Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management and Humanities

Analysis of the Reduction of Emissions from Ships in Europe

Master’s Thesis

Study Program: Electrical Engineering, Power Engineering and Management

Field of Study: Management of Power Engineering and Electrotechnics

Scientific Adviser: Doc. Ing. Julius Bemš, PhD

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MASTER‘S THESIS ASSIGNMENT

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2 Methods and strategies for reducing emissions
3 Cost-Benefit Analysis of Reduction of CO2 Emission
4 Evaluation analysis data and suggestions

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Student: Gökhan YEGNIDEMIR

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Topic: Analysis of the Reduction of Emissions from Ships in Europe

Details:

- Prepare general research on emissions from ships and cars
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I hereby declare that this master’s thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – “On maintaining ethical principles when working on a university final project, CTU in Prague”.

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Abstract

An essential part of the world's energy consumption is facilitated by the burning of fossil fuels or their synthetic derivatives, which result in the emissions of harmful gases in the atmosphere. The maritime industry contributes to the increase in greenhouse gas (GHG) and other detrimental gas emissions. The possibilities of reducing these types of emissions from ships are subject to ongoing research. The International Maritime Organization (IMO) and the European Union cooperate on the development of emission abatement measures and strategies.

This thesis aims to calculate the marginal abatement cost of measures that can be taken to reduce the CO_2 emissions from maritime transport and to examine their reduction potential. General introduction into the greenhouse gas and other harmful gas emissions is provided in the first chapter, focusing on the existing means of regulation as well. In the second chapter, the methods and strategies employed by the IMO and the European Union are analyzed. Besides, the Marginal Abatement Cost (MAC) curves that are used in the calculations are explained, with additional examples in the literature examined. The European Union (EU) Monitoring, Reporting, and Verification system (MRV; Shipping Regulation 2015/757) is used as a source for reference data. The EU-MRV shipping regulation applies to larger ships over 5000 gross tonnages on all voyages to or from the EU ports. In the third chapter, the estimated CO_2 emissions are assessed with regard to the projected increase in freight works by 2050. The used concepts and assumptions are discussed with respect to cost-benefit analysis in the same chapter. Fuel prices and discount rates were handled separately for marginal abatement cost calculations. Besides, 12 different emission abatement measures were examined in detail, and the investment and operational costs were shared. The results are presented while using MAC curves for nine different ship types, which, according to the EU-MRV data, cause 95% emissions in the European ports. Within the last chapter, emissions are estimated by ship type in 2050, once again using the EU-MR data. The sensitivity analysis is conducted for emission reduction potentials for different fuel price scenarios, and potential emission abatement scenarios of the measures are shared. At the end of the thesis, the EU maritime transport emissions are estimated for the abatement scenarios until 2050.

Keywords: CO_2 Emissions; Greenhouse Gases (GHGs); Green Ships; Cost-Benefit Analysis; Marginal Abatement Cost (MAC) Curves

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List of Abbreviations

BAU	Business As Usual
CH_4	Methane
CNG	Condensed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DWT	Deadweight Tonnage
EC	European Commission
ECAs	Emission Control Areas
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EFTA	European Free Trade Association
EIA	U.S. Energy Information Administration
EMSA	European Maritime Safety Agency
EOS	Economy Of Scale
ETS	Emission Trading System
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHGs	Greenhouse Gases
GT	Gross Tonnage
HC	Hydrocarbons
HFCs	Hydrofluorocarbons
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curves
MEPC	Marine Environment Protection Committee (IMO)
MRV	Monitoring, Reporting and Verification system (EU)
NG	Natural Gas
N_2O	Nitrous oxide
NOx	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
PFCs	Perfluorocarbons
PM	Particulate Matter
SECAs	Sulfur Emission Control Areas
SEEMP	Ship Energy Efficiency Management Plan
SF_6	Sulphur Hexafluoride
SOx	Sulphur Oxides
TEN-T	Trans-European Transport Network
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compounds
WHO	World Health Organization
WHR	Waste Heat Recovery
WMO	World Meteorological Organization

1. Introduction

The rapidly growing world population and developments in the field of technology are increasing energy consumption that constitutes critical environmental problems. Air pollution forms an essential part of environmental issues. There are many factors that cause air pollution, but the main factor is combustion. A necessary part of the world energy consumption is obtained by burning fossil fuels or their synthetic derivatives. The harmful gases are produced as a result of the combustion of fossil fuels. These gases create the greenhouse effect and pollute the atmosphere.

Polluted air or smog harms human health, living life, and ecological balance. The leading causes of air pollutions are air emissions. The primary hazardous air emissions released into the atmosphere are; Carbon dioxide (CO_2), Methane (CH_4), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulphur Oxides (SOx), Volatile Organic Compounds (VOC), Particulate matter (PM), Hydrocarbons (HC) [3, 8]. Preventing the spread of such gases into the air is one of the foremost research topics of recent years.

Global warming is a natural process that periodically warms up the atmosphere with the greenhouse effect. Our atmosphere works like a greenhouse, so temperature rises, precipitation changes, glaciers melt, and sea levels rise [10]. Many factors cause the greenhouse effect and climate change. Increasing urban air pollutants and CO_2 or greenhouse gases (GHGs) emissions in recent years are closely related to heavy traffic, which is a part of our daily lives; much of the heating comes from emissions from human activities. To reduce the impacts of climate change, we need to reduce or prevent these emissions [15].

The Paris Agreement sets the global action objective to avoid climate change by reducing global warming to below 2 °C and following efforts to keep it to 1.5 °C. In this context, the Intergovernmental Panel on Climate Change (IPCC) has prepared the Sixth Assessment Report (Global warming of 1.5 °C) related to global greenhouse gas emission pathways. This report shows that a temperature rises of more than 1.5 °C compared to pre-industrial levels could exceed critical thresholds and cause irreversible damage to ecosystems [26, 27, 28].

The World Health Organization (WHO) also states that most of the climate change and urban air pollution is caused by the burning of fossil fuels [17]. Especially CO_2 and other harmful gases, emitted by the combustion of fossil fuels have a great impact on climate change. Reducing this type of emissions is the key to avoiding the most disastrous impacts of climate change, human health, and the environment.

The atmospheric concentrations of greenhouse gases such as CO_2 and others have increased significantly since the beginning of the industrial revolution. Unfortunately, an essential share in greenhouse gas (GHG) emissions belongs to the transportation sector. The transportation sector group consists of several industries, including airlines, marine, road and rail, transportation infrastructure, and freight and logistic services [16]. A known fact that transportation has many harmful effects on people and the environment. The European Union (EU) and the member states are therefore taking several measures to reduce the impact of transport on health and have achieved some success. It is possible to further improve the situation with innovative solutions and local actions [18].

Europe, which is responsible for approximately 10% of global GHG emissions, is playing a leading role concerning the shift to an economy with net-zero GHG emissions. Europe, roads, railway lines, inland waterways, inland and maritime ports, airports, and railway stations are connected. The trans-European transport network (TEN-T) alone consists of more than 138,000 km of railway lines, 136,700 km of roads, and 23,506 km of inland waterways [19]. The means of transportation used in this network are increasing day by day. Because of this increase, air emissions, especially GHG emissions, are also growing. According to the European Environment Agency report; In 2016, the transport sector contributed 27 % of the total EU-28 (EU-28 Countries–list of the countries can be found in Appendix 1) GHG emissions [20].

There are many regulations for decreasing greenhouse gases in Europe as well as globally. Sector-based regulations help obtain more effective results to reduce these harmful gases. In this study, an analysis will be made on CO_2 emissions from ships.EU Regulation 2015/757 which is the EU-MRV regulation to report CO_2 emissions from ships published by the European Union will be used as the main reference source [40].

In summary, this thesis is going to explain the topics as follows. In the first chapter of the study, the general situation in Europe and the international shipping will be examined, and the regulations will be mentioned about emissions. In chapter two, the methods and strategies of the European Union and International Maritime Organization (IMO) will be examined, and the methods used to reduce the greenhouse gas emissions from maritime will be mentioned. Also, MAC curves samples will be shared. In chapter three, the cost-benefit analysis will be calculated with appropriate reference reduction techniques for different types of ships. The results will show via Marginal Abatement Cost Curves (MACC). In chapter four, analysis results of CO_2 reduction potentials will be compared with reference ships, and abatement potentials for different fuel types will be found for sensitivity analysis. Ships in EU-MRV data will be presented with an assessment for 2050 as a result of applying these potentials. Besides, suggestions will be made for future studies. The overall summary of the results and the comprehensive evaluation is described in the conclusion part.

1.1. General information about emissions

Emissions are a term used to describe gases and particles emitted from a plant or vehicle to the atmosphere as a result of collection, separation, transport, and other mechanical processes such as synthesis, decomposition, evaporation, burning of fuel, and so on [21]. Emissions from human beings vary depending on factors such as industrial development, population, urbanization, and geographical and physical characteristics of the region. Analyzing these human-made emissions into two further categories may facilitate understanding of the process.

Air emissions can be classified into two main groups:

- Greenhouse Gas Emissions (GHGs)
- Air Pollutants

1.1.1. Greenhouse gas emissions

One of the most critical problems of recent years is the global climate changing. The most important reason for global climate-changing is the increase in the amount of carbon dioxide, a greenhouse gas, in the atmosphere. Scientists have been aware of the planetary effects of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere for many years. In recent years, however, concern has been raised about global climate change due to the accumulation of these gases [23].

The amount of greenhouse gases in the atmosphere indicates greenhouse gas emissions. Greenhouse gases trap heat and make our planet warmer. The most important natural greenhouse gas in the atmosphere is water vapor. Greenhouse gases can occur naturally or can be caused by human activities. The use of fossil fuels, the destruction of forests, the use of synthetic fertilizers, industry, and animal husbandry are human-made conditions that increase GHG emissions [10, 24].

The primary sources of human-made greenhouse gases are [10, 11, 33]:

- Carbon dioxide (CO_2); burning of fossil fuels such as coal, oil, gas, etc.
- Methane (CH_4); agriculture and fossil fuel extraction
- Nitrous oxide (N_20); agriculture (Especially from fertilized soils)
- Hydrofluorocarbons (HFCs); use of industrial fluorinated gases.
- Sulphur hexafluoride (SF_6)
- Perfluorocarbons (PFCs)

The latest analysis (GHG Bulletin No.14) of the World Meteorological Organization (WMO) shows that CO_2 is the single most crucial GHG in the atmosphere, contributing approximately 66% of the radiative effect by long-lived GHGs [25].

According to Eurostat data, fuel combustion and fugitive emissions from fuels (without transport), Transport (including international aviation), Agriculture, Industrial process and product use, and waste management are the main responsible for Greenhouse Gas (GHG) emissions (EU-28 countries) [12]. The percentages, according to the source sectors for 2017, can be found in Figure 1.

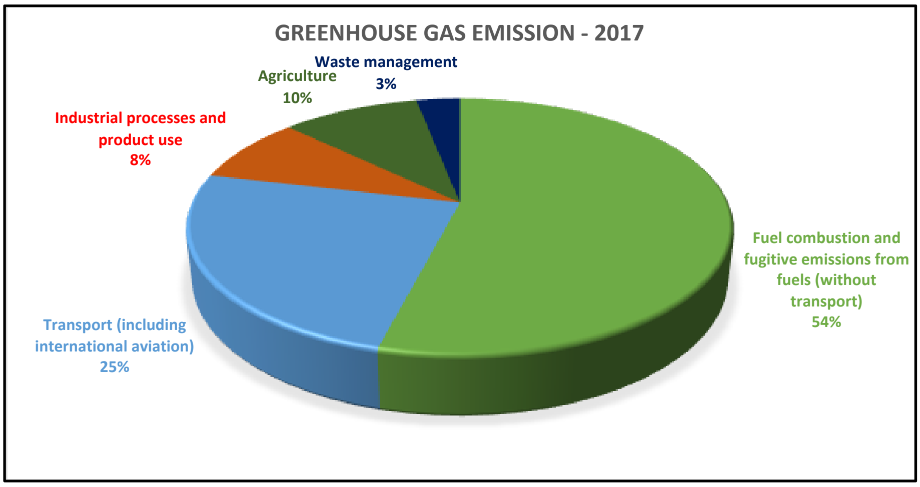

Figure 1. Greenhouse gas emissions by source sector, EU-28, 2017, based on data from [12].

The figure shows that transport (including international aviation) (25%) is one of the essential GHG emissions sources according to 2017 data. Reducing emissions from transport is crucial; therefore, there are many regulations on reducing GHG emissions from transportation.

According to the data provided by the European Environment Agency, (“*Data on greenhouse gas emissions and removals, sent by countries to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism (EU-28)”),* a figure of emissions from transport is as follows [20]. The below figure 2 shows that the percentages share of transport greenhouse gas emissions in 2016.

