043°00'W and 043°18'W longitude, see Figure 4.1. The port of Rio de Janeiro is the second largest in the country after the port of Santos. The bay has an area of approximately 384 km^2, including islands. On its western shore lies the city of Rio de Janeiro and fifteen other municipalities, with 12 million people in 2017 based on the Brazilian Institute of Geography and Statistics data (IBGE).

International shipping associated with the country's development and petroleum industry increased the marine traffic through the Bay. GB poses significant risks to biodiversity and the marine environment, the livelihood of the coastal communities, and the fishing and tourism industries.

Five types of facilities are distributed throughout the Bay involving dry cargo terminals, passenger terminals, petroleum terminals, shipyards, navy facilities, and yacht clubs.

4.2.2 Santos Area

The Port of Santos is located in Santos Bay in the State of São Paulo. Santos Port is considered one of the biggest ports in Latin America and the most important

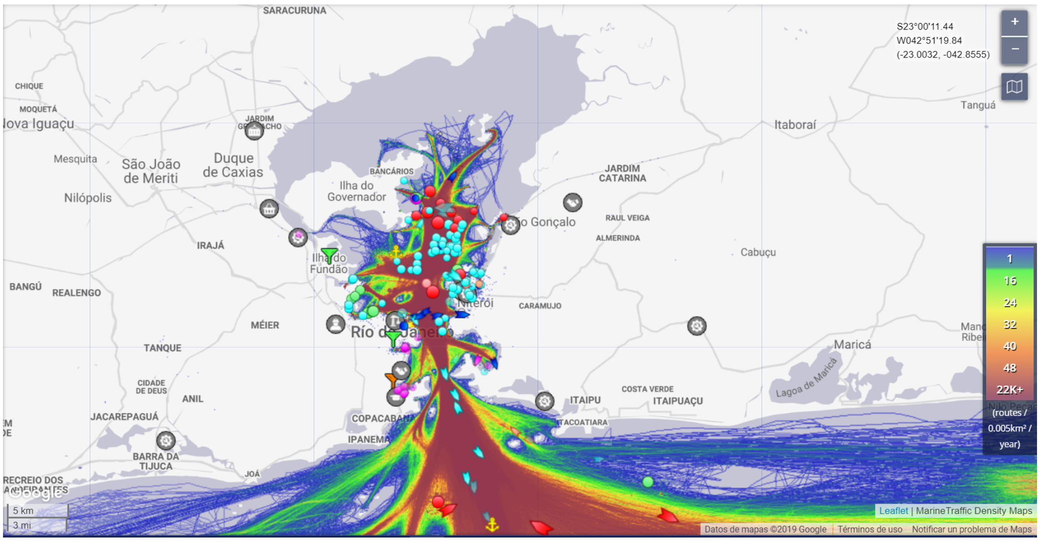

Figure 4.1: View of the Guanabara Bay including the density of AIS navigation 2016, and 2017.

The points (ships with speed = 0 knots) and the arrows (ships with speed > 0 knots) on the map represents the ships in the area, each color is a Vessel Type.

Brazilian Port, representing an economic influence more significant than 50% of the national gross domestic product and 25% of its foreign trade, see Figure 4.2. In total, the Port counts on 65 berth quays, spread on both margins, and receives multiple types of ships, including containers, solid and cargo bulk carriers, cruises, and Ro-Ro.

The biggest cities that make up this region are Santos, São Vicente, Guarujá, and Cubatão, which have a total of 1.2 million people (pp) living there in 2018, based on data from the Brazilian Institute of Geography and Statistics (IBGE).

4.2.3 Database

In this case study, twelve months of AIS data, according to Table 4.1, that represents 118 892 901 registers, were utilized to estimate the emission inventory over the area of the study.

During the period of the research 6 186 vessels were registered, of which 4 991 were included in this study. The ships that presented less than 500 AIS position reports in the DB were disregarded. The vessels without static ship data (19%) were not considered.

To avoid to analyse scarce data and partial routes of vessels, a minimum quantity of AIS records has been set up to 500. Only vessels having 500 records or above

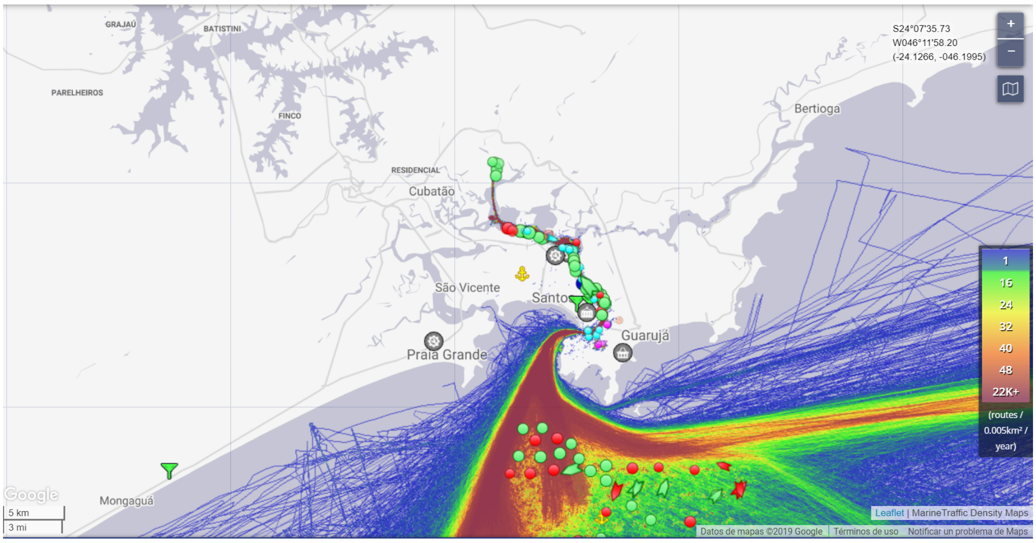

Figure 4.2: View of Santos Bay included the density of AIS navigation 2016, and 2017.

The points (ships with speed = 0 knots) and the arrows (ships with speed > 0 knots) on the map represents the ships in the area, each color is a Vessel Type.

are considered in this study. This criteria could be changed, and it is not a rigid rule, but, in the analysis of the data, this number works fine in all of the applied cases. The simulation of the movements of the vessels can prove that above 500 AIS records, the route path of the ships are continuous and well defined without discontinuities. However, it may vary depending on the area of the study and the coverage of the AIS based station. Satellite data (not used here) may solve some of these inconsistencies due to a more consistent reception of the VHF data packages.

Table 4.1: Months with AIS records in Brazil areas

Month	**2018**	**2019**	**Month**	**2018**	**2019**
January	✓	✓	July		
February	✓	✓	August	✓	
March	✓	✓	September	✓	
April	✓		October	✓	
May			November	✓	
June			December	✓	

Within the area of the study, the distribution of the type of ships is about 4991 vessels amongst 48% are cargo vessels, 17% are tankers, 9% are work ships or containers vessels, 7% are passenger ships, 6% are supply vessels, 2% are fishing vessels, and 2% are miscellaneous, see Figure 4.3.

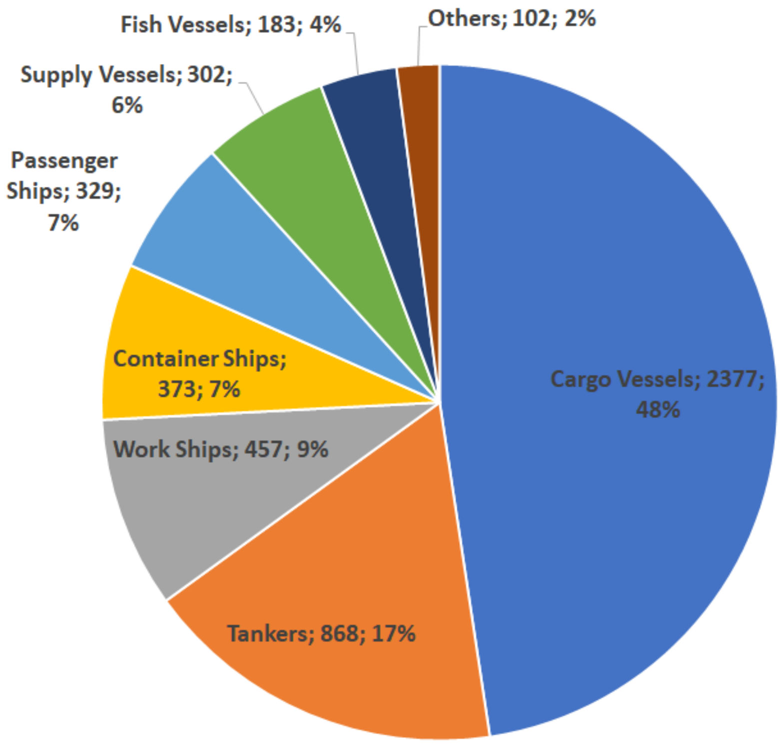

Figure 4.3: Distribution of Ship types in Santos and Rio de Janeiro Area.

4.2.4 Results

The largest ships can consume more fuel and, in consequence, emit more pollution than smaller ships. The volume of merchandise trade in Santos Port is about 27 363 319 tons, while in Rio de Janeiro Port is about 1 795 436 tons. The total volume of merchandise trade of these two ports is in total 29 158 755 tons. The values represent for Rio de Janeiro around 6% of the total volume, while Santos represents 94% of the total volume of merchandise from these two ports, [181].

The methodology developed first calculated the quantity of energy demanded, or fuel consumption, and then estimated the ship emissions. Figure 4.4 shows the quantity of fuel consumption demand by ship type in the Case Study 1, [31]. The AIS data allowed plotting a high-resolution geographical characterization of emissions.

Total estimated emissions from ships, year 2018, are presented in Table 4.2. CO_2 emissions are the most important with over 2 330 033 tons per year, followed by NO_X and SO_X emissions.

Just as the order of magnitude in the volume of cargo moved predominated in the Port of Santos with more than 90%, the port emissions also have a similar order of

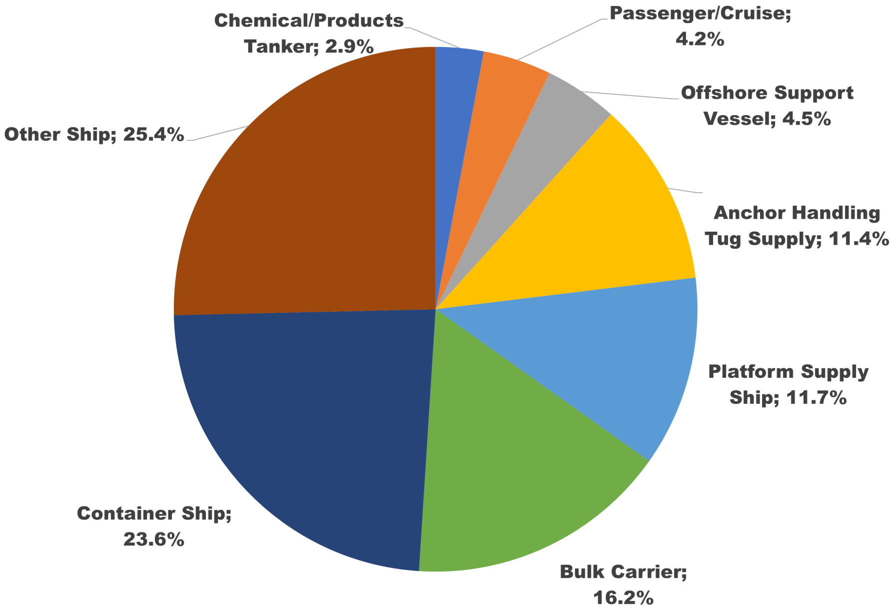

Figure 4.4: Final fuel consumption percentual demand by ship type in Rio de Janeiro and Santos Port

magnitude.

The heat maps of the quantitative assessment of the emissions at Rio de Janeiro (Guanabara Bay) are illustrated in Figures 4.5, 4.6, 4.7, and 4.8. These maps have been constructed using Google maps API through a solution provided by Raffael Vogler in (www.joyofdata.de). The API calculates the heat map based on the contribution of each point in 50 pixels of distance. The map's maximum intensity is fixed at 2.5 t and is represented by the red colour. Colour gradient follows the default order: light green, yellow, orange and red, representing roughly 25%, 50%, 75% and 100% or more of the maximum intensity. The peak of the emissions is observed in the south part of the bridge between Rio de Janeiro downtown centre and Niteroi municipalities, [31].