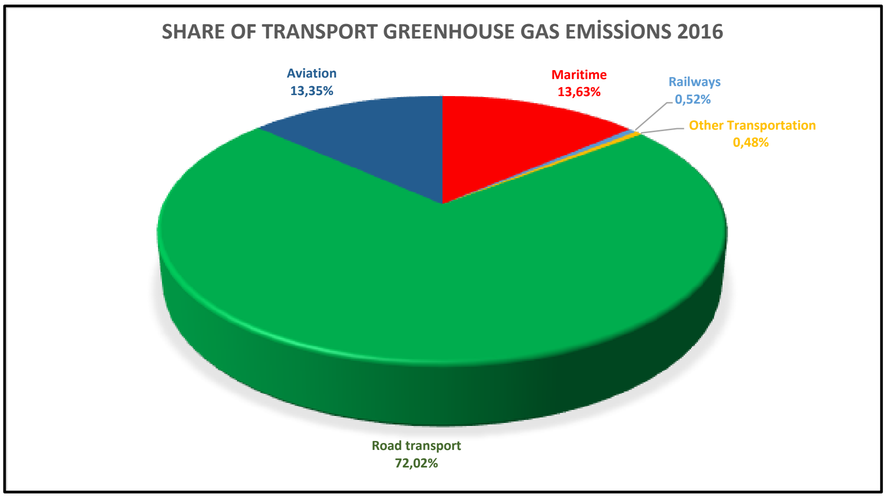

Figure 2. Share of Transport Greenhouse Gas Emissions, EU-28, 2016, based on data from [20]

According to Figure 2, in 2016, road transport accounted for 72.02%, and maritime transportation accounted for 13.63% of greenhouse gases. As a result, transport (including international aviation and international shipping) GHG emissions (especially CO_2 emission) are quite active in the global climate changing.

Due to all these reasons, there are various decisions taken by the European Union not only for transportation but also for other sectors. The EU target for all industries is to reduce GHG emissions by at least 20% below 1990 levels by 2020. This target is achieved by looking at the 2017 data (22% reduction) [12]. The new target is to reduce GHG emissions by 40% in 2030. As stated in the Paris Agreement, when we look at EU long-term targets for reducing GHG emissions, 2050 targets, has been adopted net-zero GHG emission [14].

1.1.1.1. GHG emissions in ships

The Kyoto Protocol covers six primary greenhouse gas emissions for the first period [33]. These gases are examined in the above Greenhouse Gas Emissions section. Nevertheless, CO_2 is one of the most important greenhouse gasses emitted from maritime. Other greenhouse gas emissions are as critical as CO_2 [34]. According to the Third IMO GHG Study 2014, maritime transport emitted approximately 938 million tonnes of CO_2 in 2012. It is representing 2.6% of the world's global CO_2 emissions [35].

The global CO_2 emissions are compared with the shipping sector between 2007 and 2012 in The Third IMO GHG Study. The values in Table 1 are taken from the Third IMO GHG Study [35].

Table 1. Shipping CO_2 emissions compared with global CO_2 emissions, based on data from [35]

Third IMO GHG Study 2014 CO_2 Emissions [million tonnes]					
Year	Global CO_2	Total shipping	% of global	International shipping	% of global
2007	31409	1100	3.5%	885	2.8%
2008	32204	1135	3.5%	921	2.9%
2009	32047	978	3.1%	855	2.7%
2010	33612	915	2.7%	771	2.3%
2011	34723	1022	2.9%	850	2.4%
2012	3564	938	2.6%	796	2.2%
Average	**33273**	**1015**	**3.1%**	**846**	**2.6%**

According to the IMO study [35], CO_2 emissions are expected to increase between 50% and 250% by 2050 in a business scenario where maritime transport is overgrowing. In 2050, CO_2 emissions are expected to increase approximately between 3.9% and 9.1% if no action is taken.

The International Maritime Organization (IMO) has adopted its initial strategy to reduce 50% of GHG emissions from the maritime transport sector by at least 50% by 2050 compared to 2008. IMO's Marine Environment Protection Committee (MEPC) has set out the future GHG strategies for maritime. The plan also includes short, mid, and long-term measures [35, 36].

Moreover, the Third IMO GHG study shows that other emissions increase in parallel with CO_2 and fuel consumption. Methane emissions depend on LNG usage. LNG is expected to increase Methane emissions. By using new-generation engines, Nitrogen emissions will increase less than CO_2. Particulate matter and SOx emissions will an exact decrease until 2050 because of the IMO regulations and strategies [35].

The European Commission published for the first GHG emissions information in large ships (over 5000 gross tonnages) related to the European Economic Area (EEA)[1] on 30 June 2019. This information includes around 11000 ships of various types. According to the CO_2 emissions report by ships, in 2018, more than 130 million tonnes of CO_2 emissions were emitted in the EEA [39]. All information is accessible in the web-base [40].

1.1.1.2. GHG emissions in cars

Nowadays, climate change is one of the most pressing environmental threats facing the world. In the last few years, changes in weather conditions have shown how disastrous the effects can be. Energy (fuel consumption) use is Increasing, and that is one of the most critical factors in climate change. Growth in energy use is higher than in other applications for the transport sector. Road transport, mostly light-duty vehicles such as cars and freight transport, are primary drivers of global transport energy growth [17, 41].

Globally, the transport sector was responsible for 25% of total CO_2 emissions, around 8 gigatonnes CO_2 in 2014. Road transport was responsible for approximately 20% in the same year [43].

The transport sector is Europe's one of the most important sources of carbon emissions, approximately 25% of Europe's total CO_2 emissions. In 2016, road transport accounted for 72.02% GHG emissions to compare with another transport sector [12]. The figure below shows comparatively the emissions from road vehicles and other transportation sources in 2016 [2016]. The figure below shows comparatively the emissions from road vehicles and other transportation sources in 2016[20].

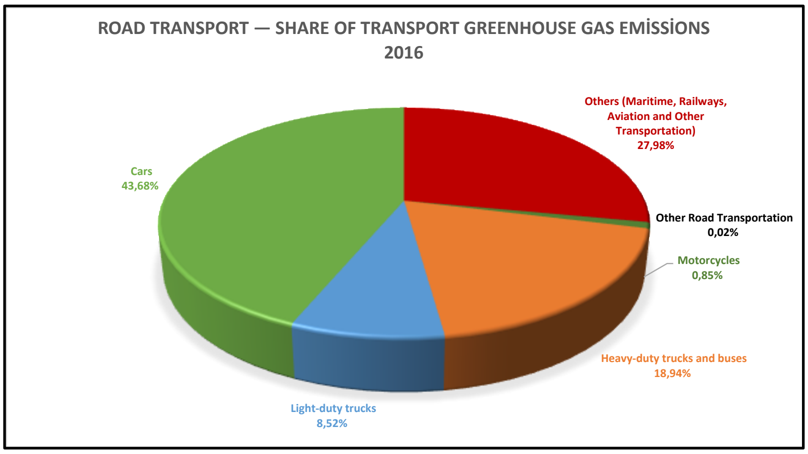

Figure 3. Road Transport, share of transport Greenhouse Gas Emissions, EU-28, 2016, based on data from [20]

According to Figure 3, passenger cars (43,68%), heavy-duty trucks and buses (%18,94), and light-duty trucks (8,52%) are responsible for the GHG emissions for the road transport.

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[1] *"The European Economic Area, abbreviated as EEA, consists of the Member States of the European Union (EU) and three countries of the European Free Trade Association (EFTA) (all except Switzerland, namely: Iceland, Liechtenstein and Norway)."*

1.1.2. Air pollutants

Air pollution, which is one of the most critical environmental problems today, is threatening the world of the future and posing ecological hazards. The world population is rapidly increasing, and also, the use of energy, the development of industry and urban pollution caused by urbanization have adverse effects on human health and other living things.

The leading causes of air pollutions emitted directly to the atmosphere, including Carbon Monoxide (CO), Sulphur Oxides (SOx), Nitrogen Oxides (NOx), Volatile Organic Compounds (VOC), Particulate matter (PM), and Hydrocarbons (HC) can be a significant cause of poor air quality [3, 30].

The main sources of air pollutant are [3, 30, 31]:

- Nitrogen Oxides (NOx); naturally produced amounts of nitrogen oxides (by bacterial and volcanic effect and by lightning) are much higher than human-made emissions. Human-made NOx is caused by mainly the burning of fossil fuels for energy production and transportation.
- Sulphur Oxides (SOx); the essential source of Sulphur is a fossil fuel. Coal combustion is the primary source of human-made SOx, about 50% of global emissions, and the oil burning rate is 25-30%. Notably, the large ships are primarily burning what's called Heavy Fuel Oil (HFO) at sea. HFO fuel is not heavily refined, so the burning of heavily non-refined fuels has high Sulphur, and they produce a lot of SOx and NOx.
- Particulate matter (PM); Particulate Matter is emitted from a wide variety of sources. The most important sources are transport, non-combustion processes, industrial combustion plants and processes, commercial and residential heating, and energy production. Natural resources are less important.
- Carbon Monoxide (CO); Carbon Monoxide occurs in the exhaust of vehicles. This is because insufficient oxygen cannot convert all carbon in the fuel to CO_2. Carbon monoxide is generally emitted from idling and slow-moving road vehicles. Road transport is the source of CO emissions by three quarters.
- Volatile Organic Compounds (VOC); VOCs can be found both indoors and outdoors because they are the main component of many products and materials. When we look at the primary sources of VOC, vehicles, using chemicals, industrial processes, home, and office equipment are seen as the essential sources except for natural causes.
- Hydrocarbons (HC); Hydrocarbons are the result of incomplete combustion or leakage of fuels. Hydrocarbons are not poisonous but have many harmful effects. Hazardous hydrocarbons are valued at around 100 million tonnes worldwide and are estimated to account for only one-twentieth of natural resources [32].

These mentioned emissions negatively affect the living life of the earth by polluting the air layer with the wastes generated during the production and consumption activities resulting from various activities of people. Reducing such emissions, multiple studies, and regulations are published across the world. The high sulfur fuels (like HFO) are used in the maritime industry. There are many regulations taken by IMO and the European Union to keep gases from such fuels to a minimum. These regulations are detailed in the next section.

1.2. Regulations

1.2.1. Regulations for ship emissions

A known fact, the maritime structure is not only limited to one country, but also it is a form of trade with the cooperation of different nations across borders. Thus, it is known that success will be achieved only if the innovations to be made in the field of maritime are made in unity and togetherness rather than individuality. Within the scope of all this, it was decided to establish International Maritime Organization (IMO), which is the first maritime organization in the world with a contract signed in 1948 within the United Nations. The IMO is considered the appropriate organization to regulate GHG emissions from international shipping [35, 37].

IMO started that its work on the prevention of air pollution from ships in the 1970s. In 1997, IMO ship pollution rules are contained in the *"International Convention on the Prevention of Pollution from Ships"*, known as MARPOL 73/78[2] [29]. The MARPOL sets rules for nitrogen oxides (NOx) and sulphur oxides (SOx) emissions in the exhaust gas. In the same year, IMO started work in regulating GHG emissions from ships [34].

The First IMO Study of greenhouse gas emissions from ships was published in 2000 (MEPC 45/8), and it was estimated that ships trading internationally contributed approximately 1.8% of the total CO_2 emissions in the world. In 2009, IMO published The Second IMO Study (MEPC 59/4/7 and MEPC 59/INF.10). The commission updated international shipping emission values. The second study was estimated to have emitted 880 million tonnes, or about 2.7% of the global emissions of CO_2, in 2007. The 59th session of MEPC in July 2009 also approved the mandatory the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). After five years, the Third IMO GHG Study published in 2014. The study estimated international shipping emissions, and the Second IMO GHG Study values are updated. Maritime transport emitted approximately 938 million tonnes of CO_2 emissions in 2012. It is representing 2.6% of the world's global CO_2 emissions [34, 35, 37].

The EEDI is one of the most important technical measures for new ships. The index aims to classify the CO_2 emitted by the ship by ship type and size and to promote the use of more efficient equipment and engines. The SEEMP is an operational measure that provides a mechanism for improving the energy efficiency of a ship cost-effectively. this plan also offers shipping companies the ability to manage ship and fleet efficiency and performance using the Energy Efficiency Operational Indicator (EEOI). [34, 38].

European Union support to IMO energy efficiency projects and policy frameworks. The "Sulfur Directive" prepared by the European Union (EU 2016/802) one of the most important ones. The directive is control of sulfur oxide emissions used in ships has been the reference for regulating the sulfur content of the fuels used in ships and CO_2 emissions from ships [3]. Given the expected increasing global greenhouse gas emissions of maritime transport, the European Commission has published the Monitoring, reporting, and Verification (MRV) regulation for GHG emissions information from ships (Regulation 2015/757) in 2015. Data of MRV contain large ships (over 5 000 gross tonnage cargo or passengers) in the European Economic Area (EEA) [4].

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[2] *"The MARPOL Convention was adopted on 2 November 1973 at IMO. 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. In 1997, a Protocol was adopted to amend the Convention and a new Annex VI was added which entered into force on 19 May 2005. MARPOL has been updated by amendments through the years."*

Besides GHG emissions, it has also set some limits for emissions for IMO SOx and NOx. Sulfur limits for ships using heavy fuel oil have been tightening over the years. Beginning in 2020, it will be limited to 0.5% globally. Since 2015, it has been limited to 0.1% for Emission Control Areas (ECAs) or Sulfur Emission Control Areas (SECAs). In the Baltic Sea, North Sea, North America, it is very important to set emission limits for Emission Control Areas (ECA) that regulate sulfur oxide (SOx) and/or nitrous oxide (NOx) emissions [103]. The Figure 4 (below) shows the SOx limits by years in the global, ECAs, and SECAs regions.

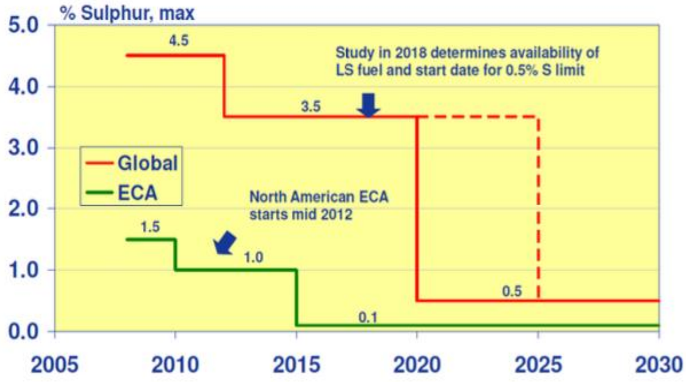

Figure 4. Global and Sulphur Emission Control Areas (SECAs) SOx Limits [34]

The NOx emissions measured in grams per kWh should be reduced by 75% after Tier III for ships built after 2011. The ranges given in this table are changed according to the ship engine type [34, 103]. Values are given in Table 2 for NOx limits.

Table 2. MARPOL Annex VI NOx emission limits [103]

Tier	Date	NOx Limit [g/kWh]
Tier I	2000	17.0 - 9.8
Tiear II	2011	14.4 - 7.7
Tiear III*	2016	3.4 - 2.00

* In NOx Emission Control Areas (Tier II standards apply outside ECAs).

The EU Emissions Trading System (ETS) Directive, (by Directive (EU) 2018/410 of the European Parliament and the Council), underline the need to reduce shipping emissions as well as all other sectors in 2018 [4].

1.2.2. Regulations for car emissions

Globally, road transport was responsible for 20% of total CO_2 emissions in 2014 [43]. The number of motor vehicles worldwide is expected to reach over 2 billion by 2050 [45, 46, 47]. Energy and power-related regulations must be implemented to stop GHG emissions from growing further [47].

The CO_2 emissions contributed nearly 21% of the EU's total emissions of CO_2 in 2016 [44]. Europe has been implementing a series of policies to reduce greenhouse gas emissions from vehicles for more than 25 years. However, due to the developments in recent years, the studies carried out in the last years have increased considerably. In 2009, European Union regulation (Regulation (EC) No 443/2009) was adopted on mandatory targets for average CO_2 emissions from new passenger cars. New cars registered in the EU-28 must achieve the average emission target of 130 grams of CO_2 (g CO_2/ km) per kilometer by 2015. In a medium-term target, the average emission that all new passenger cars can achieve by the end of 2020 is 95 g CO_2/km [46]. According to the European Environment Agency 2015 technical report [49], in 2014, passenger cars' CO_2 emission changing values from 2000 to 2014 in Europe (EU-28) demonstrated in Figure 5.

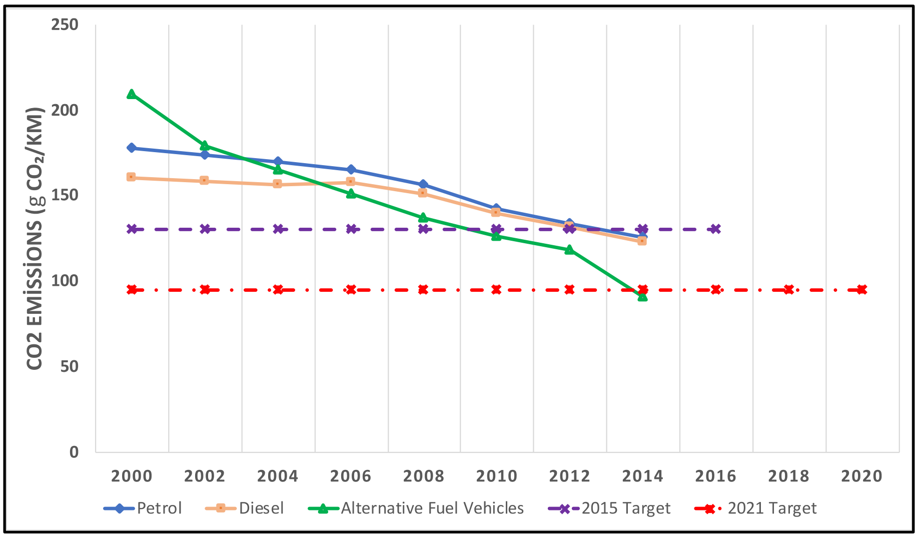

Figure 5. Changes of CO_2 emissions from new passenger cars by fuel type[3], EU-28, based on data from [49]

According to Figure 4, the CO_2 emissions target has been achieved for all types of fuel by cars in 2014. The decrease in CO_2 emissions in alternative fuel vehicles type vehicles is faster due to the increase in the number of electric vehicles and plug-in hybrid vehicles. Besides, based on the data given, Alternative Fuel vehicles reached 2021 targets in 2014.

After regulation for passenger cars, in 2011, a new regulation was prepared for light commercial vehicles (vans) (Regulation (EU) No 510/2011). The light commercial vehicles in the European Union are 175 gCO_2/km by 2017. The target for 2020 is 147 g CO_2/km [46].

The primary source of emission is fuel, which is a significant source in reducing GHG emissions from the transport sector. According to EU regulations, the greenhouse gas concentration in fuels needs to be reduced by 10% by 2020 (Directive 2009/30/EC) [44].

The European Parliament and the Council adopted a new regulation on 17 April 2019. The regulation, which will be implemented from 1 January 2020, sets new CO_2 emission standards for cars and vans. This is Regulation (EU) 2019/631 [44].

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[3] *"The value for alternative fuel vehicles includes pure electric, liquefied petroleum gas (LPG), natural gas (NG), ethanol (E85), biodiesel, and plug-in hybrid vehicles."*

2. Methods and Strategies for Reducing Emissions

Method$_2$ and strategies are taken by Europe and IMO to reduce CO_2 emissions are discussed in this chapter. General information is mentioned about Marginal Abatement costs and curves that are using for cost-benefit analysis are included in this section, and MAC curve applications are shared as a result of the literature research.

2.1. European Union strategies

The strategic actions taken as a result of European regulations will be mentioned in this section. Although there is no direct mention of ship emissions in the Paris agreement, these emissions need to be reduced with various strategies due to rapidly increasing commercial developments [4, 37]. IMO and the European Commission have some strategy. In 2013, the European Commission adopted an approach linked to previous efforts to reduce greenhouse gas emissions from the shipping industry [4].

The European Commission follows three consecutive strategies for reducing emissions from maritime transport [4];

- Monitoring, reporting, and verification (MRV) of CO_2 emissions from above 5,000 gross tonnes ships using EU ports (MRV Regulation (EU) 2015/757[4])
- Setting new targets for greenhouse gas reduction for the maritime transport sector
- Medium and long-term further new measures to take market-based measures

According to EU-MRV regulation, from 1st January 2018, shipping companies have to share CO_2 emission and other parameters for vessels which are above 5000 gross tonnages (GT) calling at an EU port. The data collected in 2018 can be found online on the European Maritime Safety Agency (EMSA) website [40]. In this thesis, analyzes will be made on these data.

Also, The European Environment Agency shared transport sector CO_2 emission values in 2016. According to this report, the most important source of GHG emissions is from vehicles. Passenger cars are the main reason these types of emissions [20]. The regulations mentioned in the first chapter are part of the strategies. With these regulations, the European Commission sets various targets and follows these targets for new passenger cars.

One of the most prominent strategies in this context is the implementation of penalties. If the manufacturer's average CO_2 emissions exceed the target for a given year, the company must pay the excess emission premium for each registered car. As of 2019, the penalty for each goal exceeding g/km will be 95 euro [5].

The European Commission has established rules for monitoring CO_2 emissions of new cars (Regulation (EC) No 443/2009). According to this regulation, member states are obliged to record information for each new passenger car registered in their country. Each country submits these records to the European Commission. In this report, details such as manufacturer name, specific CO_2 emissions values, engine

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[4] *" Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC."*

capacity and power, fuel type and mode, eco-innovations, and electricity consumption are mandatory. The collected data can be accessed from the European Environment Agency 's database [50].

2.1.1. Monitoring, Reporting and Verification (MRV) System for maritime transport

The European Union (EU) MRV (Monitoring, Reporting, and Verification system) Shipping Regulation 2015/757 (Directive 2009/16/EC) is on monitoring, reporting, and verification of greenhouse gases (especially CO_2) from maritime transport. It was adopted by the EU on 1 July 2015 [4, 40, 51].

The EU-MRV regulation applies to larger ships over 5000 gross tonnages on all voyages to or from EU ports [4]. The shipping companies have to upload the data to the system according to the rules within the scope of this regulation. Regardless of the flag state; for ships voyages to the EEA States (including EU member states, Iceland and Norway) [40]:

- Submit to greenhouse gas monitoring plans to the verifying body (accredited independent verifier under EU-MRV Shipping) for evaluation by August 31, 2017;
- As of 1 January 2018, for each ship CO_2 emissions and other navigational data specified in the rules; It must be monitored and verified annually.

The following timeline shows EU-MRV implementation steps [52]:

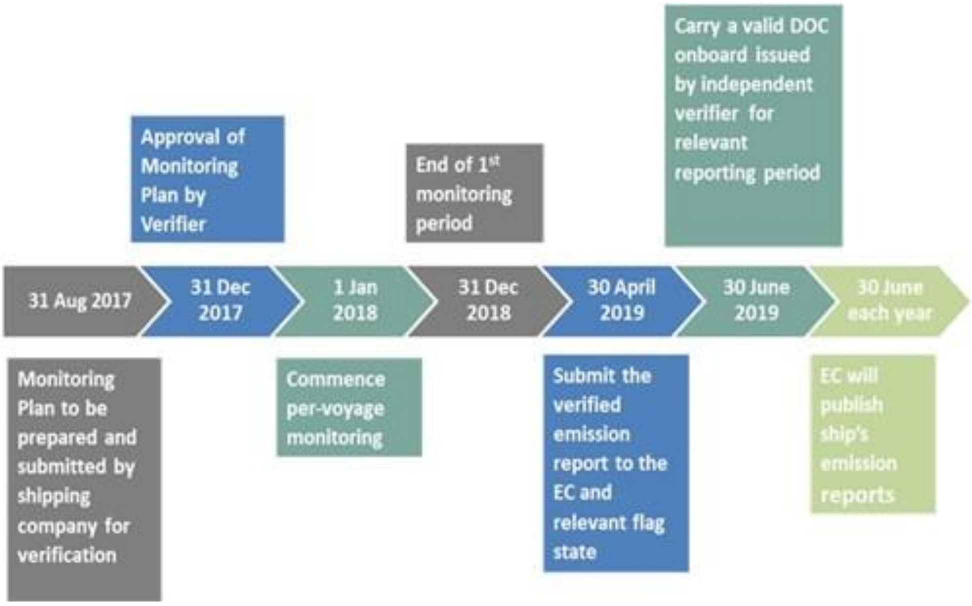

Figure 6. MRV Regulation Implementation Timeline [52]

The European Commission (EC) shares data on the internet by June 30th of each year [4, 40, 51]. The primary data available in the report and to be used in this study are as follows;

- ship name, IMO number, and port of registry or home port;
- ship efficiency (EEDI or EIV, where applicable);
- Total CO_2 emissions (annually);
- Total Fuel consumptions (annually);
- Average fuel consumption and CO_2 emissions per distance traveled of voyages;

- Average fuel consumption and CO_2 emissions per distance traveled and cargo carried on voyages (annually);
- Annual total time spent at sea in voyages.

2.2. Estimation of Emissions from ships

The Third IMO GHG study (2015) shows that maritime transport demand for cargo transported per unit increases rapidly because it is strongly linked to Gross Domestic Product (GDP). Therefore, it is estimated that marine CO_2 emissions will increase significantly [35].

IMO's four Business as Usual (BaU) scenarios estimated an increase of 50% to 250% of CO2 emissions by 2050 with depending on future developments, as shown in Figure 7 [35].

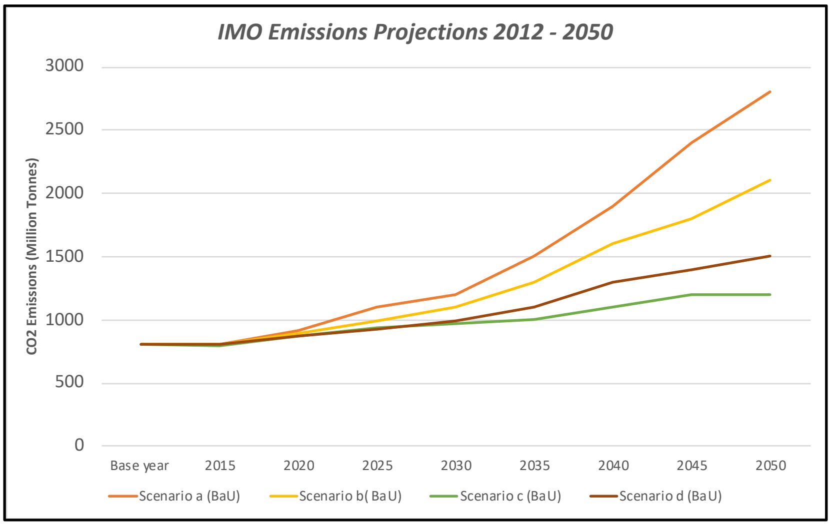

Figure 7. IMO Emissions projections for the BaU transport demand scenarios, based on data from [35]

Figure 6 shows the Third IMO study (2014) projections of emissions growth based on four scenarios with varying assumptions for efficiency improvements from the base year (2012) to 2050. After 2030, CO_2 emissions increase for all situations. The figure also demonstrates that the highest transport demand scenario emits twice CO_2 emissions as significant as the lowest transport demand scenario.