Table 4.2: Estimation of total of emission due to marine traffic in Rio de Janeiro and Santos, in tons, 2018

Polluted Gas	Both Ports	Rio de Janeiro	Santos
SO_X	2 907	717	2 191
NO_X	45 859	874	44 985
$PM_{2.5}$	1 090	69	1 021
CO_2	2 330 033	43 457	2 286 576

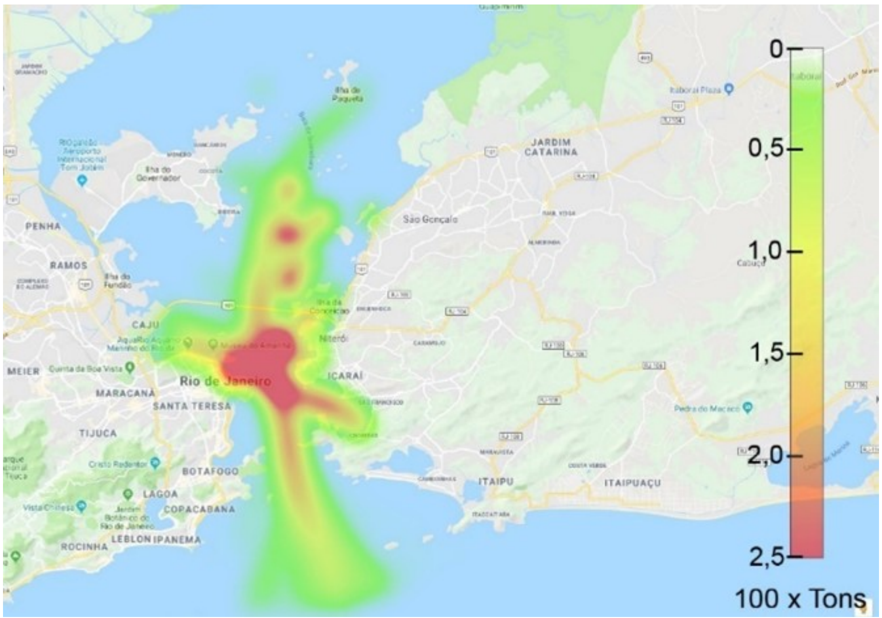

Figure 4.5: Distribution of CO_2 emissions in tons per year around Rio de Janeiro (Guanabara Bay)

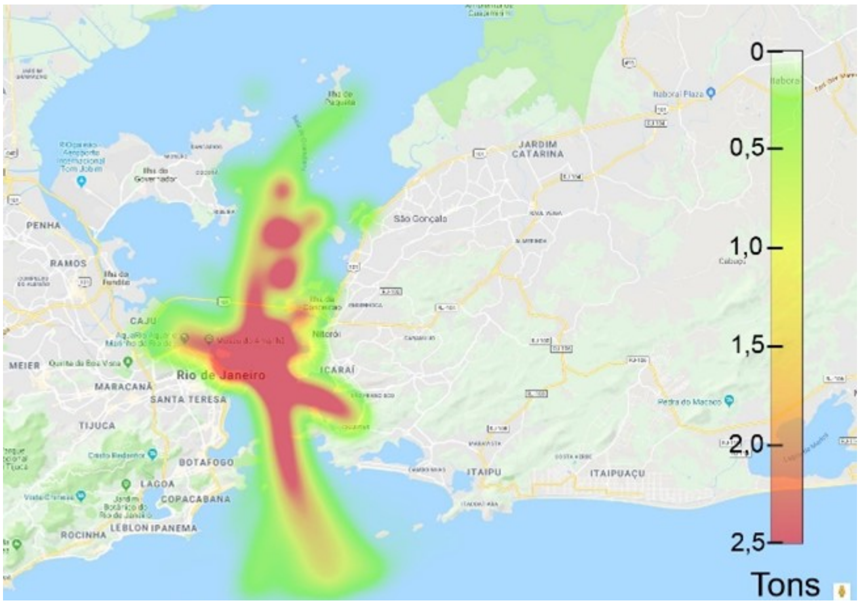

Figure 4.6: Distribution of SO_X emissions in tons per year around Rio de Janeiro (Guanabara Bay)

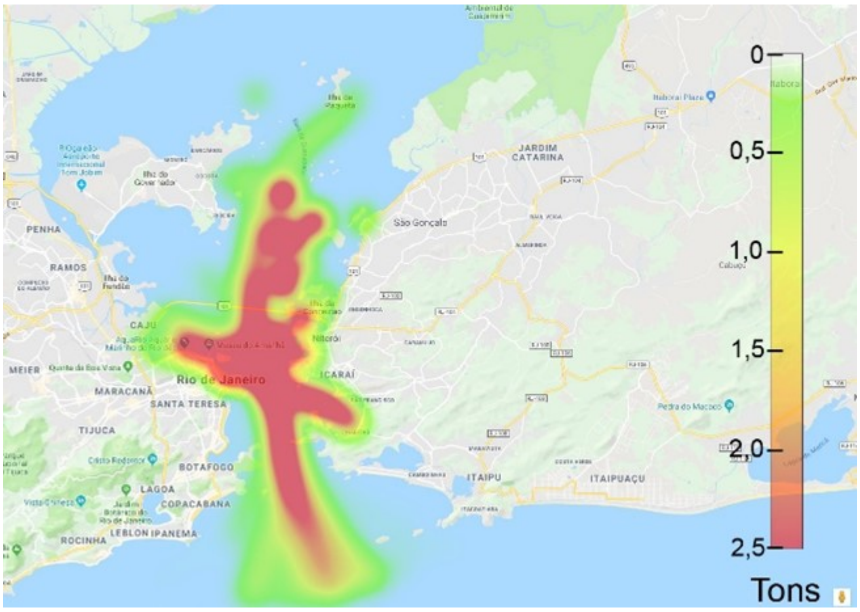

Figure 4.7: Distribution of NO_X emissions in tons per year around Rio de Janeiro (Guanabara Bay)

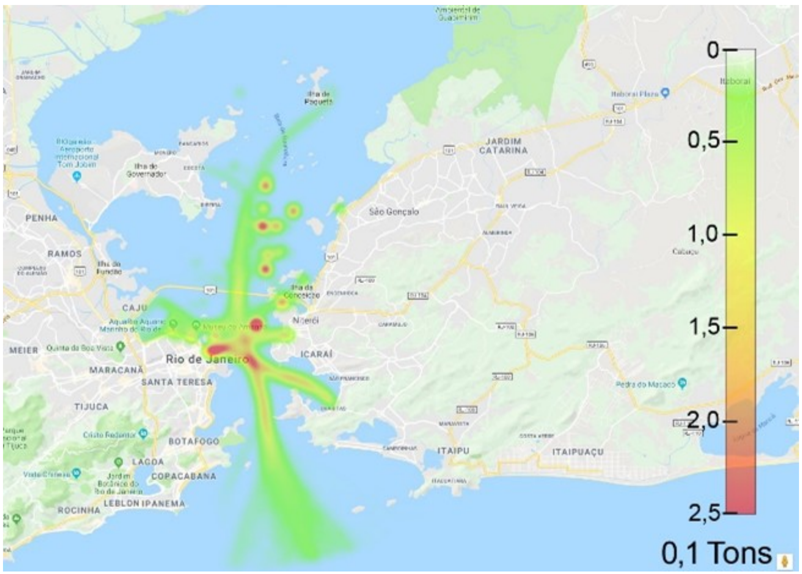

Figure 4.8: Distribution of $PM_{2.5}$ emissions in tons per year around Rio de Janeiro (Guanabara Bay)

Life-cycle assessment

The assessment of the emission impacts on the surrounding municipalities' population is in the scope of this study. The Life Cycle Impact Assessment (LCIA) for Rio de Janeiro and Santos is present in Table 4.3.

The LCIA was calculated using the factors of characterization and normalization available in the LCA-ReCiPe website (rivm.nl/en/life-cycle-assessment-lca/recipe), based on the total emissions estimated.

Table 4.3: LCIA of actual annual average emission due to marine traffic in Rio de Janeiro and Santos Region, HH in DALY/kg CO_2 eq., ED in Species year/kg CO_2 eq., where DALY means Disability Adjusted Life Year.

Endpoint	Midpoint	Individualist	Hierarchist	Egalitarian
HH	Global Warming	189.199	2162.271	29125.413
HH	Fine PM formation	685.61	4388.860	4388.860
HH	POF	42.875	42.875	42.875
ED	Global Warming	1.240	6.524	58.252
ED	POF	6.078	6.078	6.078
ED	Acidification	4.116	4.116	4.116

HH means Human health, *ED* means Ecosystem diversity, and *POF* means Photochemical ozone formation

Figure 4.9 also shows the Human health impact on marine traffic in Rio de Janeiro and Santos Region, where Global Warming and Fine particulate matter formation are the most alarming results.

Figure 4.10 shows the Ecosystem Diversity impact on marine traffic in Rio de Janeiro and Santos Region, where Global Warming again has the most significant results.

These results express the magnitude and significance of the social and environmental costs associated with maritime activities in Rio de Janeiro and the Santos Region.

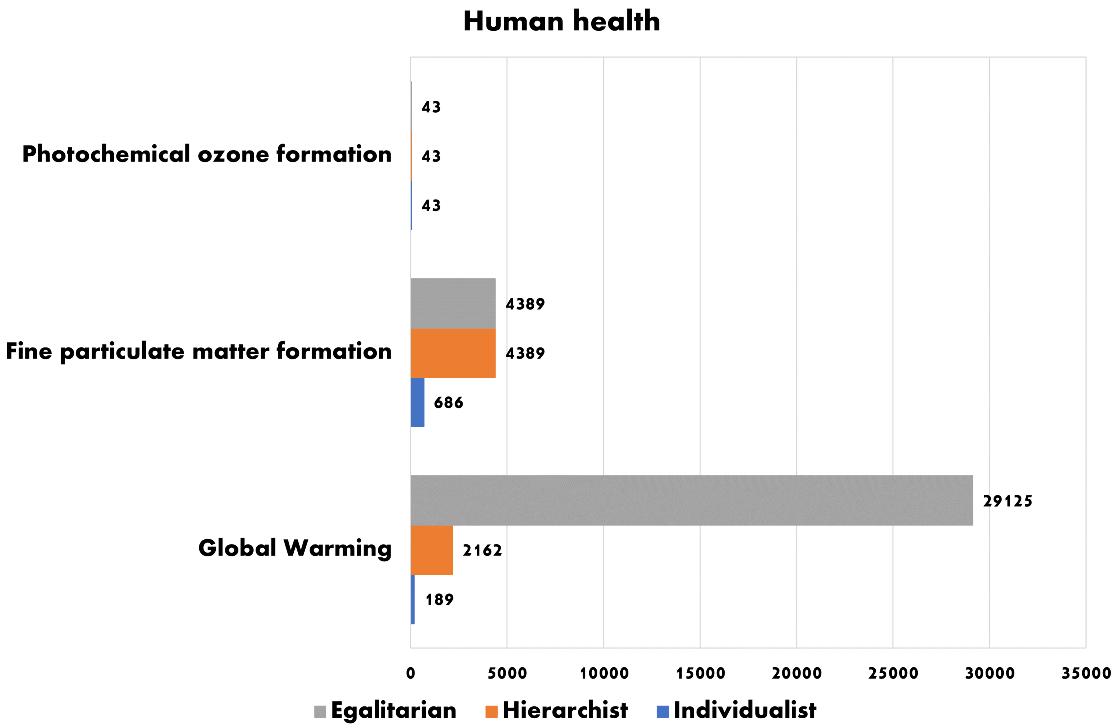

Figure 4.9: Human health impact to marine traffic in Rio de Janeiro and Santos Region.

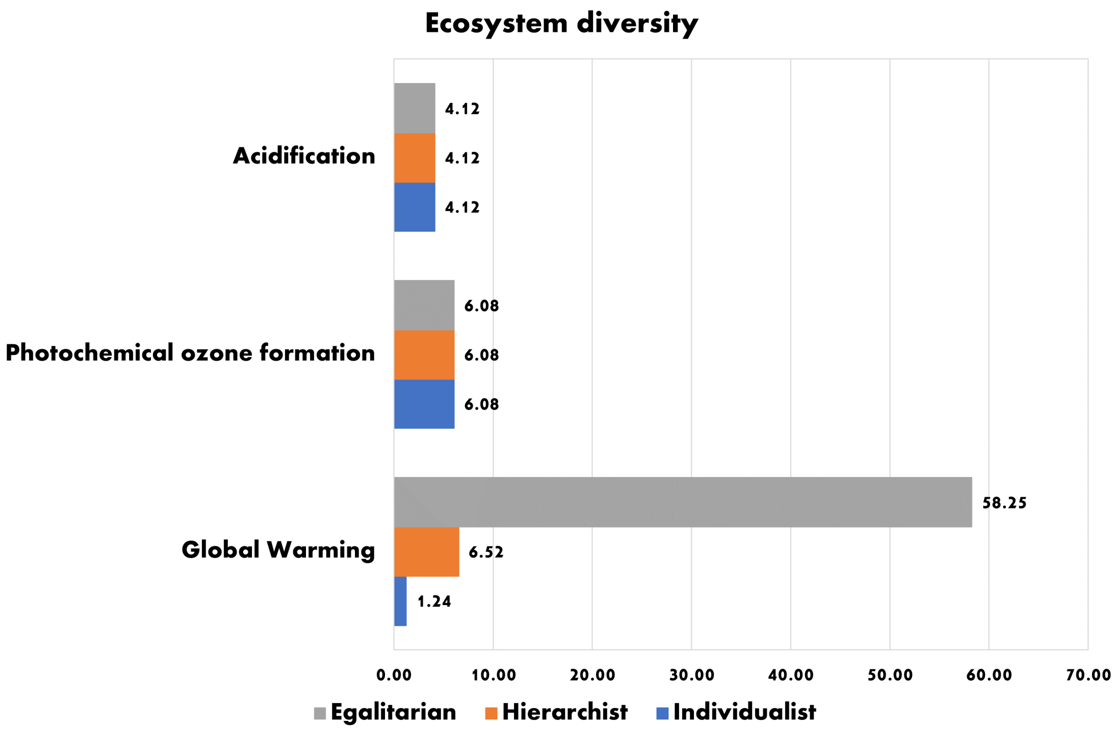

Figure 4.10: Ecosystem Diversity impact to marine traffic in Rio de Janeiro and Santos Region.

4.2.5 Discussion

Rio de Janeiro and Santos are one of the most busiest ports of Brazil, has a great environmental and socio-economic importance for the region of the study. Its current state of environmental degradation including by GHG emissions pose risks to the human populations of its surroundings, who use its waters for pleasure, transportation, or for their livelihood.

This Case study focusses on the assessment of the emissions due to marine traffic base on 12 months AIS data (years: 2018-2019). The major findings of this case study, which is the first ship emission inventory for this zone, may be summarized as follows: Total estimated emissions from ships are 2 330 033 tons of CO_2, 2 907 tons of SO_X, 45 859 tons of NO_X, and 1090 tons of $PM_{2.5}$. Continuously storing AIS data allows to better understand the distribution of ship emissions around ports.

The implementation of estimation of life cycle impact assessment is an accomplished achievement quantifying the environmental impact and damages to human health (HH) as well as damages to ecosystem diversity (ED). The biggest impact is in HH endpoint in Global Warming and Fine particulate matter formation, the first one is due to the CO_2 emissions, and the last one is due to the $PM_{2.5}$ emissions. Therefore, these two emissions should be prioritized in the future.