The main reason for this increase is the estimated increase in demand for maritime transport. And also, it will increase the use of fossil fuels. For these reasons, reducing emissions is of significant importance for ships. If emissions reduction actions are not taken, and demand for maritime transport increases more than anticipated, emissions are likely to rise to higher levels [35].

To reduce the estimated increases GHG emissions in maritime transport with growing trade, the measures taken by the European Union and the IMO are of great importance. In addition to greenhouse gas emissions from ship transport, air pollutants also increase. Efforts to reduce greenhouse gas emissions will also reduce air pollutants. The following sections will focus on the measures lowering emissions.

2.2.1. Methods of reducing emissions from ships

2.2.1.1. Energy Efficiency Design Index

IMO aims to make the ship engines and other equipment less polluting, so the Energy Efficiency Design Index (EEDI) is an important topic in maritime transport for new ships. The EEDI measures from operation activities on ships (such as equipment, engines, and labor) and consider of CO_2 emissions reduction. The EEDI is a requirement for new ships from 2013. The purpose of the EEDI is to determine how much CO_2 the ship emits per mile. [38, 61, 62].

Moreover, the EEDI is an index to set down the capable equipment using through its value calculation. This index was developed by IMO and promoted the use of more energy-efficient equipment and engines of ships [61, 62, 66].

According to IMO MEPC resolutions, the below ship types are applicable for EEDI [62];

1. Bulk carriers
2. Gas carriers
3. Tankers
4. Container ships
5. General cargo ships
6. Refrigerated cargo ships
7. Combination carriers

IMO extended the scope of EEDI ship types in 2014. The below ship types are added in addition to the above ships [62].

8. LNG carriers
9. Ro-Ro cargo ships (vehicle carriers)
10. Ro-Ro cargo ships; Ro-Ro passenger ships and cruise passenger ships having non-conventional propulsion

Ships included in the EEDI cover the responsible ship types in 85% of the CO_2 emissions from international shipping [62]. Other ship types are likely to be included in IMO studies in the future years.

The EEDI calculation can be illustrated by the following simplified formula [63];

$$EEDI = \frac{CO_2\ Emission}{Transport\ Work} \qquad (1)$$

Formula 1 can be expressed following that;

$$EEDI = \frac{Engine\ Power * SFC * CF}{DWT * \ Speed} \quad [\frac{gCO_2}{ton-mile}] \quad (2)$$

In where,

- Engine Power [kW], installed power of engine
- SFC - Specific Fuel Consumption [g/kWh], represents an amount of fuel used for engines in an hour
- CF - Carbon Factor [t-CO_2/t-fuel], It is an amount of CO_2 generated per mass of fuel burned
- DWT - Deadweight Tonnage, it is a capacity of vessel that carries full load
- Speed [nm/hour]

The CO_2 emission mentioned in the formula 1 represents CO_2 emissions from the combustion of the fuel, including the main engine, auxiliary engine, and other parameters, taking into account the carbon content of the ammunition used by the ships. If below (Table 4) technologies are applied to ships, they will increase the efficiency of the ships and reduce CO_2 emissions.

Transport work is cargo capacity bringing—this value calculated by multiplying the speed with the maximum ship's load capacity [63]. Therefore, the rate is one of the essential CO_2 emission reduction factors for ship emissions.

Two criteria are important to see if a ship is energy efficient [63];

- Attained EEDI (Real EEDI value for ship)
- Required EEDI (Maximum EEDI value for ship)

The efficiency of a ship can be compared with the following equation;

$$Attained\ EEDI\ \leq Required\ EEDI \tag{3}$$

The efficiency of ships can be easily understood by comparing the Required EEDI to Attained EEDI of the ship. The above formulas (Formula 1 and 2) are used for Attained EEDI calculations. The Required EEDI calculations necessary are available in the other IMO studies [63, 66].

The following table values are reference values for Attained EEDI calculations. These emission factors shared by the IMO are used to calculate CO_2 emissions from fuel consumption. Table 3 shows values for the CO_2 emission elements and the carbon content of fuels [63].

Table 3. CO_2 emission factors and carbon content of fuels, based on data from [63]

No.	**Type of Fuel**	**Reference**	**Carbon Content**	**CF** [t-CO_2/t-fuel]
1	**Diesel/Gas Oil**	ISO 8217 Grades DMX Through DMB	0.8744	3.206
2	**Light Fuel Oil (LFO)**	ISO 8217 Grades RMA Through RMB	0.8594	3.151
3	**Heavy Fuel Oil (HFO)**	ISO 8217 Grades RME Through RMK	0.8493	3.114
4	**Liquefied Petroleum Gas (LPG)**	Propane	0.8182	3.000
		Butane	0.8264	3.030
5	**Liquefied Natural Gas (LNG)**		0.7500	2.750
6	**Methanol**		0.3750	1.375
7	**Ethanol**		0.5217	1.913

For other types of fuels, emission factors should be analyzed in the laboratory. For renewable energy sources (such as biofuel), no detailed information is available. The relevant factors are only used for CO_2 emissions. The effects of other GHG emissions are not included in this table. The reference ships used in this study are assumed to use Heavy Fuel Oil (HFO). For this reason, the carbon factor was taken as 3.114 [tonne-CO_2/tonne-fuel].

The technologies for EEDI reduction identified by IMO are summarized in the table below [64].

Table 4. Technologies for EEDI Reduction, IMO [64]

#	EEDI reduction measure	#	EEDI reduction measure
1.	Optimised hull dimensions and form	9.	Gas fuelled (LNG)
2.	Lightweight construction	10.	Hybrid electric power and propulsion concepts
3.	Hull coating	11.	Reducing on-board power demand (auxiliary system and hotel loads)
4.	Hull air lubrication system	12.	Variable speed drive for pumps, fans, etc.
5.	Optimisation of propeller-hull interface and flow devices	13.	Wind power (sail, wind engine, etc.)
6.	Contra-rotating propeller	14.	Solar power
7.	Engine efficiency improvement	15.	Design speed reduction (new builds)
8.	Waste heat recovery		

Table 4 technologies increase the efficiency of future ships while reducing CO_2 emissions and other emissions. The techniques mentioned in Table 4 can be divided into different groups or more for different ship types. While some technologies are more applicable in the future, and some technologies are appropriate to all ships. For further details, see IMO MEPC 63/INF.2 [64]. In this section, only emission reduction technologies generally accepted by IMO are mentioned.

The techniques mentioned above are generally about reducing the energy required to achieve the desired design speed or reducing the energy use required by reducing the design speed. In general, the design of cargo-carrying vessels (such as Bulk Carriers or tankers) is based on carrying maximum loads with minimum cost. There are also difficulties in applying these techniques to such ships; however, this has been prevented with new technologies. Techniques apply to many types of ships [34].

Many studies have been made on EEDI, which has been a mandatory index for new ships since 2013. One of them is the "*GHG emission reduction potential of EU-related maritime transport and on its impacts*" from TNO report R11601 [34]. It is under a contract of the European Commission.

Four main scenarios related to emission abatement systems were identified, and these were calculated according to reference ships, and the impact of energy efficiency on CO_2 emission was determined in the TNO Report R11601. these scenarios are grouped as follows. The first scenario is the "Baseline." The baseline was shipping characteristics (ship size and efficiency) in 2012. The second scenario is the "Economy of Scale (EOS)." For the EOS scenario, the authors estimated the expected sizes for ships (gradual growth of average ship size). The third scenario is that they used two components together, which are EOS and EEDI. in the last scenario, the authors used three variables (EOS, EEDI, and using different fuel (LNG)) at the same time and it is called Reference[5] scenario[34].

According to the above information, Table 5 was obtained where CO_2 emission values for European maritime transport [34].

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[5] *"The reference scenario included the analysis of the transportation volume, the economic growth rate (4.25% global and 1.55% for Europe annually) and the development of ship specifications (growth of average ship size and implementation of EEDI and LNG as a fuel)"*

Table 5. CO_2 Emission European Maritime Transport for Four Scenarios, (Million Tonne CO_2 per year), based on data from [34]

Year	2012	2020	2025	2030
Baseline	190	215	232	251
EOS	190	209	220	224
EOS + EEDI	190	206	213	210
Reference	190	205	212	208

The values given in Table 5 are a million tons CO_2 per year. According to the Baseline scenario, the CO_2 emissions, which was 190 million tons in 2012, would be 251 million tons in 2030 if no action was taken. When we draw the figure below with the values in the table, the change can be observed better.

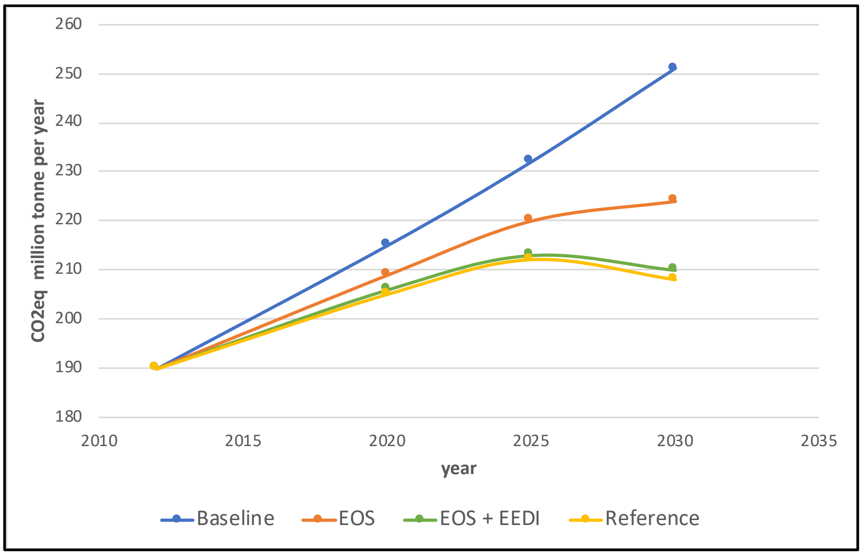

Figure 8. CO_2 Emission European Maritime Transport for Four Scenarios, based on data from [34]

Figure 8 and Table 5 show that in the baseline scenario, CO_2 emissions of maritime transport will be increased almost correctly. When the EOS criteria are applied, the baseline will be reduced by 10%. In the third scenario, EOS and EEDI have been implemented at the same time on ships. CO_2 emissions were expected that there would be a change between 15% and 18% in 2030. The last scenario (Reference) includes the effects of EOS, EEDI, and LNG as a fuel. With this scenario, CO_2 emissions are expected to be around 208 million tons.

The approach applied by TNO will be used in chapter 3 and chapter 4. CO_2 emission reduction rates of newly built ships will be tried to be calculated with reference CO_2 abatement measures.

2.2.1.2. Ship Energy Efficiency Management Plan

According to the decision of the IMO - Marine Environment Protection Committee (MEPC) 62. term meeting (July 2011), Ship Energy Efficiency Management Plan (SEEMP) certificate is mandatory for all ships to use the energy used efficiently and to leave a clean world. The SEEMP is a plan that helps shipowners increase the energy efficiency of their ships. The SEEMP is mandatory for all international ships over 400 gross tonnages (GT) from 2013 [62, 67].

The SEEMP specifies the energy-saving measures undertaken and how effective these measures are for improving energy efficiency. It also defines what actions can be applied to further improve the energy efficiency of ships [62, 67].

It is encouraged to allocate enough time to the SEEMP to develop the most appropriate, effective, and feasible plan for a ship. The technologies for SEEMP reduction identified by IMO are summarized in the table below [64].

Table 6. Technologies for SEEMP reduction, IMO [64]

#	SEEMP reduction measure	No.	SEEMP reduction measure
1	Engine tuning and monitoring	6	Trim/draft
2	Hull condition	7	Voyage execution
3	Propeller condition	8	Weather routing
4	Reduced auxiliary power	9	Advanced hull coating
5	Speed reduction (operation)	10	Propeller upgrade and aft body flow devices

The above SEEMP measures are significant to improve the energy efficiency for ships. New operational technologies could be included in a SEEMP measure. The marginal abatement cost Curves, which will be used in the following chapters, will show other technologies besides these technologies, and cost-effectiveness will be better understood.

2.2.1.3. Energy Efficiency Operational Indicator

An Energy Efficiency Operational Indicator (EEOI) is a voluntary guideline for ships. While EEDI calculates the energy efficiency value according to the design of the ship, EEOI shows how the ship can be more efficient. The primary source of CO_2 emissions from ships is the combustion of fuels, and EEOI can also provide information on a ship's fuel efficiency [62, 65, 68].