The present study also shows the impacts of marine emissions through the Disability-Adjusted Life Years (DALY). However, ti be more precise, the model requires a special attention to the construction of consistent databases on the ship engines power auxiliary power particulars.

4.3 Case Study 2: Ecuador, the Galápagos Islands

The Case Study 2: Ecuador area includes the Galápagos Islands. The islands are known for their large number of endemic species and were studied by Charles Darwin during the second voyage of HMS Beagle. His observations and collections contributed to the inception of Darwin's theory of evolution using natural selection. Galapagos Islands Study is a practical example. It shows that although database acquisition is not our own, the methodology develop can be applied to other areas in a standardized way.

4.3.1 Galápagos Islands Area

The Galápagos Islands, located in the Pacific Ocean surrounding the center of the Western Hemisphere, 906 Km west of continental Ecuador. The islands are found at the coordinates 1°40'N–1°36'S, 89°16'–92°01'W. The Galápagos are a series of volcanic islands and islets in the Pacific Ocean at the Equator line, see Figure 4.11. Galápagos Islands consist of 18 main islands, three smaller islands, and 107 rocks and islets.

The Islands considered an extraordinary natural laboratory that was declared World Heritage by UNESCO, and it is one of the most famous destinations in the world for observing wildlife. The Islands are one of the world's premier ecotourism destinations, and that Gálapagos tourism contributes hundreds of millions of dollars to Ecuador's national economy.

4.3.2 Database

In this case study, six months of AIS data, from first January until 31 of June 2018, were utilized to estimate the emission inventory over the study area. It is important to note that these data has been acquired from Marine traffic service has the author of the work does not have access to any terrestrial based station.

During the period of the research, 72 vessels were recorded, of which 52 are those that are considered in the study. There are around 984 000 records of ship positions. The ships that presented less than 50 AIS report position in the database have been disregarded in this study, corresponding to 28% of vessels.

The distribution of the ships type, classified by a flag of AIS navigation, in the period between first of January until 31 of June 2018 are in the Figure 4.12. The AIS data analysis helps us understand that 54% of the fleet is local, and the other

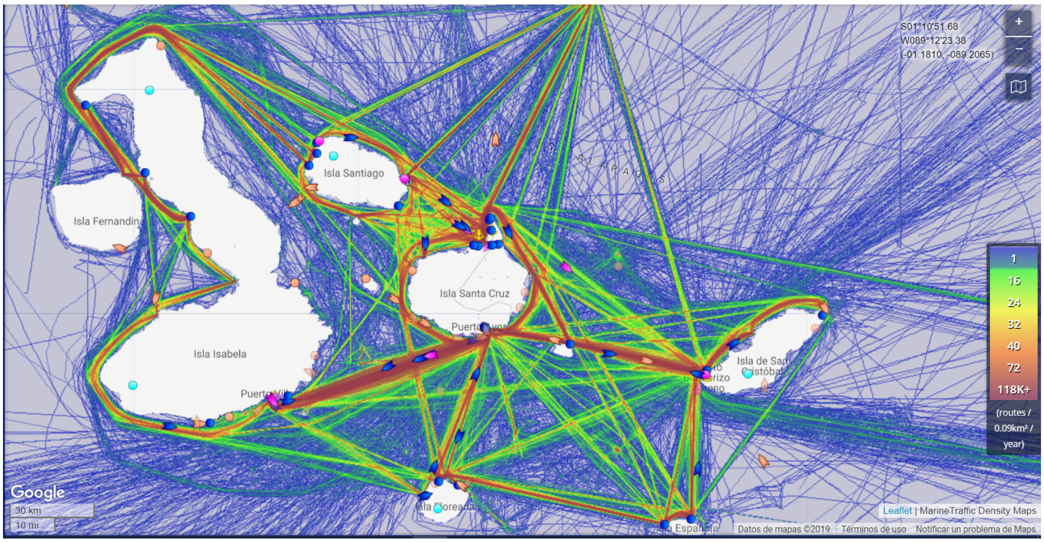

Figure 4.11: View of Gálapagos Island included the density of AIS navigation 2016, and 2017.

The points (ships with speed = 0 knots) and the arrows (ships with speed > 0 knots) on the map represents the ships in the area, each color is a Vessel Type.

46% of the fleet is international. It highlights the importance of the tourism of international yachts in this area.

The distribution of the type of ships of the 52 vessels in the database is 36% passenger ships, 21% yacht, 13% sailing vessel, 10% general cargo ship, 8% fishing vessels, 4% research/survey vessels, 4% patrol vessels, and 4% tankers, see Figure 4.13.

The AIS database coming from Marine Traffic (2018) is combined with the database of the Maritime Authority of Ecuador (2018) for the static data. Finally, with both data sources the emission estimation is based on 748 vessels representing 29 800 GT, see Figure 4.14.

In Galapagos Islands, around 90% of the ships are passenger ships or related to tourism. This corresponds to 26 866 GT and 368 vessels. Fishing vessels in quantity are the second on the list with 275 ships. However, this quantity only represents 5% of the total GT, see Figure 4.14.

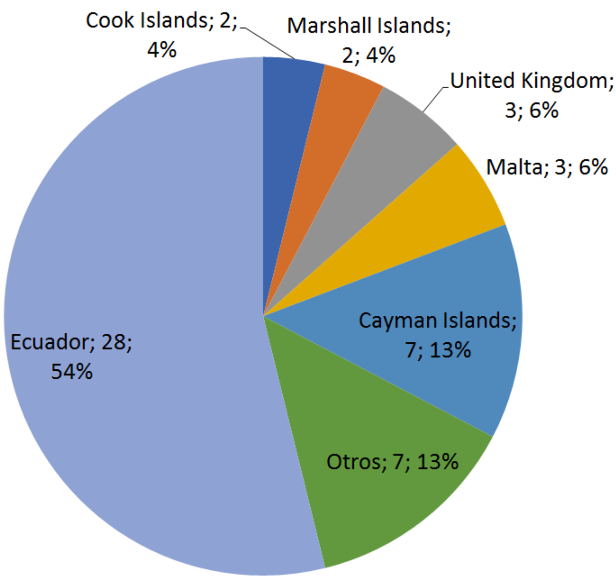

Figure 4.12: View of Gálapagos Island ships, classified by a flag of AIS navigation, in the period first January until 31 of June 2018.

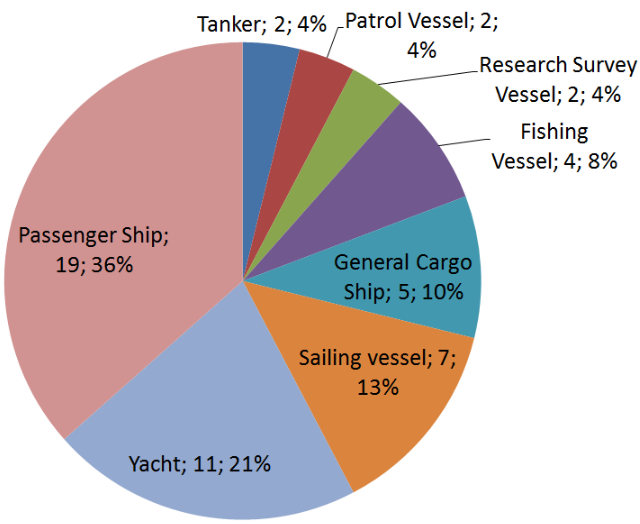

Figure 4.13: Ship types in Gálapagos Island in the database of the study, in the period between first January until 31 of June 2018.

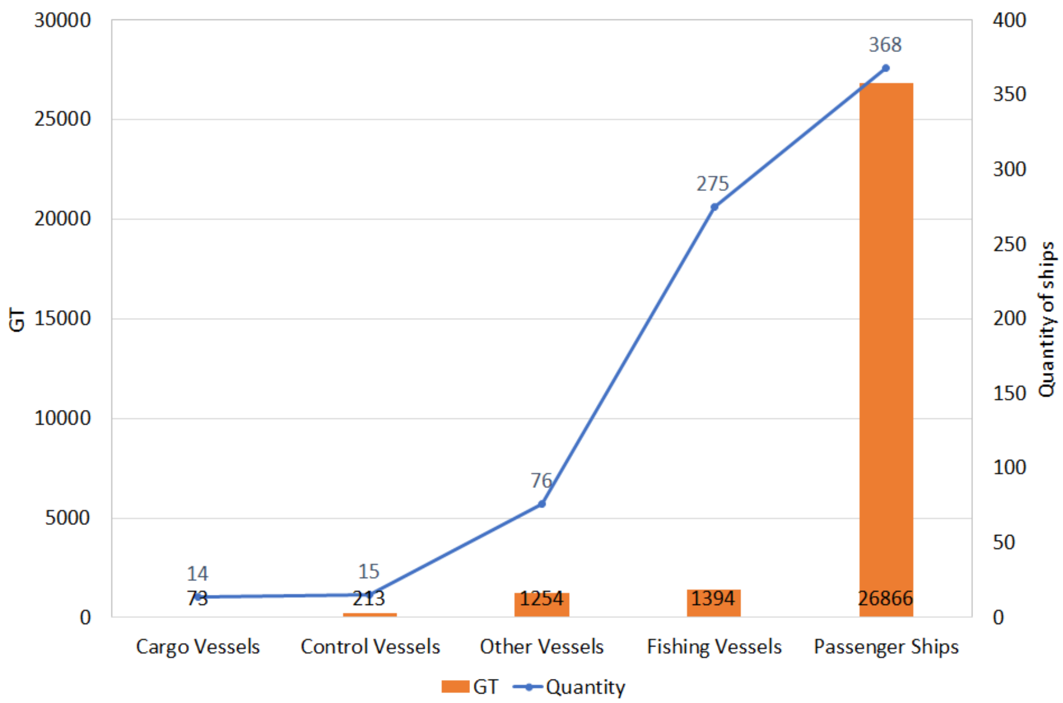

Figure 4.14: Ship types in Gálapagos Island in the Final database of the study, the year 2018.

4.3.3 Strategies of decarbonization

In Maritime Transport, the GHG reduction needs a combination of technical, operational, and innovative solutions. Strategies of GHG reductions have several restrictions since technologies in the marine industry do not presents enough technical maturity.

Figure 4.15 shows some of the strategies, along with indications of their approximate GHG reduction potential meanwhile section 2.2 presents a deeper analysis of this topic.

The selection of decarbonization alternatives must be applied to each type of vessel in the analyzed fleet to observe significant impact. However, the challenge is that the ships are unique products, with their properties depending on the service, technical characteristics, propulsion systems, energy systems, etc.

To comply with IMO objectives, an alternative is to define scenarios with different scopes and combinations of emission reduction strategies, i.e., only one technology will not be enough to reach the IMO goals. Therefore, one can define scenarios as low, medium, and high impact of decarbonization.

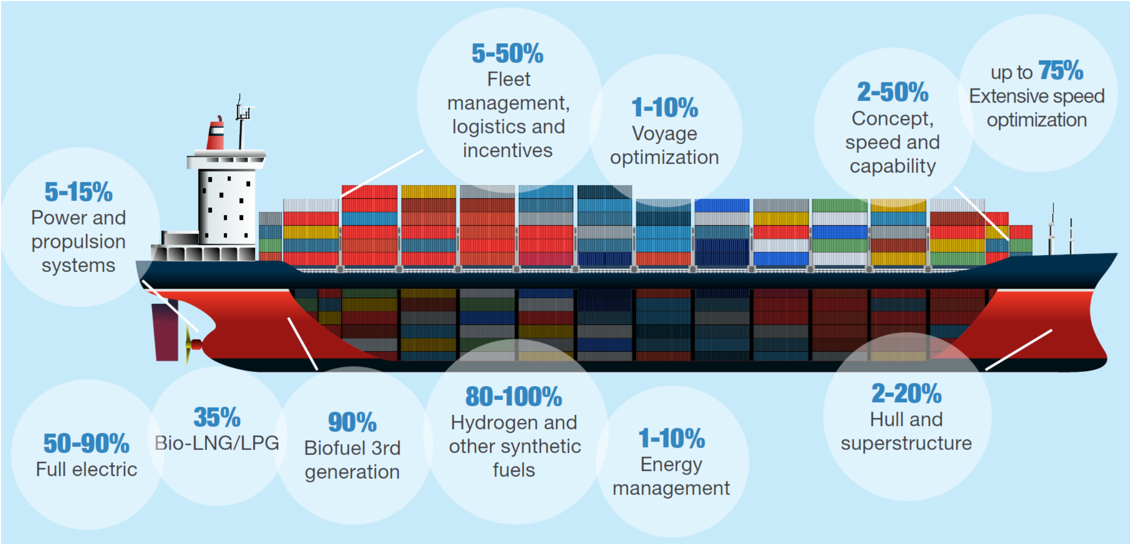

Figure 4.15: A wide variety of design, operational and economical solutions of GHG reduction potential, [9].

The scenarios low, medium, and high will be a combination of the following strategies:

- Power and propulsion systems
- Fleet management, logistics, and incentives
- Concept, speed, and capability

The strategies should be detailed with their advantages and disadvantages. This information is essential to justify the selection of decarbonization alternatives to reduce GHG emissions. The public policies must be applied, together with the technical measures.

The GHG abatement technologies are helpful for this purpose enumerated in the section 2.2.

The development of decarbonization scenarios needs the requirements or restrictions of the Maritime Authority involved and the government's policies. For this dissertation, the author used the information and requirements of the Ecuadorian government through the project of the action plan for the sustainable energy transition of the Galapagos Islands.

The constraints and needs of the governmental entities are vital because this information is a tool to establish the requirements and the focus of the decarbonization. In the case of the Galapagos, the goal of the policy is a zero-carbon to 2040.

In maritime transport, with one-of-a-kind products as ships and no serial products (for example, cars in the case of road transport), these policies of energy transitions have to apply one by one. Sometimes it is not feasible, but the case study of Galapagos Island is an excellent start to make this complex analysis possible.

In this thesis, the application of scenarios of decarbonization has only been applied to the Galápagos Islands case study. Indeed, this region is relatively isolated and mainly connected to the mainland through Ecuador.

This analysis has not been done for Rio de Janeiro and Santos due to the fact that these port are a part both interconnected with local transport mode as well as to the worldwide shipping maritime lanes. This make it more complex. However, it could be done in future work.

To propose scenarios of decarbonization, the first step is considering the key factors (type of service, ship age, autonomy, and the fuel of main propulsion and auxiliary machinery of the vessels), the availability of alternative energies, the region of applying the new policies, and the studies analyzed in the literature review.

From these factors the following options are defined for the realization of the models and scenarios:

- Ship speed reduction - Slow steaming for all the fleet involved.
- Windpower - Sails except for fast vessels.
- Enhanced power management - Engine efficiency for vessels that do not switch to clean energy must change their engines to more efficient engines that guarantee a minimum efficiency increase.
- Solar power for auxiliary engines for big ships.
- LNG as an alternative fuel for big ships.
- Marine bio-fuel as an alternative fuel for the transport ships, except for fishing, passenger vessels, tourism vessels (between island and short day tours), will use marine biofuel in their principal and auxiliary engines to reduce emissions.
- Electric propulsion engines for vessels with low autonomy, slow velocity, and that stay a lot of time in ports.

Type of service

By specifically studying the case of Galapagos, the following vessels are identified by the type of service:

1. Tourism boats, passengers, and high-speed boats
2. Dry and liquid cargo ships
3. Fishing vessels
4. Others (Port/ocean, workboats, and patrol/control vessels)

In Figure 4.16 the characterization of the vessels is shown, according to their type of service, where the number of boats for each classification and their average age by 2020 are specified. This factor is essential because it is possible to classify the vessels present on the islands, allowing the analysis of the existing technologies to calculate the GHG of greater importance associated with the fuel consumption of the ships in Galapagos.

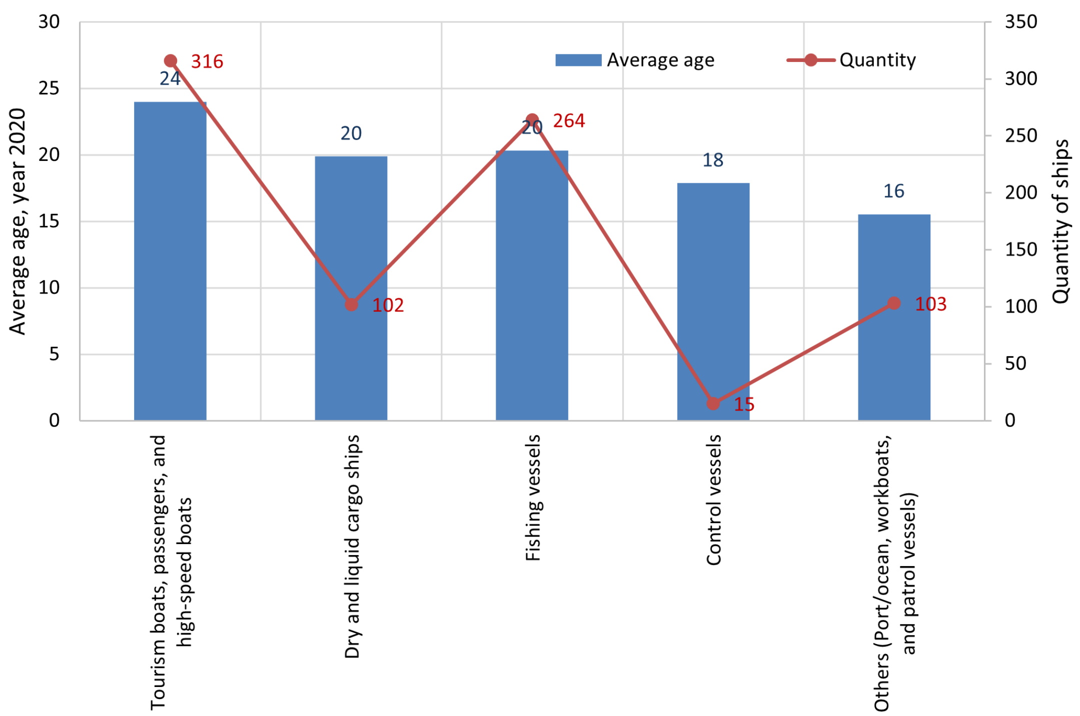

Figure 4.16: Number of Vessels according to their type and average age by 2020, in operational status registered in the Galapagos Islands.

The analysis of the fleet in Galapagos will indicate the most important vessels, consequently contributing to generating more GHG emissions. These vessels are:

Passenger ships between 12 and 35 passengers (40%), Passenger ships >35 passengers (33%), Yachts (9%), Ferries (5%), Artisanal fishing (3%). 82% of the GT accumulated by the vessels in the study corresponds to those for tourist purposes on the islands, defined as tourism, passenger, and high-speed vessels.

By characterizing the vessels in the fleet, it will be possible to establish which are the key characteristics to make proposals for energy alternatives. For example, overnight tourist boats will prioritize comfort and the number of passengers on board. In contrast, inter-island vessels will prioritize speed and number of passengers on-board, and thus respectively each of the decarbonization techniques should fit with the ship type and the service provided.

Ship age

This factor is vital since the ship's age is associated with the construction and propulsion technologies. Therefore, the energy efficiency of the boat will depend on this factor. In Figure 4.16 the characterization of the vessels of the fleet is shown. It is essential to perform a detailed statistical distribution by average age ranges of the fleet and by type of vessel to carry out the recommendations adequately. Nine vessel age categories will be used in this study, as described below:

1. 1-5 years
2. 6-10 years
3. 11-15 years
4. 16-20 years
5. 21-25 years
6. 26-30 years
7. 31-35 years
8. 35-40 years
9. $>$ 41 years

This statistical analysis indicates that, on average, 50% of the vessels of the Galapagos fleet will pass the limit of their useful life. Consequently, public policies for fleet renewal should be a fact to maintain the vessels' efficiency, with adequate propulsion and energy systems, see Figure 4.17. Policies may be established so that new constructions comply with the IMO objectives. In certain cases, adequate energy technologies may lead to a zero net emissions of GHG.

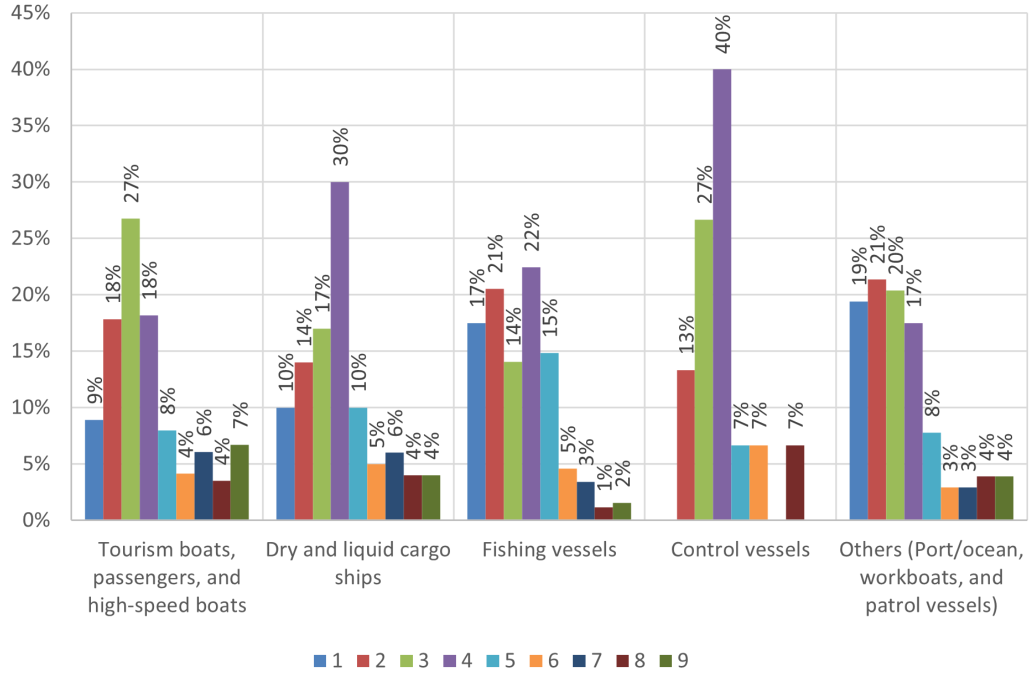

Figure 4.17: Classification of Vessels in operational condition registered in the Galapagos Islands, the year 2019, according to the category of age range.

Autonomy

The autonomy of the vessels is another critical factor that will influence the decisions of energy alternatives for decarbonization. Vessels with an autonomy of fewer than 4 hours, short sailing distances, and low speed (less than 6 knots) will be those that will favorably have more facilities to make an energy change to electric motors.

In boats with autonomy greater than 4 hours, greater navigation distances, and speeds greater than 6 knots, the disruptive technological changes will be limited, and the alternative will be the use of systems to reduce fuel consumption such as sails, slow steaming, and or solar panels for an auxiliary energy generation.

Fuel for main and auxiliary engines

This factor is of fundamental importance since new, less polluting alternatives with greater energy efficiency are starting to be available.

The combination of clean energies will help to reduce carbon emissions on the islands. Among the alternatives available for the fleet we have:

- Solar Energy - Power generation for auxiliary systems.

- Second and/or third-generation marine bio-fuel - Reduction of emissions from main engines.

- LNG as fuel- Reduction of emissions from main engines.

When it comes to the type of fuel associated with the principal and auxiliary engines of the vessels, the renewal of engines with modern and efficient ones should be considered, see Figure 4.18.

Figure 4.18 shows us how the engine's efficiency has changed substantially in the last 60 years, which supports the change of engines to more efficient ones if the useful life of the vessels makes it technologically and economically feasible.

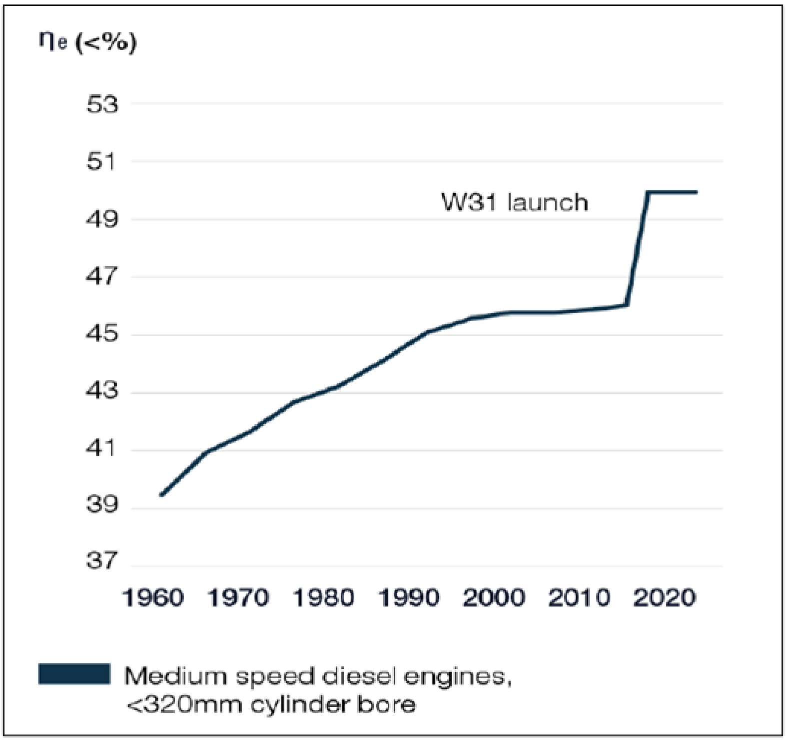

Figure 4.18: Evolution of the efficiency of a Wärtsilä fuel engine, [10].

Achieving the goals of IMO's initial GHG strategy will require a combination of technical, operational, and innovative solutions applicable to ships, [9]. Some of them, along with an indication of their approximate GHG reduction potential, are highlighted in Figure 4.15.

The vision of the initial strategy on reducing GHG emissions from ships, adopted in April 2018, includes:

- Reduction of CO_2 emissions (carbon intensity), on average in international maritime transport, by at least 40% by 2030, with efforts towards 70% by 2050, compared to 2008.
- Reduction of total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008, while at the same time continuing efforts to phase them out as called for in the vision, to achieve the CO_2 emissions. Reduction is consistent with the objectives of the Paris Agreement.

The IMO GHG strategy provides a comprehensive list of possible short, medium and long-term measures. It including, for example, further enhancement of the EEDI and SEEMP, national action plans, enhanced technical cooperation, port activities, research and development, support for the effective adoption of low and zero-carbon alternative fuels, innovative emission reduction mechanisms, etc.

One fact is that the vessels registered in the Galapagos Islands are less than 400 GT. Of the entire fleet, there are only eight vessels registered with more than 400 GT. Therefore, the application of the IMO requirements to improve the EEDI and the SEEMP for the entire fleet is not applicable since the technical and operational energy efficiency measures are for all ships over 400 GT.

However, this does not indicate that measures cannot be taken to reduce GHG emissions from vessels navigating around the islands. Wind-assisted propulsion could reduce fuel consumption, mainly for slow boats, but the commercial case remains difficult. In the case of the Galapagos, there are no vessels that carry out this type of transport of cargo inputs on international routes, or even to the continent, and that has local registration. Therefore the application of wind-assisted propulsion as a complement to the reduced fuel consumption is a possibility.

Although it is not a new technology, wind-assisted propulsion will require some development work to make a significant difference for modern ships. It refers to the fact that, in each boat, as a unique project, the appropriate sail system must be designed for it.

Other solutions, such as the use of slow steaming, increase the efficiency of the propulsion system are possible. The use of slow steaming is one of the most effective ways to reduce greenhouse gas emissions worldwide. The IMO considers mandatory slow steaming as the default option to comply with established regulations.

In addition to the IMO proposals, several studies on slow steaming indicate that the application in vessels of various types, not only in container carriers, is efficient.