Developed by IMO, EEOI is one of the internationally established tools for obtaining a numerical indicator of the energy efficiency of a working vessel or fleet. It is recommended that the EEOI be calculated in accordance with the Guidelines (MEPC.1/Circ.684) developed by IMO and that it can be adjusted to a specific ship or commercial operation if necessary [62, 68].

2.2.2. Emission reduction options

The most critical work to reduce CO_2 emissions is to increase energy efficiency. Accordingly, in the Second IMO GHG Study 2009, the following table was created to minimize CO_2 emissions from ships. This table consists of two parts. The first section shows the measures and techniques to be taken during the construction of new ships. The second section shows the operational and technical measures [55].

The following table shows the saving of CO_2 emissions due to energy efficiency by using existing technologies [55].

Table 7. Reductions of CO_2 emissions by using existing measures (%), based on data from [55]

Reduction Option	**CO_2 Reduction per tonne Nautical mile**	**Combined**	**Combined**
Design (New ships)		10% to 50%*	25% to 75%*
Concept, speed and capability	2% to 50%*		
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%		
Low-carbon fuels	5% to 15%+		
Renewable energy	1% to 10%		
Exhaust gas CO_2 reduction	0%		
Operation (All Ships)			
Fleet management logistics and incentives	5% to 50%*	10% to 50%*	
Voyage optimization	1% to 10%		
Energy management	1% to 10%		

** "Reductions at this level would require reductions of operational speed"*

+ "CO_2 equivalent, based on the use of Liquefied Natural Gas (LNG)"

2.2.3. Emissions abatement curves for ships

Combustion in engines that convert fuel into power and exhaust gases is often the primary source of GHG emissions. Solutions to reduce GHG emissions and their impacts have been part of many studies [34]. The most effective methods proposed in most of these studies are presented with Marginal Abatement Cost (MAC) curves. The MAC curves show reduction potentials for ships. Cost-effective potential can be calculated with marginal abatement costs.

2.2.3.1. Marginal Abatement Cost (MAC) Curves

Various options are available to reduce greenhouse gas emissions from ships, such as propeller polishing, autopilot, weather routing, speed-controlled pumps, lighting, solar panels, etc. Marginal abatement cost curves are used to compare methods to reduce greenhouse gas emissions from ships [56, 57, 58]. The MAC curves technically allow comparison of emission reduction options. The MAC curve provides information about reducing cost and reduction potential for mitigation measures [57].

Generally, the Marginal Abatement Cost (MAC) curves measure the cost of reducing a unit of pollution. We can assume our volume and cost of opportunities by looking at these MAC curves to reduce greenhouse gas emissions [59].

The MAC curves are defined as a figure that usually shows the cost in terms of currency per tonne CO_2 emissions (€/tCO_2), depending on the amount of emission reduction (typically yearly cumulative tonnes of CO_2 emissions) and the marginal cost. Therefore, such a figure compares the marginal reduction cost on the Y-axis and the emission reduction level on the X-axis [60].

The below figure shows an overview of Marginal Abatement Cost (MAC) curves [57].

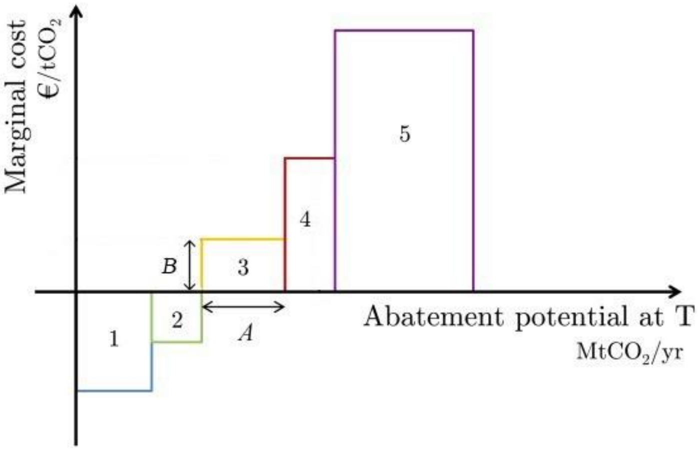

Figure 9. Classic stepwise marginal abatement cost curves

Figure 9 shows that MAC curves are divided into discrete boxes (or measures). Each box represents an individual or a set of similar carbon reduction opportunities. The width of the box (in the figure: “A”) shows emissions reduction potential. The height of each box shows (in the figure: "B") the average net cost of abatement one tonne of CO_2. Furthermore, the boxes in the figure are ordered from the lowest cost to the highest cost. Generally, the values on the X-axis represent cumulative effects which means the impact of the last method is shown on the effect of the previous process.

2.2.3.2. Previous studies of marginal abatement cost curves for ships

IMO did one of the most critical studies on the CO_2 emissions reduction potential of ships. The following steps are followed to show the marginal abatement cost (MAC) curves for the ships. These steps were developed by IMO (MEPC 62/INF.7). Each step is described as follows [70].

Table 8. IMO - Marginal Abatement Cost Method Six Steps [70]

Step	Marginal Abatement Cost Calculation Method	Remarks
1	**Identification of CO_2 abatement technology.**	Identify technologies and operational measures.
2	**Calculation of the cost-effectiveness of individual measures**	This is also referred to as marginal abatement costs (MAC)
3	**Evaluation of the sensitivity to input parameters**	Fuel prices and discount rates, etc.
4	**Identification of constraints and barriers to implementation**	The technical barriers
5	**Rank ordering technologies**	The rank-ordering ship type, size, and age, etc.
6	**Calculation of MACC as a function of ship type**	Plot MAC curves

The steps mentioned above are determined for different ship types. These include installation and operation, purchase, etc. cost. In total, IMO (MEPC 62/INF.7) [70] analyzed the marginal abatement costs associated with each measure such as types, sizes, and age combinations for 318 ships. Then the prices of each combination are listed. A simplified version of the equation used in the calculations is as follows [56, 69, 70];

$$MAC = \frac{\Delta C_j}{\alpha_j * CO_2} = \frac{K_j + S_j - E_j + \sum O_j}{\alpha_j * CO_2} \quad (4)$$

In where;

- ΔC_j = Capital Cost
- K_j = ΔC_j discounted by the interest rate and service years
- S_j = Service cost of the measure
- E_j = Energy savings from that energy-saving measure, which is a product of the price of energy and the saving of energy
- $\sum O_j$ = Opportunity cost related to lost service time due to the installation of the energy-saving measure and the discounted costs related to alternative uses of capital.
- α_j = Energy reduction rate of energy-saving measure j
- CO_2 = Original CO_2 emissions from a ship

Using the relevant formula, ICCT has prepared a report [69]. In the study conducted by ICCT, analyzes were made according to marginal abatement costs according to 15 different categories. The following figure shows the effects of CO_2 emissions reduction and marginal abatement cost by ship type [69].

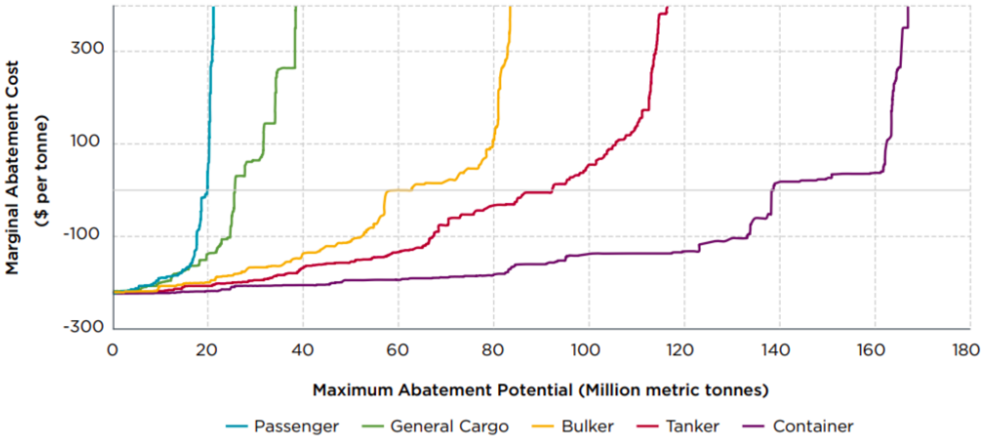

Figure 10. Central estimate of abatement potential by ship type [69]

Figure 10 was made for five different ship types, and the increase in Marginal abatement cost compared to the measures used was shown. Emission reduction methods are less useful for passenger type ships, while CO_2 emissions can be significantly reduced for container type ships at lower costs.

The below figure shows the effects of the reduction significance applied to the five primary ship types.

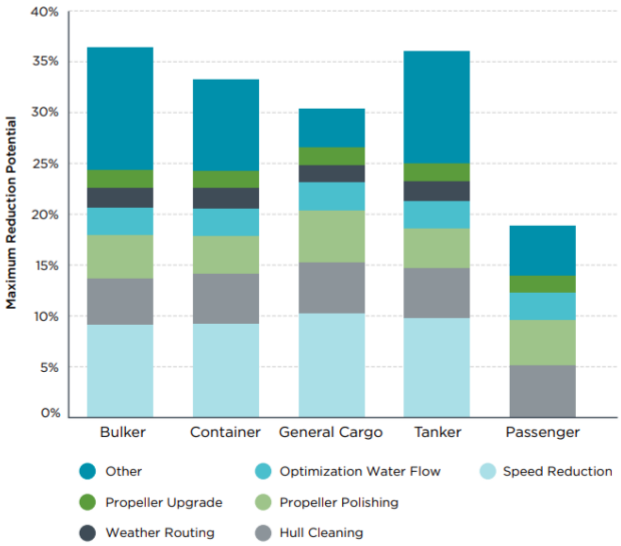

Figure 11. CO_2 abatement measures by ship types [69]

Figure 11 shows speed reduction is beneficial for CO_2 emissions. The reduction measure can use for all ship types except passenger ships. On the other hand, if all abatement measure use on the ships (except Passenger ships) achieved more than a 30% CO_2 reduction.

On the other hand, the Marginal Abatement Cost (MAC) curves prepared by ICCT for different reference ships will be as follows. For example; Propeller polishing has the lowest average MAC value with average CO_2 reduction potential. Speed reduction has the most significant reduction potential at a moderate cost [69].

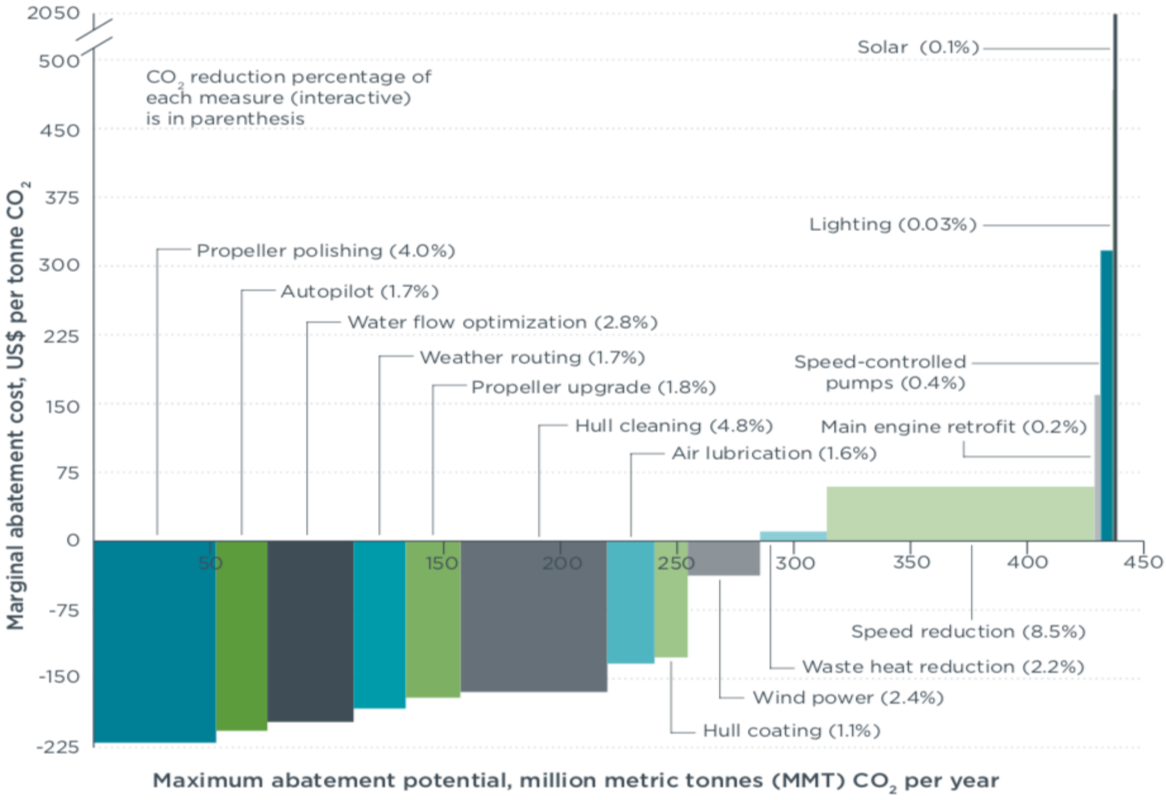

Figure 12. Marginal Abatement Cost (MAC) Curves options for ships [69]

According to Figure 12, the technologies described above to improve ship efficiency are quite cost-effective. Each box represents an individual or a set of similar carbon reduction opportunities. The width of the box represents emissions reduction potential from the ships. The height of each box represents the weighted average cost of abatement one tonne of CO_2. For instance, Autopilot (a 1.7% efficiency gain), propeller upgrade (a 1.8% efficiency gain), and speed reduction (an 8.5% efficiency gain). However, The speed reduction has positive MAC value, which means CO_2 emission will be a reduction, but our investment has a negative net present value. Furthermore, the boxes in the figure are ordered from the lowest cost to the highest price [56, 59].