Using a clean and renewable source of electricity anywhere, such as solar energy, can also reduce the consumption of fossil fuels with a set of strategies. In the Galapagos vessels, those that represent the highest consumption are the overnight and inter-island tourist boats. In this type of ship, where comfort is a priority, auxiliary motors will put the electrical system into operation. In this case, the solar panels for use in auxiliary engines (generators) are pertinent. Together, it provides autonomy to the boat, which will allow the transport systems between the islands to be permanently operational.

The renewal of engines for modern and efficient engines will be another option available see Figure 4.18. Finally, the change in technology in the main engines, such as LNG or second and/or third-generation marine bio-fuel, will be the alternatives available for the characteristics of these vessels in the fleet.

Before defining the strategies or policies that will be modeled as emission reduction scenarios, it is important to evaluate one by one of the available energy alternatives, see section 2.3.

As established by the IMO, the GHG reduction strategy requires a combination of technical, operational, and innovative solutions applicable to the vessels of the fleet. In this particular case study the author has prepared a summary presented in Table 4.4.

Table 4.4: Strategies considered for the implementation of GHG abatement technologies of the Galápagos Islands, according to the type of vessel

Ship/Strategies	**SSR**	**WPS**	**EPM**	**SP**	**LNG**	**MBF**	**EPE**
Engine Affected	ME	ME	ME	AE	ME	ME & AE	ME
Cargo Ships	•	•	•				•
Other passenger	•	•					
Fishing	•	•					•
Control	•					•	
Other	•	•				•	
Cruise	•	•	•	•	•	•	
Yacht	•	•	•			•	
Sports or recreation	•	•	•				•
Daily tour	•	•	•			•	•
Between islands	•		•	•		•	
Foreign ships	•					•	

where SSR means Ship speed reduction, WPS means Wind power - Sails, EPM means Enhanced power management, SP means Solar power, MBF means Marine bio-fuel, EPE means Electric propulsion engines, ME means Main Engine and AE means Auxiliary Engine

Table 4.4 shows how each strategy is applied or not for each type of vessel. In addition, it established if the application of the strategy will affect the main engine and, or auxiliary engines.

4.3.4 Proposals for 2040 scenarios for Galápagos Island

This section describes the scenarios proposed for the year 2040 to implement the decarbonization of the maritime transport sector of the Galápagos Islands. The decarbonization scenarios are:

1. Reference Scenario (REF).
2. Low impact scenario (LOW SCENARIO).
3. Medium impact scenario (MEDIUM SCENARIO).
4. High impact scenario (HIGH SCENARIO).

Each of these scenarios will use the combination of decarbonization strategies proposed for each of the types of vessels earlier. However, it should be noted that the zero carbon emission is not achieved even for the high impact scenario. As previously contextualized, today, there are no zero-carbon technology available that can match all types and sizes of vessels.

Reference Scenario

The reference scenario (REF) consider the actual situation of the fleet of Galapagos with a base year of 2018. The actual speed, design speed, the ship type, size, and age are considered.

Low impact scenario

It is a fleet re-motorization scenario, or so called low impact scenario (LOW SCENARIO)

- Slow Steaming (prescriptive speed reduction):
    1. 2030: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 5%.
    2. 2040: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 15%.
- Sails on-board:

1. 2030: Scenario where the ships of the fleet, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel design to decrease 5% of the total fuel consumption of the main engine.
2. 2040: Scenario where the ships, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel's design to decrease 10% of the total fuel consumption of the main engine.

- Change to more efficient engines based on fossil fuel:

1. 2030: Scenario where cargo vessels, tourism cruises with cabins, tourist vessels without cabins, and inter-island vessels that do not switch to cleaner energy must change their engines to engines more efficient that guarantee a minimum efficiency increase of 2.5%.
2. 2040: Scenario where cargo vessels, tourist cruises with cabins and tourist vessels without cabins as well as inter-island vessels, that do not switch to some cleaner energy, must change their engines to engines more efficient that guarantee a minimum efficiency increase of 5%.

- Solar panels for auxiliary systems:

1. 2030: The scenario where inter-island tourist vessels with cabins, which do not switch to some cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary systems by a minimum of 5%.
2. 2040: The scenario where inter-island tourist vessels with cabins, which do not switch to some cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary systems by a minimum of 10%.

- LNG implementation:

1. 2030: Scenario where tourist vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing a minimum participation of the fleet of 5%.
2. 2040: Scenario where tourism vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing a minimum participation of the fleet of 10%.

- Electric propulsion. The electricity supply will be from the sustainable public grid of the Galápagos:

    1. 2030: Scenario where Fishing Vessels, Other Passenger Vessels, Bay tour and daily tourism that do not switch to cleaner energy must replace their main engines with electric motors, guaranteeing a minimum participation of the fleet of 20%.
    2. 2040: Scenario where Fishing Vessels, Other Passenger Vessels, Bay tour, and daily tourism that do not switch to cleaner energy must replace their main engines with electric motors, guaranteeing a minimum participation of the fleet of 40%.

- Implementation of marine biofuel:

    1. 2030: Scenario where the ship fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their principal and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 10%.
    2. 2040: Scenario where the ship fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their main and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 20%.

Medium impact scenario

It is a fleet re-motorization scenario, or so-called medium impact scenario (MEDIUM SCENARIO)

- Slow Steaming (prescriptive speed reduction):

    1. 2030: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 10%.
    2. 2040: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 17.5%.

- Sails on-board:

    1. 2030: Scenario where the ships of the fleet, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel design to decrease 10% of the total fuel consumption of the main engine.

2. 2040: Scenario where the fleet ships, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel's design to decrease 20% of the total fuel consumption of the main engine.

- Change to more efficient engines based on fossil fuel:

  1. 2030: Scenario where cargo vessels, tourism cruises with cabins, tourist vessels without cabins, and inter-island vessels that do not switch to cleaner energy must change their engines to engines more efficient that guarantee a minimum efficiency increase of 5%.
  2. 2040: Scenario where cargo vessels, tourist cruises with cabins and tourist vessels without cabins, as well as inter-island vessels, that do not switch to cleaner energy, must change their engines to engines more efficient that guarantee a minimum efficiency increase of 10%.

- Solar panels for auxiliary motors:

  1. 2030: The scenario where inter-island tourist vessels and cruise vessels with cabins, which do not switch to cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary systems by a minimum of 15%.
  2. 2040: The scenario where inter-island tourist vessels and cruise vessels with cabins, which do not switch to cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary motors by a minimum of 30%.

- LNG implementation:

  1. 2030: Scenario where tourist vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing minimum participation of the fleet of 10%.
  2. 2040: Scenario where tourism vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing minimum participation of the fleet of 20%.

- Electric propulsion. The electricity supply will be from the sustainable public grid of the Galápagos islands (onshore and offshore wind farms):

1. 2030: Scenario where fishing vessels, other passenger vessels, bay tour and daily tourism that do not switch to some cleaner energy must replace their main engines with electric motors, guaranteeing a minimum participation of the fleet of 40%.
2. 2040: Scenario where fishing vessels, other passenger vessels, bay tour, and daily tourism that do not switch to cleaner energy must replace their main engines with electric motors, guaranteeing minimum participation of 40%.

- Implementation of marine biofuel:

1. 2030: Scenario where the fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their main and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 20%.
2. 2040: Scenario where the fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their main and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 40%.

High impact scenario

It is a fleet renewal scenario, or so called high impact scenario (HIGH SCENARIO)

- Slow Steaming (prescriptive speed reduction):

1. 2030: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 10%.
2. 2040: Scenario where the speed of all ships in the fleet uniformly reduces their speed by 30%.

- Sails on-board:

1. 2030: Scenario where the ships of the fleet, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel design to decrease 15% of the total fuel consumption of the main engine.
2. 2040: Scenario where the fleet ships, except military and control vessels, inter-island vessels, and foreign vessels, will add appropriate sails to the vessel's design to decrease 30% of the total fuel consumption of the main engine.

- Change to more efficient engines based on fossil fuel:

    1. 2030: Scenario where cargo vessels, tourism cruises with cabins and tourist vessels without cabins, and inter-island vessels that do not switch to cleaner energy must change their engines to engines more efficient that guarantee a minimum efficiency increase of 10%.
    2. 2040: Scenario where cargo vessels, tourist cruises with cabins and tourist vessels without cabins, as well as inter-island vessels, that do not switch to cleaner energy, must change their engines to engines more efficient that guarantee a minimum efficiency increase of 15%.

- Solar panels for auxiliary motors:

    1. 2030: The scenario where inter-island tourist vessels and cruise vessels with cabins, which do not switch to cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary systems by a minimum of 25%.
    2. 2040: The scenario where inter-island tourist vessels and cruise vessels with cabins, which do not switch to cleaner energy, will have to add solar panels for their auxiliary systems to reduce the consumption of fossil fuel, guaranteeing a reduction in fuel consumption of the auxiliary motors by a minimum of 50%.

- LNG implementation:

    1. 2030: Scenario where tourist vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing minimum participation of the fleet to 20%.
    2. 2040: Scenario where tourism vessels with cabins must change the main engines to dual-fuel or LNG to reduce emissions, guaranteeing minimum participation of the fleet to 40%.

- Electric propulsion: The electricity supply will be from the sustainable public grid of the Galápagos islands (onshore and offshore wind farms):

    1. 2030: Scenario where fishing Vessels, other passenger vessels, bay tour and daily tourism that do not switch to cleaner energy must replace their main engines with electric motors, guaranteeing a minimum participation of the fleet of 50%.

2. 2040: Scenario where fishing vessels, other passenger vessels, bay tour, and daily tourism that do not switch to cleaner energy must replace their main engines with electric motors, guaranteeing minimum participation of the fleet of 100%.

- Implementation of marine biofuel:

  1. 2030: Scenario where the fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their principal and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 30%.
  2. 2040: Scenario where the fleet, except fishing, other passenger vessels, bay tour, and daily tourism, will use marine biofuel in their main and auxiliary engines to reduce emissions by guaranteeing minimum participation of the fleet of 60%.

4.3.5 Proposal of Public policies

The implementation of public policies in the Galápagos Islands should be based on the three following scenarios. These public policies must be following the legislation of the maritime authority in order to exercise control and compliance with them.

As general considerations, we have the following:

1. It is crucial to establish an integrated policy with the continent so that lower emissions can be carried out at the maritime transport level.

2. A reforestation policy on the mainland or the islands can be an alternative to maintain a percentage of fossil fuel at the maritime transport-level due to the high costs of change and the lack of available technology that meets the service characteristics desired of the vessels.

3. The production of biofuel in the Galapagos Islands should be proposed. Otherwise, fuel transportation from the mainland will have to include the transportation logistics (and related emissions) like the one currently carried out to transport fossil fuel. This last alternative will be attractive if a bio-refinery is proposed.

4. The batteries of electric motors must have a recycling policy so that after their life cycle, they will be recycled in a sustainable way.

5. Hydrogen and other alternatives fuels are potential solutions that could be explored, including the generation infrastructure carried out on the island. However, these technologies are mainly developed for larger vessels due to their complexity and associated risks.

Low and medium scenario

- Regulate the life cycle of vessels operating in the Galápagos Islands, limiting the use of vessels having a age over 40 years.
- Policy in producing new vessels for operation in the Galápagos Islands must comply with the strategies established for the year 2040.
- The area needs a fishing incentive policy, seasonally and according to the government regulators.
- Port infrastructure projects for the supply of new fuels should be considered.

High scenario

- Regulate the life cycle of vessels operating in the Galápagos Islands, limiting the use of vessels over 40 years.
- Policy in producing new vessels for operation in the Galápagos Islands must comply with the strategies established for the year 2040.
- Fleet renewal policy must comply with the strategies established for the year 2040.
- The area needs a fishing incentive policy, seasonally and according to the government regulators.
- Port infrastructure projects for the supply of new fuels should be considered.
- The area needs a plan to reduce speed for inter-island vessels, restrict schedules, and modify the type of transport to vessels with a greater capacity (scale effect). They will make a change to more efficient engines.
- Vessels using amrine diesel will use second or third-generation biofuels.

4.3.6 Results

The environmental regularization and control of the projects being implemented or intended to be implemented in the Galṕagos Area are vital for maintaining the functionality and the provision of environmental services of the Insular and Marine Ecosystems.

The methodology developed first calculated the quantity of energy demanded, or fuel consumption per ship, see Figure 4.19. With the energy requirement of the Galápagos Islands in 2018, a future demand can be estimated until 2040. The types of fuels of the maritime energy demand classified in Figure 4.20. The Galápagos maritime fleet consumes two types of fuels, diesel, and gasoline (outboard engines), prioritizing the demand for diesel, which represents around 75% of consumption, over 25% of gasoline consumption.