These MAC curves show the shipowners and companies with the most precise possible CO_2 emissions of reduction potential. Likewise, with these MAC curves, ship efficiency will be increased, and they will be entitled to receive certificates issued by IMO. It is possible to come across different mac curves prepared by various authorities. MAC curves for CO_2 emissions may differ from the difference in techniques used. However, it is clear that emission reduction techniques increase the efficiency of ships and reduce the impact of harmful gases.

2.3. Estimation of emissions from Cars

With the rapidly increasing number of cars in the world, cars-generated exhaust emissions cause serious problems. Failure to control exhaust emissions to the atmosphere will make the planet uninhabitable. At this point, the increasing limitation of exhaust emission standards leads researchers and engine manufacturers to develop systems that can be used to reduce car-generated exhaust emissions. The European Union (EU) recently has a target of 95 gCO_2/km in 2021 for CO_2 emissions for new passenger cars. Significant importance must be taken to achieve this goal [72]. In the first chapter (see section 1.2.2), general information about CO_2 emissions of passenger cars with the European Union is given. In this section, the situation forecast will be discussed.

According to the ICCT latest report (August 2019), the below figure shows historically CO_2 emission values and targets [71].

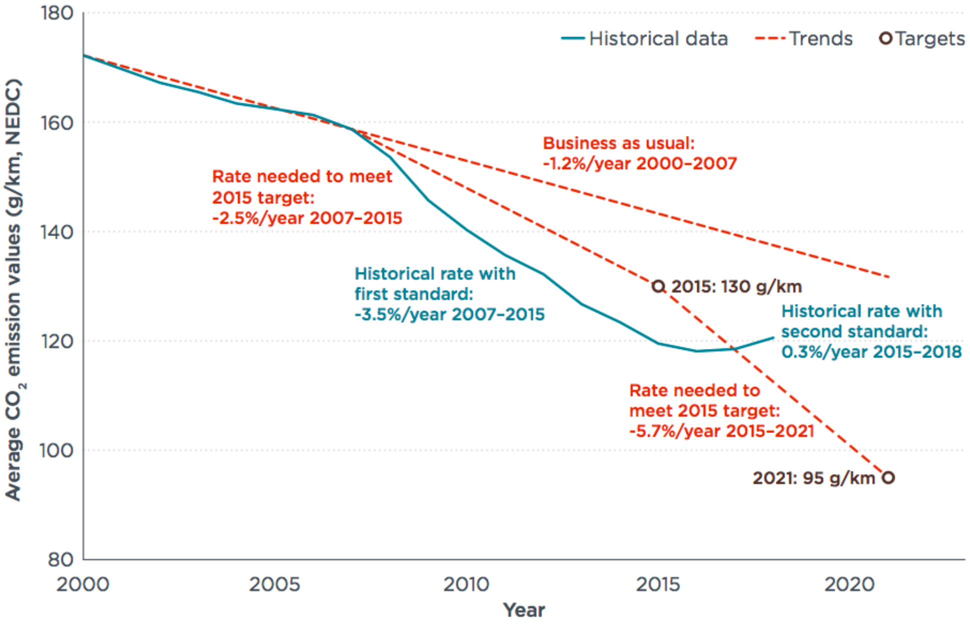

Figure 13. Historical average CO_2 emission values, targets, and annual reduction rates of new passenger cars in the EU [71]

Figure 13 shows that emissions from passenger cars have declined rapidly since 2008 due to European Union targets and significant actions taken. Due to the targets taken since 2008, emissions decreased by 3.5% with the actions taken by the car manufacturers. The 2015 targets were achieved in this way. As of 2018, emissions from passenger cars are expected to decrease by 7.6% to reach the 2021 targets [71].

The target of the European Union for GHG emissions in 2030 is to reduce by at least 40% compared to 1990. One of the essential systems is the EU's Emissions Trading System (ETS). The ETS is a crucial system to reduce GHG emissions from large-scale facilities in the power and industry sectors, as well as the aviation sector. Around 45% of the EU's GHG emissions are covered the ETS.[4, 14]. This system does not apply to the Transport sector but plans to reduce GHG emissions by at least 30% to 2030 by baseline 2005. The importance of the European Union includes passenger cars, vans, and light-duty vehicles [73].

Future estimations of emissions from cars in the European Union were made considering various importance in the report prepared by ICCT [73]. Even with these considerations, it is predicted that a satisfactory result will not be achieved, and only the use of other means of transport is expected to reach the targets for CO_2 emissions.

The below figure shows the estimation of CO_2 emissions from cars in the EU [73];

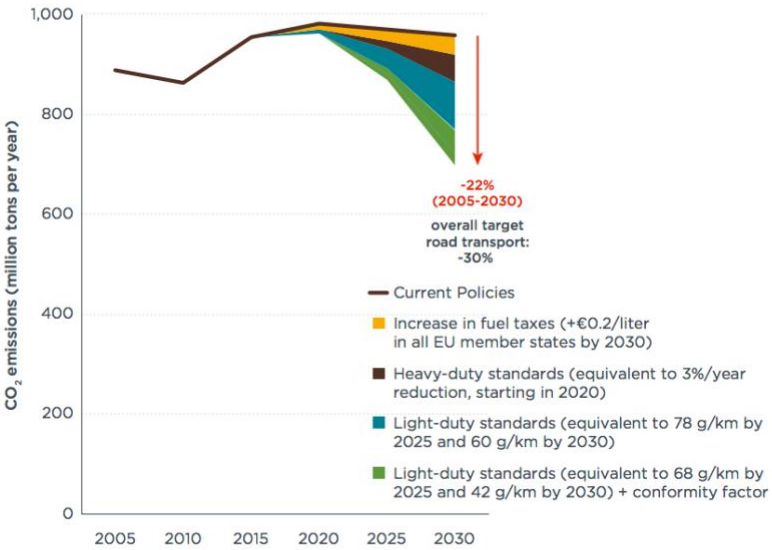

Figure 14. Annual CO_2 emissions from passenger cars, light-commercial and heavy-duty vehicles in the EU [73]

Figure 14 shows the annual CO_2 emissions from passenger cars, light commercial vehicles, and heavy-duty vehicles in the European Union. Considering 2005 (base year), it is expected that there will be a 22% decrease, according to the ICCT study. In addition, the graph shows us that a sufficient reduction cannot be achieved with the current policies, but that the reduction rate of CO_2 emissions can be increased by increasing fuel taxes and making new plans for other types of cars.

2.3.1. Previous studies marginal abatement cost curves for cars

The MAC curves have been used in different studies in cars, just as on ships. The most notable of these is Chine's road transport analysis between 2010 to 2050. In Chine, a case study was carried out to reduce CO_2 emission on road transport due to the increasing traffic density and a comparison was made for the following cars [74]. Car types used:

- Heavy duty trucks (HDTs)
- Medium duty trucks (MDTs)
- Light duty trucks (LDTs)
- Mini trucks (MTs)
- Heavy duty buses (HDBs)
- Light duty buses (LDBs)
- Cars (Passenger Cars)
- Minivans (MVs)
- Motorcycles (MCs)

Besides, four different fuel types were used for the analysis: gasoline, diesel, liquefied petroleum gas (LPG), and condensed natural gas (CNG). According to the results of the study, in 2050, MAC curves are as follows [74].

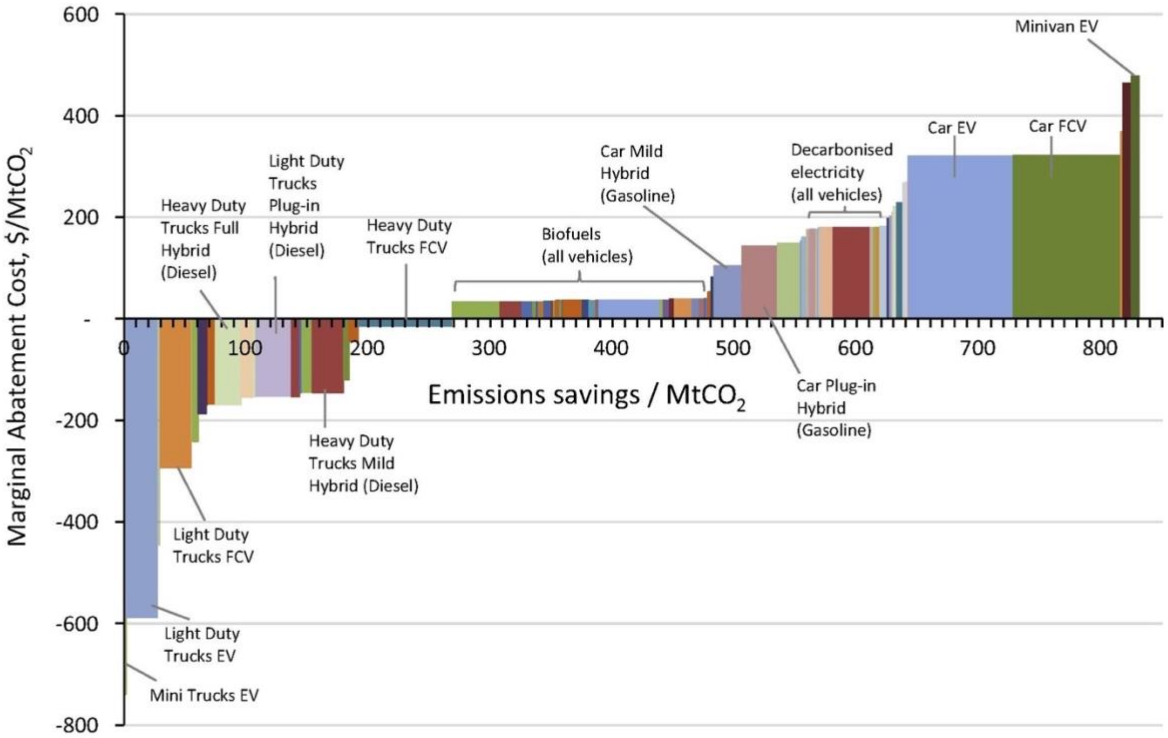

Figure 15. Marginal abatement cost curve for cars in 2050[6] [74]

According to Figure 15, the essential CO_2 emission reduction potential was found for cars with the broadest range in the figure. Passenger cars and heavy-duty trucks are at an important place for future CO_2 emission reduction. However, trucks appear to be significantly lower costs than passenger cars. The area under the MAC curves represents the total additional annual cost in 2050, to the low-carbon scenario compared to standard scenarios as usual. This cost $64 billion for Chine (US2010). A 5% discount rate was used for calculations [74].

A similar study can be done in Europe. The cost-benefit analysis of measures to reduce future CO_2 emissions for different vehicle types can be easily observed. In this study, MAC curves were created for the different types of ships, and it was tried to show the effects of the measures used to reduce CO_2 emissions.

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[6] *"All cost figures in USD2010; EV = Electric Vehicle; FCV = Fuel Cell Vehicle; Colors/shading for clarity only (i.e. different abatement options are not color-coded). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)910A. Gambhir et al./Applied Energy 157 (2015) 905–917 [74]"*

3. Cost-Benefit Analysis

In this chapter, various emission abatement measures will be shared. The marginal abatement cost calculations will be made for these measures. Analysis results were shown with Marginal Abatement Cost (MAC) curves. Besides, CO_2 emissions will be estimated using EU-MRV data by 2050.

3.1. EU – MRV System data analysis for maritime transport

The importance and details of the EU-MRV system were discussed in chapter two. EU-MRV publication information is one of the primary sources used in this thesis study. Thanks to this data, the reference ships were tried to be estimated. According to EU-MRV public data [40], economic analyzes (the cost-benefit analysis) were trying to be made. According to the relevant data, the value of CO_2 emissions in the European Economic Area (EEA) was presented to be around 139 million tonnes in the reporting period [40]. Total fuel consumption [million tonnes] and CO_2 emissions (million tonnes) values by ship types are detailed in the table below.

Table 9. EU-MRV Maritime transport summary table, base data from [40]

Ship Type	Number of Ship	Sum of Total fuel consumption [million tonnes]	Sum of Total CO_2 emissions [million tonnes]
Bulk carrier	3701	5.73	17.98
Chemical tanker	1314	2.92	9.18
Combination carrier	7	0.03	0.08
Container ship	1750	14.08	44.20
Container/ro-ro cargo ship	77	0.51	1.61
Gas carrier	306	0.79	2.45
General cargo ship	1088	1.90	5.97
LNG carrier	198	1.90	5.47
Oil tanker	1821	5.74	18.06
Other ship types	116	0.34	1.05
Passenger ship	148	2.03	6.37
Refrigerated cargo carrier	145	0.57	1.78
Ro-pax ship	350	4.31	13.83
Ro-Ro ship	260	1.92	6.05
Vehicle carrier	448	1.63	5.10
Grand Total	**11729**	**44.40**	**139.19**

The details of the version of EU-MRV data used in this study are as follows.