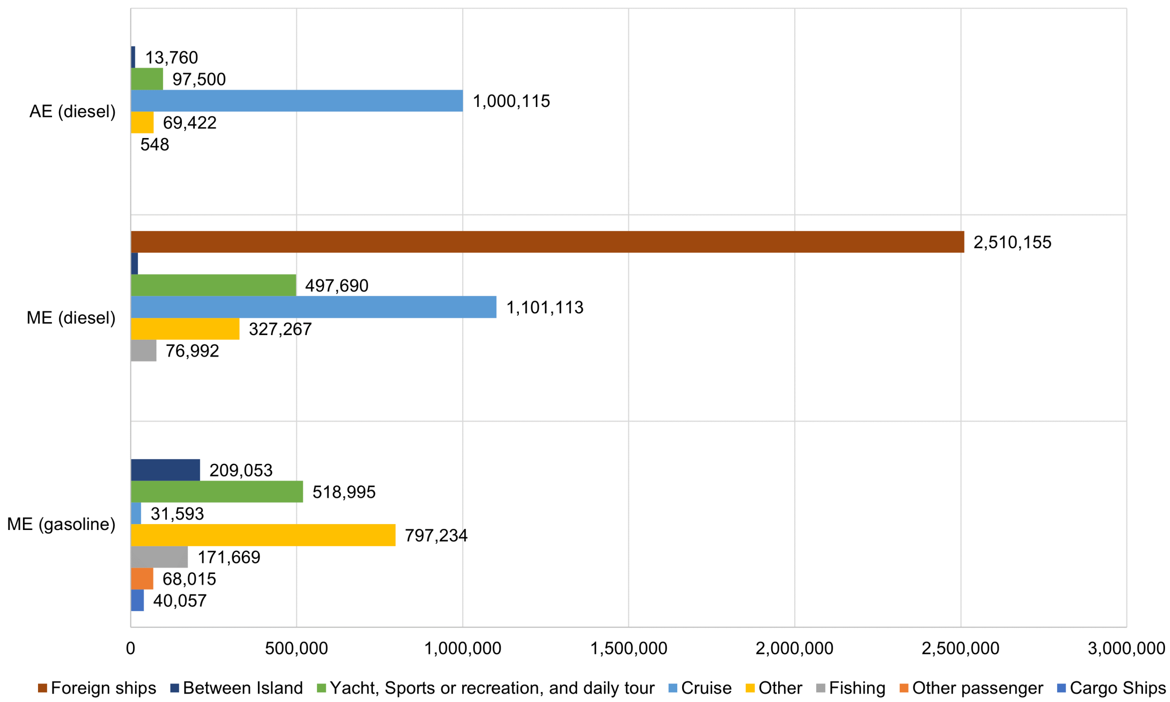

Figure 4.19: Final energy demand by type of ship and fuel in Galápagos Islands, year 2018, gallones

Total annual estimation emissions from ships, 2018, are presented in Table 4.5. CO_2 emissions are the most important with over 75 560 tons per year, followed by NO_X and SO_X emissions. TSP are the concentrations of total suspended particulate (TSP) including PM_10 and $PM_{2.5}$.

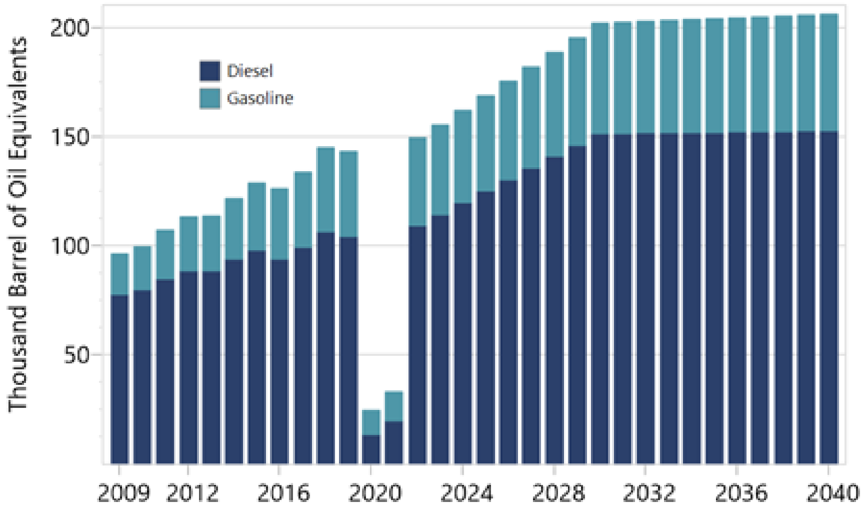

Figure 4.20: Final energy demand by type of fuel in Galápagos Islands, inventory and estimation

Table 4.5: Total of emission due to marine traffic in Galápagos Islands, in tons, 2018

Type of Gas Emission	CO_2	SO_X	NO_X	TSP PM_{10} $PM_{2.5}$
Annual average	75 560	94	1 485	43

Compared to the low, medium, and high impact scenarios, the reference scenario shows a decrease in energy demand for these proposed scenarios. The results indicate that there is an energy efficiency gain in the three alternative scenarios.

Figure 4.21 shows the energy demand for each one of the proposed GHG abatement technologies scenarios.

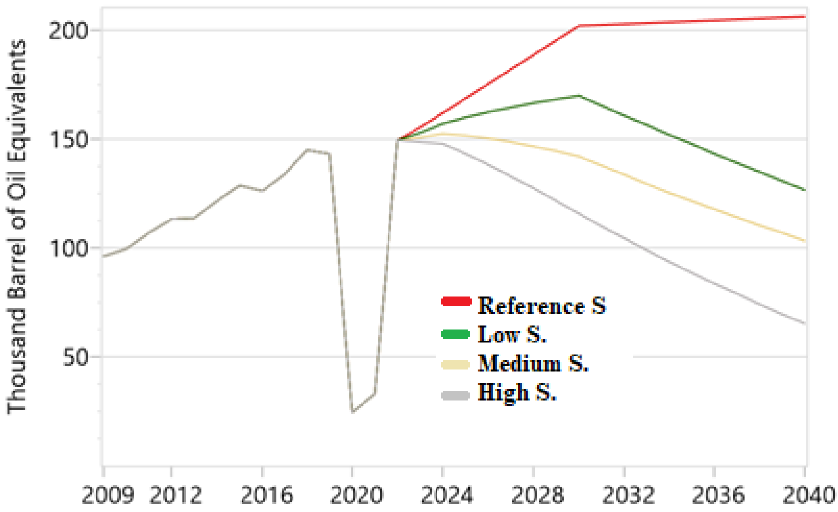

Figure 4.21: Final energy demand by scenarios in Galápagos Islands

In each of the proposed scenarios, fuel substitution policies achieve the objective of reducing fossil fuels, gasoline, and diesel, being replaced by other less-polluting energy sources. Figure 4.21 shows the implementation of the medium impact scenario, where fuel substitution and decarbonization policies represent a decrease of around 33% in energy demand.

Figure 4.21 also shows the implementation of the high impact scenario, where fuel substitution and decarbonization policies represent a decrease of around 53% in energy demand.

The decrease in energy demand and the substitution of fuels has the effect of drastically reducing direct greenhouse gas emissions from the maritime transport sector, as seen in Figure 4.22 by scenario. This GHGs decrease in the low impact scenario represents around 53%. The medium-impact means around 68%, the high impact represents around 95% compared to the reference scenario.

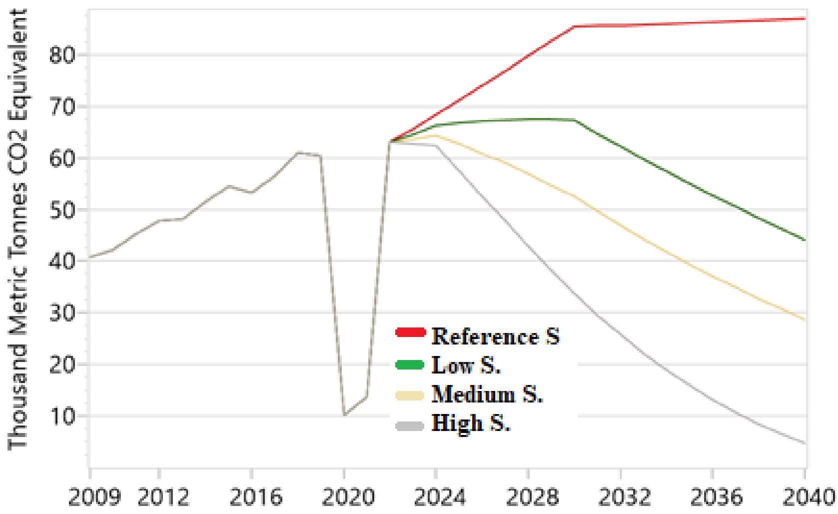

Figure 4.22: Emissions from the maritime sector, by scenarios in Galápagos Islands.

Life-cycle assessment

The assessment of the emission impacts on the surrounding population is in the scope of this study. The Life Cycle Impact Assessment (LCIA) for Galápagos Islands is presented in Table 4.6.

The LCIA was calculated using the factors of characterization and normalization available in the LCA-ReCiPe website (rivm.nl/en/life-cycle-assessment-lca/recipe), based on the total emissions estimated.

Table 4.6: LCIA of actual annual average emission due to marine traffic in Galápagos Islands. HH in DALY/kg CO_2 eq., ED in Species.year/kg CO_2 eq.

Endpoint	Midpoint	Individualist	Hierarchist	Egalitarian
HH	Global Warming	6.135	70.120	944.500
HH	Fine PM formation	27.047	146.941	146.941
HH	POF	1.360	1.360	1.360
ED	Global Warming	0.040	0.212	1.889
ED	POF	0.193	0.193	0.193
ED	Acidification	0.133	0.133	0.133

HH means Human health, *ED* means Ecosystem diversity, and *POF* means Photochemical ozone formation

Figure 4.23 also shows the Human health impact on marine traffic in Galápagos Islands, where Global Warming and Fine particulate matter formation are the most alarm results.

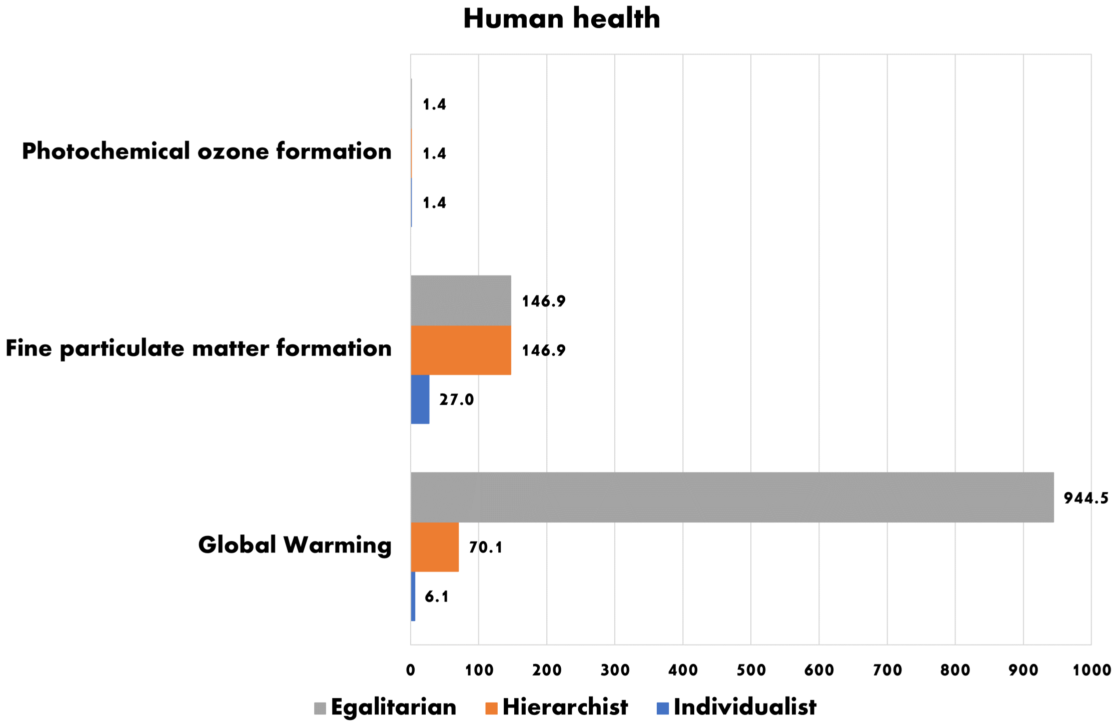

Figure 4.23: Human health impact to marine traffic in Galápagos Islands.

Figure 4.24 shows the Ecosystem Diversity impact on marine traffic in Galápagos Islands, where Global Warming again has the most significant results.

These results express the magnitude and significance of the social and environmental costs associated with maritime activities in Galápagos Islands.

Of all the 18 mid-points, only six were directly affected by the considered pollutants and only two of the three end-points. Each polluted contributed to at least one of these mid-points and were converted to the equivalent unit when necessary, following the ReCiPe's factors. The resultant impact on Human health measured in DALY (Disability-Adjusted Life Year), which is a measure of overall disease burden, expressed as the cumulative number of years lost due to ill-health, disability, or early death. In short, the DALY sum up the years lived with disability and the years of life lost. Moreover, the DALY is an established term in the medical world. The resultant impact in ecosystem diversity, it's on the other hand measured in species loss per year.

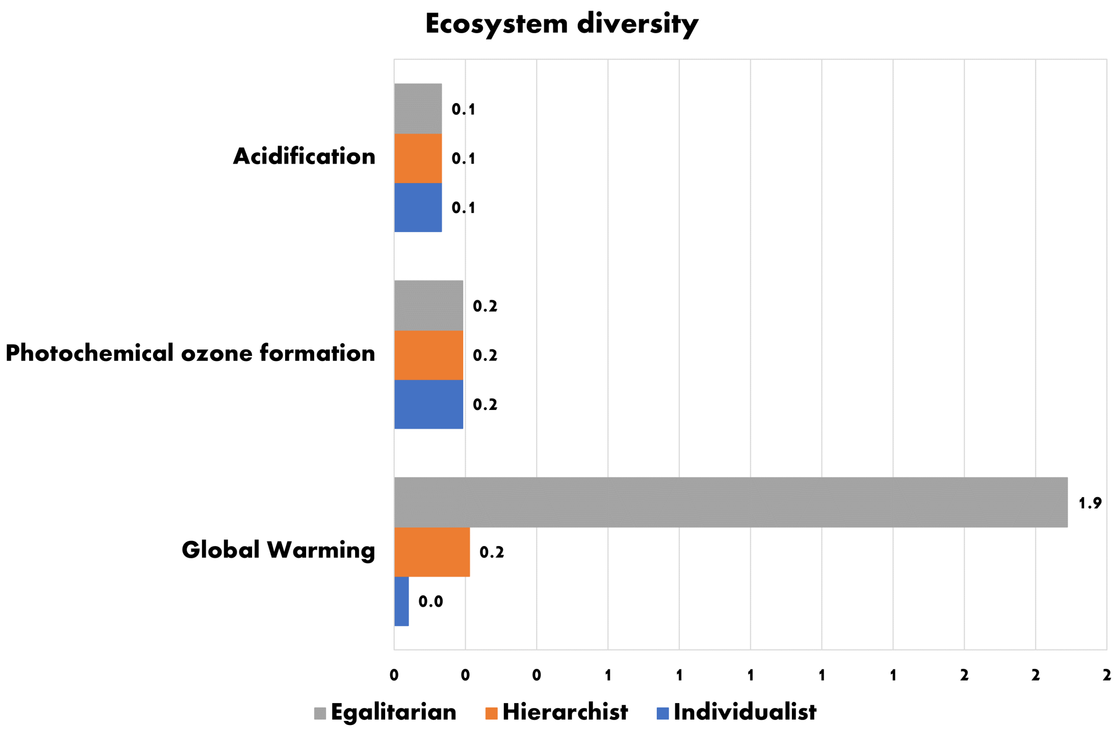

Figure 4.24: Ecosystem Diversity impact to marine traffic in Galápagos Islands.