- Data version: 2018-v87-19102019-EU MRV Publication of information [40]
- Data are available for 15 different ship types (over 5000 gross tonnages ships). The types of these ships are shown in Table 9.
- The total number of ships is 11,729.
- The sum of total CO_2 emissions from all ship types is around 139 million tonnes.

- The amount of total fuel consumption from all ship types is approximately 44 million tonnes.

Also, the following graph was created to view the correlation between the number of ships and CO_2 emissions over the relevant data.

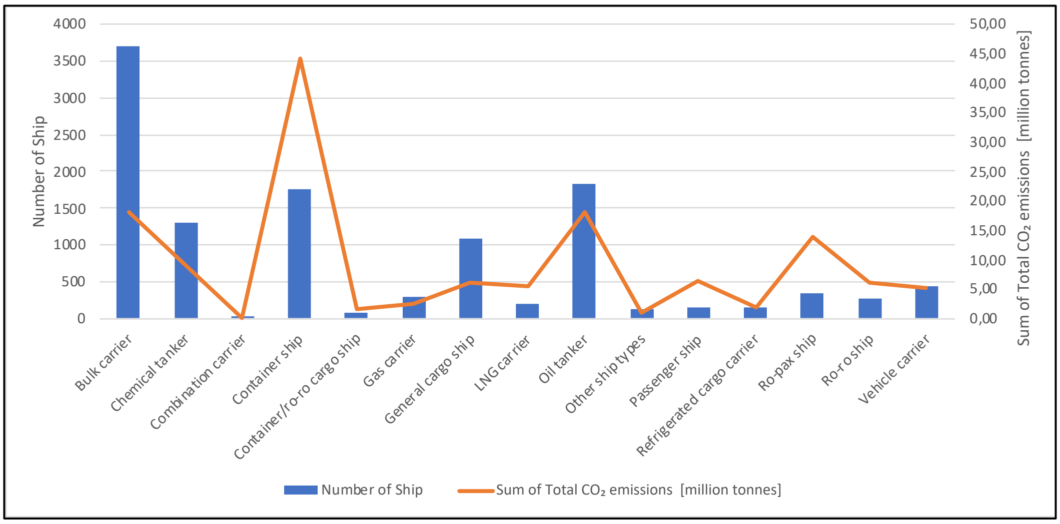

Figure 16. Correlation of number of ship vs total CO_2 emissions per ship type, base data from [40]

Figure 16 shows the emissions of CO_2 emitted by ship type. There is no correlation between the number of ships and the emissions of CO_2. Accordingly, it is concluded that analyzes should be made on ship types, not numbers. Using ship types in the analyses is a more effective method to reduce CO_2 emissions.

Consideration of total CO_2 emissions per ship type the following ship types are causing around 95% CO_2 emissions on all voyages to or from EU ports; Container, Oil tanker, Bulk carrier, Ro-Pax ship, Chemical tanker, Passenger (Cruise) Ship, Ro-Ro & Vehicle carrier, General cargo ship and LNG carrier. Ro-Ro ships and Vehicle carriers are considered in the same category. The ratios between ship types and CO2 emissions were also analyzed with Python programming [104] as follows.

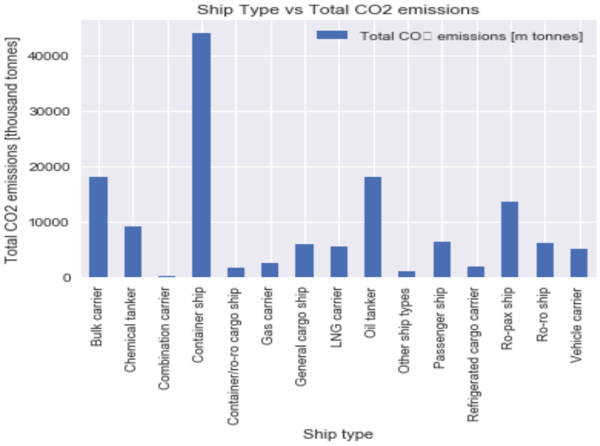

Figure 17. Ship Types vs Total CO_2 emissions [metric tonnes], base data from [40]

Statistical analysis of big data can be done quickly with Python programming. Data analysis was made with this application for also EU-MRV data. The details of these analyzes are available in Appendix 5. The following libraries were used for these analyzes.

- `import pandas as pd`
- `import numpy as np`
- `import matplotlib.pyplot as plt`
- `import seaborn as sns`
- `import matplotlib as mpl`

These libraries are the most common libraries used for data analysis in Python.

3.2. Maritime transport treads up to 2050 in Europe

According to TNO Report R11601 [34], freight works are expected to double till 2030 (the base year 2012). The results of this report were mentioned in chapter two. In this thesis, the period up to 2050 years was estimated for the European Economic Area (EEA). The EU-MRV data were used for calculations. The EU-MRV used 2018 as a base year [40]. Base year values are used in calculations according to the relevant data version.

Some reference values (like GDP) need to be obtained from previous studies to make future predictions about CO_2 emissions. Based on the estimations made by the European Union and diverse organizations, analyzes are made in the following sections.

3.2.1. Prediction of freight works up to 2050

One of the first variables to be used for these calculations is freight works. There are many different sources for future freight works estimation, and it can be uncertainty in the estimated values. However, the OECD report published in 2019 was used for the consistency of the data [75]. According to OECD transport outlook 2019; estimated values are as follows;

Table 10. Estimated growth rates of freight transport demand annually (%) [75]

Freight Works	2015-2030	2015-2050
Rail	2.7	2.5
Road	3.5	3.2
Inland Waterways	3.4	3.8
Aviation	5.5	4.5
Sea	3	3.6
Freight Transport Demand	3.1	3.4

The above table shows all the transport sector annual growth rate for two different estimated period. According to these reports, especially maritime transportation will increase by 3.6% annually, and that means maritime transport will grow threefold between 2015 to 2050. It is estimated that there will be a growth in this rate among general freight works in the same report. As mentioned in the same statement, ships are expected to perform more than three-quarters of all product movements by 2050 [75]. Since there will be a correct proportion between CO_2 emissions with the increase of demand, it is evident that if action is not taken, it will cause pollution at this rate.

3.2.2. Prediction of GDP up to 2050

The second most important variable to be used for these calculations is the GDP. If an estimate will be made for the future; GDP is one of the best reference points. It is seen that GDP is taken as a reference in the TNO Report R11601 [34] and the Third IMO GHG Study [35]. For this reason, the European GDP growth rate was used in calculations. The annual rate of increase in GDP actually represents the rate of increase we will use for baseline. The 2018 Ageing Report (EU) calculated the expected future EU growth rates [76]. Table 11 shows the GDP rates as a percentage.

Table 11. Potential GDP annual growth rate (%), based on data from [76]

	2016-2020	**2021-2030**	**2031-2040**	**2041-2050**	**2016-2050**
Euro Area (EA)	1.2	1.1	1.1	1.4	**1.2**
EU	1.4	1.3	1.3	1.4	**1.35**
EU27	1.4	1.2	1.2	1.3	**1.28**

The values given in the table are the average values between the relevant years. Values in columns 2016-2050 were calculated by taking the arithmetic average of the values in the report. The 'EU' row value between the years 2016-2050, which is 1.35%, is used for calculations. The Baseline calculation is being made with this value.

3.2.3. CO_2 emissions scenarios up to 2050

Emissions are directly proportional to the size and speed of the ships. In the IMO study and TNO Report R11601, it is seen that there will be no significant change in the speed of the ships for the future. However, the increase in the average ship capacity (DWT) of the ships is an essential factor for emissions [34, 35]. However, it was assumed that the speed and size of all ships had the same characteristics in this chapter estimations, and therefore the effects of these two factors were considered constant. Different calculations can be found by observing these factors in future studies.

In light of the data described in the previous sections, the following five different scenarios were created. These five different scenarios were calculated from 2018 to 2050.

1. Baseline: CO_2 emissions with the 2018-2019 period in EU-MRV data
2. IMO Best projections: The best-case projections (BaU) for depending on future economic and energy developments up to 2050 in the Third GHG IMO Study [35]
3. IMO Worst projections: The worst-case projections (BaU) for depending on future economic and energy developments up to 2050 in the Third IMO GHG Study [35]

4. OECD projections: The value that OECD estimates for freight works are thought to be proportional to the increase in CO_2 emissions [75].
5. EEDI & SEEMP Effect: CO_2 emission with EEDI and SEEMP implemented

When we view the above-given methods in more detail;

- **Scenario 1:** Baseline

Baseline (2018-2019) estimates that freight works will increase with GDP. It is assumed that the increase in freight work increases CO_2 emissions in direct proportion. According to section 3.2.2, the annual GDP growth rate is used in this section as 1.35%. The following calculation method can be used for the baseline to estimate future years' CO_2 emission.

$$FutureCO_2 \cong BaseCO_2 + (BaseCO_2 * GDP\ growth\ rate\%) \quad (5)$$

For instance; if we want to calculate 2020 CO_2 emission; (Baseyear (2018 to 2019) = 139 million tonnes)

2020 CO_2 Emissions $\cong$ 139 + (139*1.35%) = 141 (million tonnes)

- **Scenario 2 & Scenario 3:** IMO Best & Worst projections

According to the Third IMO GHG Study (2014) [35], different scenarios were handled up to 2050, and CO_2 emissions were estimated. According to these estimates, it has been observed that there will be a CO_2 change between 50% and 250%. These scenarios have been rated by IMO based on future economic and energy developments. Also, these are estimated for all existing ships. In this study, an estimate has been made using these data for European ports. All scenarios are Business as Usual (BaU) scenarios.

Table 12. IMO CO_2 emissions best and worst projections (BaU), base data from [35]

Scenario [million tonnes]	2015	2020	2025	2030	2035	2040	2045	2050
IMO Worst projection (BaU)	810	910	1100	1200	1500	1900	2400	2800
IMO Best projection (BaU)	800	870	940	970	1000	1100	1200	1200
Variation for Worst projection (%)	-	12	36	48	85	135	196	250
Variation for Best projection (%)	-	7	16	20	23	36	48	50

- **Scenario 4:** OECD projections

The value that OECD estimates for freight works are thought to be proportional to the increase in CO_2 emissions [75]. Calculations, according to this ratio are calculated just like in the first scenario (formula 5)—the growth rate used as 3.6% annually. The demand for freight works, or shipping, is increasing rapidly.

- **Scenario 5:** EEDI & SEEMP Effect

The importance, measures, and other details of EEDI and SEEMP were shared in chapter two. The EEDI and SEEMP is briefly a necessary regulative tool on ships to improve energy efficiency on ships and reduce ship emissions. Besides, in the same section, a previous study (TNO Report R11601 [34]) and the effect of EEDI were presented. In this study, the data in the TNO and IMO studies [34, 35, 55] were combined, and the following values were taken as reference. The positive effect of CO_2 emissions on the increase in the baseline emissions was calculated.

- The TNO Report R11601 expected impact of EEDI is 5 to 8% until 2030, and this percentage values can increase after 2030 [34].
- According to the Third IMO GHG study, EEDI + SEEMP efficient values estimated between 0-22.5% till 2030 (the base year 2012). Due to the technological developments after 2030 and the lifetime of the existing ships, highly productive new ships are expected to be produced. Therefore, two different predictions were made for EEDI and SEEMP data after 2030[35].

An average value was calculated according to the data of these two different sources, and it was assumed that the effects increased in this value range until 2030. Since the SEEMP effect will decrease over the years, calculations can also be considered as the EEDI effect in. Moreover, since TNO values are for Europe, the weight of these values is taken as 60%, and IMO values are taken as 40%.

$$Weighted\ Average = \frac{(w_1 n_1 + w_2 n_2 + w_3 n_3 + \cdots w_k n_k)}{(w_1 + w_2 + w_3 + \cdots w_k)} \qquad (6)$$

When calculations are made according to the above formula, the Table 13 is obtained.

Table 13. EEDI and SEEMP Efficient

	Efficient of EEDI&SEEMP	Weight	Weighted Average
TNO Min	5%	60	3%
IMO Min	0%	40	
TNO Max	8%	60	14%
IMO Max	22.5%	40	

The values given in the table are distributed linearly in a way that increases according to the years. It is assumed that a 14% value has 50% more useful for the period after 2030. In other words, it is assumed that it will affect about 22% in 2050.

3.2.4. Estimation of CO_2 emissions results up to 2050 in Europe

Based on the information shared above, the CO_2 emissions were estimated for Europe. For the EEDI + SEEMP scenario, interim years were assumed to increase cumulatively every year, with a reference of 3%. The reason for this is the increasing number of EEDI reference ships and the assumption that more new ships will be used in sea transportation. According to the years prepared accordingly, the table is as follows;

Table 14. Estimation of CO_2 emissions results up to 2050 in Europe

Year	2018	2020	2025	2030	2035	2040	2045	2050
Baseline	139	141	151	161	172	184	197	211
IMO Best projection	139	149	161	166	172	189	206	209
IMO Worst projection	139	156	189	206	257	326	411	487
OECD projection	139	144	172	205	254	292	349	416
EEDI & SEEMP Effect	139	141	139	139	145	151	158	164

Baseline values given in the table are calculated according to a 1.35% GDP rate. Accordingly, it is expected that freight works, and CO_2 emissions will increase by 52% until 2050. CO_2 emissions will be about 211 million tonnes. Also, two different scenarios were made according to the Third IMO GHG Study [35] references. IMO best protection is almost the same with the baseline scenario, but IMO worst protection CO_2 emission will be by nearly 500 million tonnes. Also, it is seen that CO_2 emissions for OECD will increase by 200% compared to the base year. If EEDI and SEEMP are applied to all ships according to baseline, emissions are estimated to decrease by 22% in 2050.