4.3.7 Discussion

The energy demand of the maritime sector is in accordance with the type of vessels, i.e., the highest energy demand comes from tourist boats, passenger and high-speed vessels, followed by foreign ships, other vessels, fishing vessels and finally general cargo vessels.

It can also be seen, from the analysis of Figure 4.5, that the sectors directly related to tourism, tourist boats, passengers and high-speed boats, gradually increase their relative participation in the energy demand, consolidating at around 63% of the same. With regard to energy sources, the types of fuels of maritime energy demand can be identified. Figure 4.20 shows that in this sector the vessels consume two types of fuels, Diesel and gasoline, prioritizing the demand for Diesel, which represents around 75% of consumption, over 25% of gasoline consumption.

The implementation of estimation of life cycle impact assessment is an accomplished achievement quantifying the environmental impact and damages to human health (HH) as well as damages to ecosystem diversity (ED). This analysis is paramount in a protected environmental zone such as Galápagos Islands. The biggest impact is in HH endpoint in Global Warming and fine particulate matter formation, the first one is due to the CO_2 emissions, and the last one is due to the

$PM_{2.5}$ emissions. Therefore, these two emissions should be prioritized in the future.

The present study shows the impacts of Marine emissions in the Galápagos Islands through the Disability-Adjusted Life Years (DALY).

Chapter 5

Conclusion

This section concludes with the evaluation of the case studies and discusses the obtained results and their future development.

This work has proposed to assess the efficiency of several technical options to reduce the impact of ocean-going ships on the atmosphere and climate. In other words, this work examines how technological improvements and policy strategies might help reducing emissions from international shipping in the future. The main case focused Galápagos Island because the maritime authority provides all the information about the ship fleet. Furthermore, the methodology could be applied in other zones when the required data are available.

The specific objectives of this thesis have been fulfilled:

- A systematic bibliography review have been provided on the decarbonization of the maritime transportation.
- The methodology that has been developed use a set of big data tools to deal with the high quantity of data (AIS).
- An inventory of ship emissions has been provided for several case studies.
- Various technical alternatives to comply with the new IMO regulations were discussed, including a Life Cycle Assessment (LCA).

5.1 Key findings and achievements

The implementation of estimation of life cycle impact assessment (LCIA) is an accomplished achievement quantifying the environmental impact and damages to human health (HH) as well as damages to ecosystem diversity (ED). The most significant impact is in HH endpoint in Global Warming and Fine particulate matter formation. The first one is due to the CO_2 emissions, and the last one is due to the $PM_{2.5}$ emissions. Therefore, the impact of those types of emissions should be prioritized in the future.

The impacts of Marine emissions in the ports of Rio de Janeiro and Santos through the Disability-Adjusted Life Years (DALY) reaching respectively 189 (I), 2 162 (H) and 29 125 (E) for Global Warming and 685 (I), 4 688 (H) and 4 388 (E) for fine particulate matter formation.

Also, the impacts of Marine emissions in the Galápagos Islands through the Disability-Adjusted Life Years (DALY) reaching respectively 6.1 (I), 70.1 (H) and 944.5 (E) for Global Warming, and 27.0 (I), 146.9 (H) and 146.9 (E) for fine particulate matter formation.

The developed methodology including the big data tools applications was adequate for estimating the emissions. The use of AIS data for different purposes shows us the potential of using big data analytics.

5.2 Main contributions

This section describes the specific outcomes of the research developed in this thesis and explains their importance. The results shown provide elements to reply to the research problem developed in this thesis.

Using AIS data allows us to estimate emissions based on the actual movement of vessels effectively.

Implementing the Automatic Identification System (AIS) station at UFRJ–COPPE giving access to world coverage data through the AISHub platform is a fact. Unfortunately due to the pandemic, the scalability of the model with higher number of AIS stations has not been tested.

Implementing a set of big data tools to deal with the high quantity of data has been effectively applied.

The methodology to perform a ship emission inventory has been applied in various case studies.

Various technical alternatives allowing the shipping companies to comply with the new IMO regulations was compared. The implementation of the evaluation of Life-cycle assessment (LCA) is another outcome providing interesting insights.

5.3 Limitations of the study

The main limitations of the approach are listed below:

- Both case studies are using limited AIS data sample size due to acquisition costs.
- The economic impacts of the IMO policies are not considered here, e.g., GDP, etc.
- The emission dispersion due to wind and meteorological effects is not considered here. This phenomenon is definitively important for SO_x, NO_x and particular matters (PM).
- In the case study relating to the Galapagos case study, the decarbonization target that has been considered is considered too aggressive by some parties.
- In the case study relating to Rio de Janeiro and Santos ports, no Brazilian decarbonization policy strategy has been considered. For this reason, only an instantaneous emissions inventory is available here.

It was challenging to work with a high quantity of data to prove that the methodology is applicable worldwide. The initial idea was to apply this methodology with the AIS data of several hundreds of AIS stations, but the pandemic of COVID-19 made it impossible. Therefore, only two AIS terrestrial stations have been used, one for Rio de Janeiro and one for the Santos port. All the processes were initially developed in the Simulation Laboratory of Shipbuilding and Shipping Processes (LABSEN) server. The author had to change the process's environment using other Analytics platforms to process the system methodology at home.

5.4 Future works

The research presented in this thesis opens several lines of research that should be pursued as the application of the AIS data system of around 500 terrestrial AIS stations for one year period. The methodology implemented a functional Automatic Identification System (AIS) station at UFRJ–COPPE, giving access to world coverage data through the AISHub platform.

Multi-criteria decision analysis (MCDA) in the implementation of GHG abatement technologies is a possibility to solve decision and planning problems involving multiple criteria.

Part of the developed methods may be integrated in more ambitious global worldwide Integrated Assessment Models (IAMs) in order to better consider the Maritime transportation in an analysis of economical impacts of the GHG IMO policies.

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Appendix A

Emission Factors References

Table A.1: Emission factors (NO_X, and TSP) for pollute and fuel type for each engine type, in kg/tonne [12]

Engine	Phase	Engine type	Fuel type	NO_X	TSP PM_{10} $PM_{2,5}$
ME	CR	HSD	BFO	57.7	3.8
ME	CR	HSD	MDO/MGO	57.1	1.5
ME	CR	MSD	BFO	63.4	3.8
ME	CR	MSD	MDO/MGO	63.1	1.5
ME	CR	SSD	BFO	89.7	8.69
ME	CR	SSD	MDO/MGO	88.6	1.6
ME	MH	HSD	BFO	39.70	10.3
ME	MH	HSD	MDO/MGO	44.3	4
ME	MH	MSD	BFO	46.2	10.3
ME	MH	MSD	MDO/MGO	45.7	4
ME	MH	SSD	BFO	65.09	11.2
ME	MH	SSD	MDO/MGO	64.2	4.40
AE	CR - MH	HSD	BFO	49.4	3.5
AE	CR - MH	HSD	MDO/MGO	48.6	1.4
AE	CR - MH	MSD	BFO	62.5	3.5
AE	CR - MH	MSD	MDO/MGO	62	1.4

where ME means Main Engine, AE means Alternative Engine, CR means Cruise, MH means Manoeuvring Hotelling, HSD means High Speed Diesel, MSD means Medium Speed Diesel, SSD means Slow Speed Diesel, BFO means Bio Fuel Oil, MGO means Marine Gasoil, and MDO means Marine Diesel Oil.

Table A.2: Fuel mass to CO_2 mass conversion factors (CF) in tonne/tonne-Fuel [13]

Type of fuel	Reference	Carbon content	CF (t-CO_2/t-Fuel
Diesel/Gas Oil	ISO 8217[1]	0.875	3.206
Light Fuel Oil (LFO)	ISO 8217[2]	0.86	3.151
Heavy Fuel Oil (HFO)	ISO 8217[3]	0.85	3.114

[1] ISO 8217 Grades DMX through DMC, [2] ISO 8217 Grades RMA through RMD, and [3] ISO 8217 Grades RME through RMK

Table A.3: Emission factors for pollutants CO and SO_X in kg/tonne-Fuel [12]

Pollutant	BFO	MDO/MGO	Unit	Reference
CO	7.4	7.4	kg/tonne fuel	Lloyd s Register10
Sox	20*S (1)	20 * S (1)	kg/tonne fuel	Lloyd s Register10

S means percentage sulphur content in fuel

Appendix B

Linked articles

Next, it is attached the first page of each article written along the doctoral period, mentioned in Section 1.7. All have been published.

B.1 First Article

Etimating Ship Emissions Based on AIS Big Data for the Port of Rio de Janeiro, [28]

17th Conference on
Computer and IT Applications in the Maritime Industries

Estimating Ship Emissions Based on AIS Big Data for the Port of Rio de Janeiro

Maricruz A. F. Cepeda, COPPE/UFRJ, Rio de Janeiro/Brazil, maricruzcepeda@oceanica.ufrj.br
Gabriel P. Monteiro, PENO/UFRJ, Rio de Janeiro/Brazil, gabriel_premolimonteiro@poli.ufrj.br
João V. M. de Oliveira Moita, COPPE/UFRJ, Rio de Janeiro/Brazil, joaov@poli.ufrj.br
Jean-David Caprace, COPPE/UFRJ, Rio de Janeiro/Brazil, jdcaprace@oceanica.ufrj.br

Abstract

Automatic Identification System (AIS) data stores huge quantity of information regarding the safety of ships and port facilities in the international maritime transport sector. However, this big database is not only useful for the security of ships operations and port facilities. It can also be helpful for other important functions in maritime traffic such as reducing environmental impacts. This study develops an analytical approach to quantify ship emissions in the Guanabara Bay of Rio de Janeiro (Brazil) using AIS database. The model is applied to quantify Green House Gas (GHG) emissions trough the assessment of fuel consumption calculated for each individual vessel. The results shows that the proposed methodology is efficient to estimate total ship emissions over Rio de Janeiro Port area and Guanabara Bay. We suggest that quantifying the amount of emissions from ships in order to fulfil IMO regulations and reduce the health impacts of people who are living in surrounding areas of high maritime traffic is important for decision makers and for the maritime authorities.

1. Introduction

Every day, more than 2.5 quintillion bytes of data are created. This is known as big data, the datasets whose size and structure is beyond the ability of typical programming tools to data collection, store, manage and analyses in a reasonable time and exceed the capacity of their perception by a human, *Zicari (2014), Miloslavskaya and Tolstoy (2016)*.

Big data is present in key sectors and it has revolutionized the industry over the past several years. Companies across the various travel and transportation industry segments as airlines, airports, railways, freight logistics and others have been handling large amounts of data for years. In addition, today's advanced analytics technologies and techniques enable organizations to extract insights from data with previously unachievable levels of sophistication, speed and accuracy, *IBM (2014)*. Nowadays, big data is getting popular in shipping where large amounts of information is collected to better understand and improve logistics, emissions, energy consumption and maintenance. Using satellite navigation and sensors, trucks, airplanes or ships can be tracked in real-time. In shipping, the automatic identification system (AIS) and vessel traffic services (VTS) are mainly used to prevent collisions at sea. However, storing this information in data warehouse for a certain period allows the scientist to extract hidden knowledge from this bulk.

In early 2017, the ship world commercial fleet grew by 3.15% and reached a total of 1.86 billion DWT that consisted of 93161 vessels including bulk carriers, oil tankers, general cargo ships, container ships and others. Consequently, it produces a major marine traffic and a growth of fuel consumption contributing to global Green House Gas (GHG) emissions at sea impacting the climate change, *UNCTAD (2017)*. Ship emissions as a source of air pollution have been outlined in various studies worldwide, *Cooper (2003), Dalsoren et al. (2009)*. The GHG emissions of ship engines have raised the concern of International Maritime Organization (IMO) on the consequences for environment and human health. IMO first adopted MARPOL Annex VI in 1997. At present, IMO limits the main air pollutants in ships exhaust gas (sulphur oxides SO_X, nitrous oxides NO_X, Particulate Matter (PM), and Volatile Organic Compounds (VOC) emissions from tankers). It also regulates shipboard incineration, and prohibits deliberate Ozone Depleting Substances (ODS) emissions. IMO introduces Emission Control Areas (ECA), and it defines the energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP). These regulations aim to reduce emissions and increase ship energy efficiency.

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B.2 Second Article

Estimating possible near miss collisions based on AIS big data for the Port of Rio de Janeiro, [30]

DOI: 10.17648/sobena-2018-87574

SOBENA

27th International Congress on Waterborne Transportation, Shipbuilding and Offshore Constructions

Rio de Janeiro/RJ, 23rd to 25th October 2018

Estimating possible near miss collisions based on AIS big data for the Port of Rio de Janeiro

Maricruz A. F. S. Cepeda, UFRJ/COPPE, Rio de Janeiro/Brazil, maricruzcepeda@oceanica.ufrj.br
Gabriel Premoli Monteiro, UFRJ, Rio de Janeiro/Brazil, gabriel_premolimonteiro@poli.ufrj.br
João Vitor Marques de Oliveira Moita, UFRJ/COPPE, Rio de Janeiro/Brazil, joaov@oceanica.ufrj.br
Jean-David Caprace, UFRJ/COPPE, Rio de Janeiro/Brazil, jdcaprace@oceanica.ufrj.br

Abstract

Automatic Identification System (AIS) data records huge quantity of information regarding the safety of ships and port facilities in the international maritime transport sector. However, this big database is not only useful for the security of ships operations and port facilities. It can also be helpful for other important functions in maritime traffic such as estimating possible near miss ship collisions during a long period. This study develops an analytical approach to estimate possible near miss ship collisions in the Guanabara Bay of Rio de Janeiro (Brazil) using AIS database. The model is applied to rank the severity of an encounter between two vessels based on vessel conflict ranking operator (VCRO). The vessel size and the Minimum Distance to Collision (MDTC) concept are considered in the model. The results show that the proposed methodology is adequate for ranking and prioritizing encounters between ships. We suggest that ranking the possible near miss ship collisions around areas of high maritime traffic is important for decision makers and for the maritime authorities to make statements of maritime safety in relation to collision accidents.

Keywords: Ship, Near Miss Collision, Automatic Identification System, Big Data, Marine Traffic

1. Introduction

Maritime transportation is the main transportation mode for domestic and international trade. Over 80% of global trade by volume and more than 70% of its value being carried on board ships and handled by seaports worldwide, (UNCTAD, 2017).

Due to this, the growth in maritime traffic and the increase in the size of ships is inevitable. Consequently, it is essential to evaluate safety of marine traffic for the purpose of improvement of efficiency and safety of marine traffic, especially in areas where there is a high-density marine transport of passengers and/or cargo.

Therefore, it is important to develop and implement a method to know the behaviour of collisions and/or near miss collisions.

In general, Big Data has been receiving considerable attention in the specialized literature for the last 15 years. It is popular in shipping, especially on information collected about on-time ship characteristics to improve logistics, emissions, energy consumption and maintenance.

There are numerous studies focusing on the analysis of ship traffic. AIS data provides valuable input parameters in ship traffic simulation models for maritime risk analysis and for the prevention of shipping accidents. The article published by (Xiao, et al., 2015) reports the detailed comparisons of AIS data analysis between a Dutch case and a Chinese case. Another Chinese study published by (Zhang, et al., 2017) develops a tangible analytical approach to analyse ship traffic demand and the spatial–temporal dynamics of ship traffic in Singapore port waters using big AIS data. They found that the origin-to-destination pairs and navigation routes in the Singapore port waters maintain stability over time. Furthermore, they identify several hotspot areas in the Singapore Strait where ship sailing speeds are relatively high and ship sailing speeds in a few water areas vary greatly. (Zhang, et al., 2017) explored the

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B.3 Third Article

Environmental Impact of Ship Emissions based on AIS big data for the Port of Rio de Janeiro, [31]

Environmental Impact of Ship Emissions Based on AIS Big Data for the Port of Rio de Janeiro

Maricruz A. Fun Sang Cepeda(✉), Gabriel P. Monteiro, João V. M. de Oliveira Moita, Luiz Felipe Assis, and Jean-David Caprace

COPPE, Federal University of Rio de Janeiro, UFRJ, Rio de Janeiro, Brazil
{maricruzcepeda, joaov, felipe, jdcaprace}@oceanica.ufrj.br, gabriel_premolimonteiro@poli.ufrj.br

Abstract. Automatic Identification System (AIS) data records a huge quantity of information regarding the safety and security of ships and port facilities in the international maritime transport sector. However, this big database is not only useful for the security of ships operations and port facilities. It can also be helpful for other important functions in maritime traffic such as reducing environmental impacts, improve the logistics and analyses compliance with current International Maritime Organization (IMO) regulations. This study develops an analytical approach to quantify the impacts of ship emissions in the Guanabara Bay of Rio de Janeiro (Brazil) using AIS database as well as life cycle assessment (LCA) tool. The paper describes a method in two steps. First, the inventory of ship emissions is evaluated and geolocated with AIS data through the assessment of fuel consumption calculated for each individual vessel. Then, the impact of the emissions is assessed with the ReCiPe LCA method that translates emissions into a limited number of environmental impact scores by means of so-called characterization factors. The results show that the proposed methodology is efficient to estimate the environmental impact of ship emissions over the Rio de Janeiro Port area. We suggest that quantifying the number of emissions from ships in order to fulfil IMO regulations and reduce the health impacts of people who are living in surrounding areas of high maritime traffic is important for decision makers and for the maritime authorities to improve their strategies.

Keywords: Ship emissions · Environmental impact · Automatic Identification System · Bigdata · Marine traffic · ReCiPe method · LCIA · LCA

1 Introduction

The emergence of Big Data Analytics due to the data availability, storage capacity and increasing capability have become tools for to stakeholders driver in mitigating future uncertainty in all type industries [1]. Due to that, Big Data is used in countless applications.

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https://doi.org/10.1007/978-3-030-35963-8_34

B.4 Fourth Article

Detecting Possible Near Miss Collisions in Santos Bay from AIS big data, [32]

SOBENA

11th International Seminar on Inland Waterways and Waterborne Transportation

Brasília/DF, 22th to 24th October 2019

Detecting Possible Near Miss Collisions in Santos Bay from AIS Big Data

Ramiro Fernandes Ramos, UFRJ/COPPE, Rio de Janeiro/Brasil, ramirofr@oceanica.ufrj.br
Maricruz A. Fun Sang Cepeda, UFRJ/COPPE, Rio de Janeiro/Brasil, maricruzcepeda@oceanica.ufrj.br
João Vitor Marques de Oliveira Moita, UFRJ/COPPE, Rio de Janeiro/Brazil, joaov@oceanica.ufrj.br
Gabriel Premoli Monteiro, UFRJ, Rio de Janeiro/Brazil, gabriel_premolimonteiro@poli.ufrj.br
Olav Fiksdahlb, NTNU, Norwegian University of Science and Technology, Trondheim/Norway, olavfi@stud.ntnu.no
Jean-David Caprace, UFRJ/COPPE, Rio de Janeiro/Brasil, jdcaprace@oceanica.ufrj.br

Abstract

The Santos Bay, located in Brazil, holds the largest and busiest container port in Latin America. Many cargo ships pass through this Bay every day and its safety are subject of many researches. Using the Automatic Identification System (AIS) messages sent by those ships it is possible to detect possible near miss collisions events. This study develops an analytical approach to identify the most common cargo ship types involved in near miss collisions in Santos Bay (Brazil) using AIS database. It will also identify the most common type of vessel conflict in this area. The model is applied to rank the severity of an encounter between two vessels based on vessel conflict ranking operator (VCRO). The vessel size and the minimum distance to collision (MDTC) concept are considered in the model. The results show that the proposed methodology is adequate to identify various statistics in near miss collisions. Containers ship is the most common type of cargo ship involved on those situations and the crossing conflict occurs with higher frequency. Understanding the parameters involved in near miss collision around areas of high maritime traffic is important to avoid accidents. For the future, comparisons of data between different areas are suggested.

1. Introduction

Maritime transportation is crucial to the world's economy. Also, it is important for the development of many countries. In 2017, the maritime transportation was responsible for more than 80% of the global trade between all other transportation modes. As well, cargo ships are the most common type of ship, approximately 90% of the world fleet being cargo ships, (UNCTAD, 2017).
Accidents involving ships occasionally occur in the world. The most common types are grounding, collisions and fires (Guedes Soares & Teixeira, 2001). Since the ship itself and the cargo have a high value and there are human lives in risk in those accidents, it is very important to study the conditions that generate those accidents. With the results of those observations it is possible to improve the navigation safety.

Focusing on the accidents involving two or more ships, it can take place in every route where two ships cross each other. The port areas have a highest traffic of ships, so the observation of accidents in those areas has even more importance. Also, passengers' ships are very present on port areas, which increases even more the interest of improving safety in this matter.
Santos Port, located in Santos Bay, is the main Brazilian port and the biggest on the Latin America. It has a high diversity of products and services, including dry bulk, liquid bulk, containers, general cargo and passengers. Even having different types of ships for different purposes, cargos ships are the main type navigating in Santos Bay.
In 2018, there were more than 750 accidents involving navigation in Brazil and 185 people died by reason of those accidents. The accidents

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B.5 Fifth Article

A review of the use of LNG versus HFO in maritime industry, [33]

Marine Systems & Ocean Technology
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REVIEW PAPER

A review of the use of LNG versus HFO in maritime industry

Maricruz A. Fun-sang Cepeda[1] · Newton Narciso Pereira[2] · Suzana Kahn[3] · Jean-David Caprace[1]

Received: 4 January 2019 / Accepted: 26 June 2019

Abstract
Maritime transport is responsible for about 2.5% of global greenhouse gas emissions representing around 1000 million tons of CO_2 annually. The situation of shipping emissions that strongly depends on future economic grows is aggravated by the fact that global green house gas (GHG) emissions are predicted to increase between 50 and 250% by 2050. This is not compatible with the internationally agreed goal of keeping global temperature increase below to 2 °C compared to pre-industrial levels, which requires worldwide emissions to be at least halved from 1990 levels by 2050. Furthermore, ship owners are facing barriers implementing energy efficiency technologies to reduce CO_2 mainly due to reliability, and financial and economic constraints as well as due to the complexity of change. Energy consumption and CO_2 emissions of ships could be reduced by applying operational measures and implementing existing technologies. Further reductions could be achieved by implementing new innovative technologies. The aim of this study is to compare and review low carbon and advanced technologies that may help to reach international GHG reduction goals. A comparison table describing the different technologies, the estimated capital cost, technology readiness as well as the potential GHG reduction is drawn. The table also indicates if the technology suits better to new projects or to retrofitting. The comparison may help the key players to select the most convenient technology for their new projects. It will also be helpful for conversion of existing vessels.

Keywords GHG emissions · Low carbon technologies · New innovation technologies · GHG reduction goals · Shipping · Maritime transport

Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
DE	Diesel engine
DFDE	Dual-fuel engine
ECA	Emission control area
GHG	Green house gas
HFO	Heavy fuel oil
IMO	International maritime organization
IPCC	Intergovernmental panel on climate change
LCC	Life cycle cost
LNG	Liquefied natural gas
MGO	Marine gas oil
N_2O	Di-nitrogen oxide
NO_X	Nitrogen oxide
NPV	Net present value
OPEX	Operational expenditure
PSV	Platform supply Vessel
PM	Particulate matter
RORO	Roll on, Roll off
SECA	Sulphur emission control area
SO_X	Sulphur oxide
SS	Slow steaming

✉ Maricruz A. Fun-sang Cepeda
maricruzcepeda@oceanica.ufrj.br

Newton Narciso Pereira
newtonpereira@id.uff.br

Suzana Kahn
skr@pet.coppe.ufrj.br

Jean-David Caprace
jdcaprace@oceanica.ufrj.br

[1] Ocean Engineering, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

[2] School of Industrial Engineering Metallurgical at Volta Redonda - EEIMVR, Federal Fluminense University, Rio de Janeiro, Brazil

[3] Transport Engineering, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

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Springer

B.6 Sixth Article

A Dynamic Port Congestion Indicator - A case study of the Port of Rio de Janeiro, [34]

28º International Congress on Waterborne Transportation, Shipbuilding and Offshore Constructions

Rio de Janeiro/RJ, 27th to 29th October 2020

A Dynamic Port Congestion Indicator – A Case Study of the Port of Rio de Janeiro

Vinícius Barreto Martins, UFRJ/COPPE, Rio de Janeiro/Brasil, v1nybarreto@oceanica.ufrj.br
Ramiro Fernandes Ramos, UFRJ/COPPE, Rio de Janeiro/Brasil, ramirofr@oceanica.ufrj.br
Maricruz Aurelia Fun Sang Cepeda, UFRJ/COPPE, Rio de Janeiro/Brasil, maricruzcepeda@oceanica.ufrj.br
Jean-David Caprace, UFRJ/COPPE, Rio de Janeiro/Brasil, jdcaprace@oceanica.ufrj.br

Abstract

Maritime trade plays a key role in the global economy and recent technological developments have accelerated maritime logistics. However, this increase in maritime trade has had an impact on port performance, leading to port congestion in some regions. Few researches employing AIS data has explored the marine traffic congestion, hence the development of a system that makes metrics on ports more accessible is needed. This work employs an innovative methodology to analyze the port congestion level on the port of Rio de Janeiro. From the Automatic Identification System (AIS) data, three algorithms were used to find the convex hull area, the geolocation area, and the average vessel proximity. These algorithms were used to calculate the Port Congestion Indicators (PCIs): i) Spatial Concentration; ii) Spatial Density; iii) Average Service Time. Then, Machine Learning techniques were employed to cluster these indicators into low, medium, and high congestion levels. As a result, this process identified the periods when the port is most congested and the centroids of these clusters can be used to predict the behavior of port congestion levels. These indicators provide resources for better management and can motivate actions such as the redistribution of ship loading and unloading locations, improving the port performance measurement.

1. Introduction

Maritime trade represents around 90% of the global volume trade. Therefore, the port's performance is crucial to sustaining economic growth, (AbuAlhaol, Falcon, Abielmona, & Petriu, 2018). However, this increase in maritime trade has produced an impact on the Ports efficiency in some regions. In December 2019, for example, ships operated liquid chemical bulk in the Port of Santos had to wait more than 10 days for a docking opportunity, causing losses around US$ 35.000 per day for each ship, (Rosssi, 2019).

This situation is called port congestion, in which vessels must wait at areas close to the Ports for load or unload. In most cases, the port's capacity does not correspond to the demand, and the vessels, generally, must wait at anchorage areas before accessing the port, (MarineTraffic, 2020). This impact is not restricted to any part of the world, it also affects ports on Asia, North Africa, Northern Europe, and United States, (Saeed, Song, & Andersen, 2018).

Port congestion is an important issue from an economic and efficiency point of view. Because it results, not only, in longer waiting times and low service levels for vessels, but it also contributes to the decrease in competitiveness and demand (Saeed, Song, & Andersen, 2018). Understanding the aspects that influence congestion is essential for port management. However, traditional traffic analyzes are, generally, carried out through surveys that include: visual observations, radar, and aerial

B.7 Seventh Article

Executive summary of the Action Plan for the Sustainable Energy Transition of the Galapagos Islands, of the "Mechanisms and Networks of Technology Transfers related to Climate Change in Latin America and the Caribbean.", [35]