The reason for making these estimates will be to demonstrate the effect of new emission reduction measures to be applied to ships in reducing their emissions from ships. Different scenarios are shown according to the methods selected in the last part of the thesis.

The graphs showing the emissions according to Table 14 is as follows.

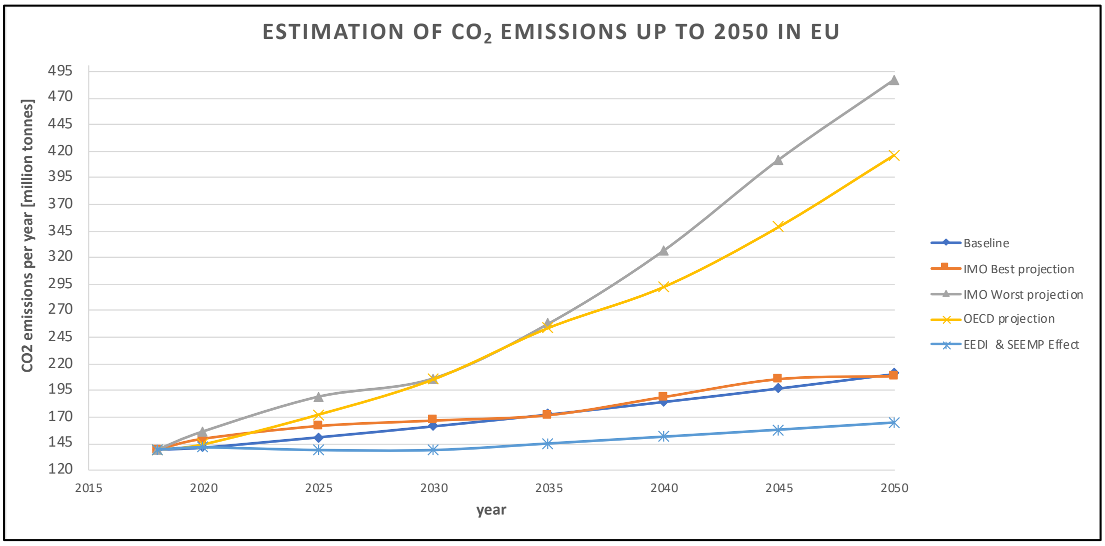

Figure 18. Estimation of CO_2 emissions up to 2050 in EU

3.3. CO_2 emissions abatement measures, costs, and curves

There are many different sources in the literature on the reduction of ship emissions and the details of the measure to use. However, there are not enough resources on the economic analysis of these effects. In this thesis, emission reduction methods and their financial report have been reviewed, and many references have been exploited. One of the most critical studies among them is IMO "*MEPC 62 / INF.7*," which name is "*Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures*" [70]. One of our second reference points is the final report published by TNO in 2014; its name is "*GHG emission reduction potential of EU-related maritime transport and on its impacts*" [34]. Besides of them, the ICCT - "*Reducing Greenhouse Gas Emissions from Ships Cost-Effectiveness of Available Options*" (white paper - 2011) [69] and CE Delft – "*Analysis of GHG Marginal Abatement Cost Curves*" (2011) [58] reports show economic analysis of reduction technologies over MAC curves.

The main focus of this study is on the cost-benefit analysis of the effects that reduce fuel consumption per freight works in European Maritime transport. Reducing fuel consumption will also reduce CO_2 emissions. The price of CO_2 emissions per tonne and the cumulative annual CO_2 emission reduction potential will be shown with marginal abatement cost (MAC) curves. At the same time, reducing fuel consumption may prevent it from spreading in other harmful gases.

In the following sections, firstly, the calculation methods used for the cost-benefit analysis were mentioned. In chapter 2, the emission reduction methods shared by IMO are combined with the measures and data shared in other studies. After, MAC curves were obtained according to reference ships.

3.3.1. Concept of the calculation and assumptions

The Marginal Abatement Cost (MAC) curves are a tool to decision making that provides a simple way of identifying which measures are the most cost-effective per unit of CO_2 emissions abated and which measures offer the most significant abatement potential. In the second chapter (see section 2.2.3.1), there are details about MAC curves. In this section, the formulas to be used in calculations will be mentioned. The MAC curves subject to the thesis were calculated with these formulas.

3.3.1.1 Net Present Value (NPV)

Net Present Value (NPV) is the present value of investment cash flows that is lower than the cost of obtaining the asset. The NPV can be positive (a net saving) or negative (a net loss). Investors want to invest in investments where the NPV value is positive. Positive NPV means that it intends to make maximum profit. Suitable investments are those where the return rates are higher than the opportunity cost. [79]. The following formula (7) is used for NPV calculations.

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - Investment \qquad (7)$$

If we examine the variables in the formula in more detail;

- Net Present Value (NPV)
- Investment is the investment cost of technology (t=0)
- The cash flow (CF_t) is net cash inflow-outflows during a single period t
- The lifetime of the technology or investment (t) is the number of years for which the measure is expected to reduce the CO_2 emissions reduction. The lifetime of technologies has been estimated to be the same as ship lifetime for most reduction measures. The standard lifetime of a ship is 25 years.
- Discount Rate (r) is applied to NPV calculations to allow for the diminishing value of money over time.

A euro earned in the future is not worth as much as a euro earned from the present time. The discount rate is one way of explaining it via NPV formula [91]. Discount rate calculation is one of the essential variables for cost-benefit analysis and MAC curves.

3.3.1.2 Discount rate to use in estimate MAC curves

It is crucial to choose the appropriate discount rate to determine the Marginal Abatement Costs (MAC) accurately. The discount rate also is known as the cost of capital, opportunity cost, or the weighted average cost of capital (WACC). Discount rates vary depending on the risk (uncertainty) of expected cash flows. The series of risk-free cash flows will be discounted at the lowest discount rate [70]. Typical discount rates could be 3% in the public sector and 9% in the private sector [78]. However, these values vary by sector type. An exclusive discount rate account for the Shipbuilding & Marine industry will provide more reliable results in MAC curves analysis.

To obtain more consistent results, I used the discount rate (Cost of Capital) values in my thesis according to the values I value from Prof. Damodaran's online page [92]. According to the most recently updated data (on 5 January 2020), the table below was created concerning the regional datasets and formula 8 [92].

$$Cost\ of\ Capital = Cost\ of\ Equity * \left(\frac{E}{D+E}\right) + AfterTax\ Cost\ of\ Dept * \left(\frac{D}{D+E}\right) \qquad (8)$$

According to the source data [92], the following table values were found using the above formula.

Table 15. Costs of capital to shipbuilding & marine industry

Industry Name **Shipbuilding & Marine**	Number of Firms	Cost of Capital (USD)	Cost of Capital (EUR)
Global	345	5.97%	4.61%
United States (US)	10	9.37%	7.97%
Europe (EU)	62	7.14%	**5.77%**

The above table shows the cost of capital estimation for shipbuilding and marine industry to the Global, the United States, and Europe. All values were received from Prof. Damodaran's online page [92], and the cost of capital was calculated concerning the last fiscal year (2019). Since Euro currency is used in this thesis study, the expected inflation rate in Euros (0.2%) and the expected inflation rate in USD (1,5%) were used to convert to EUR currency. As a result of calculations, the cost of capital (EUR) is calculated around 6% for Europe. The cost of capital (EUR) value, which is 6%, was used as a discount rate for the MAC calculation.

3.3.1.3 Marginal abatement cost

The Marginal Abatement Cost is the value that you will see on the vertical (y-axis) in the MAC curves figures. In standard MAC curves are expressed as EUR per unit of CO_2 saved per annum (e.g., EUR/tonne of CO_2) – i.e., how much the technology costs to reduce 1 unit of emissions. The EUR value comes from the NPV of technology. The group or abatement value is what you enter (e.g., tonne CO_2 saved) and is never discounted [78].

Using the following formula (9), Marginal Abatement Costs (MAC) can be found for the project or technology [77, 78].

$$MAC = \frac{-\,Net\ Present\ Value\ (NPV)}{Total\ abated\ CO_2\ Emissions} \qquad (9)$$

The NPV calculation was mentioned in the previous section. However, we are necessary to multiply NPV by minus one (-1) because a negative MAC has not an accurate cost per tonne of CO_2 abated and is associated with a positive NPV. Vice versa, if we have a negative NPV value, this indicates that the loss of CO_2 emission reduction is associated with a negative NPV. The "*Total abated CO_2 emissions*" state in the formula shows the total CO_2 emissions reduction potential that the applied emission reduction technology reduces over the lifetime of measures.

3.3.1.4 Exchange and Inflation Rates

The Euro was taken as the standard currency. The Euro (EUR) to Dollar (USD) exchange rate is used as a 1.20 (1.20 USD per 1 EUR) in this study. This value was calculated as an average of the 10-year Euro-Dollar exchange rate [94].

Inflation is a quantitative measure of the rate of increase in average prices of technologies or goods and services in an economy over a while. As in every sector, it will be affected by inflation in the marine sector. For this reason, an inflation value has been determined for operational expenses. The inflation target rate determined by the European Central Bank (ECB) for the inflation rate was indicated to be below 2% or close [100]. The inflation rate is taken 2% for operational expenses.

3.3.2. Fuel price estimation for ships

The fuel price is one of the most critical elements in the cost-benefit calculations for ship CO_2 reduction method estimation. The method used in IMO "MEPC 62 / INF.7" [70] is taken as a reference for cost calculation. It is also assumed that ships use heavy fuel oil (HFO), i.e., high sulfur fuels. Prices can be estimated for different fuel types. The estimation was based on:

1. The crude oil price estimation from the CME Group, Crude Oil Futures - February 2031 [99].
2. The correlation between historical HFO prices and crude oil prices [70].

According to the estimated 10-year future crude oil price by the CME group, the future crude oil price has been assumed for the ships used in the calculations. The crude oil is estimated at around 55 dollars per barrel by CME Group [99]. According to this estimate, two different scenarios are created which are a low and high estimation. The low and high estimations are used for sensitivity analysis.

Ships are using processed crude oil such as HSO, LSO, Diesel oil, etc. Therefore, crude oil needs to be converted to processed oils, and they need to be priced. IMO “MEPC 62 / INF.7” [70] found a well-defined relationship for this, looking at past prices for HFO and crude oil. The EIA data (Annual Energy Outlook 2009) on HFO prices in crude oil prices in Singapore and West Texas Central (WTI) was used for calculations. They estimated the WTI price in USD per barrel of HFO price in USD per metric ton. The relationship between crude oil price (USD/barrel) and HFO 180 spot price (Singapore, USD/mt) between 2000 and 2010 is below [70].

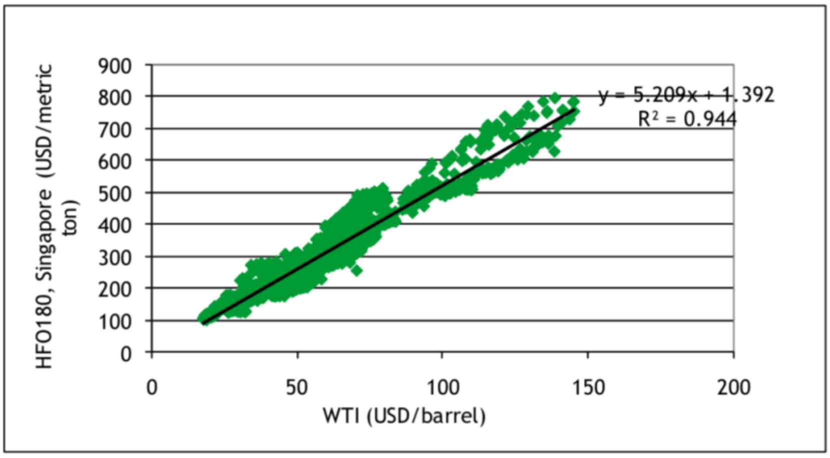

Figure 19. Historic correlation between crude oil price and HFO 180 spot price [70]

$$y = 5.209 * x + 1.392 \ [\frac{\$}{mtonne}] \qquad (10)$$

According to formula 10, the HFO price for USD per metric tonne and EUR per metric tonne is calculated approximately. Table 16 shows the results;

Table 16. Fuel price estimation scenario

Scenarios	Crude Oil Future Estimation (2030, USD/barrel)	Corresponding HFO Price (USD/tonne)	Corresponding HFO Price [EUR/tonne]
Low price estimation	30	158	150
Reference price scenario	55*	288	250
High oil price estimation	90	470	400

*CME group future crude oil estimation [99]

The corresponding euro HFO prices were calculated approximately according to the year of 10 years average USD to EUR exchange rate (around 1.20) from Statista [94]. The reference fuel price (HFO) was estimated at 250 EUR per metric tonne for cost-benefit analysis.

3.3.3. Emissions abatement measures

The importance of energy-saving measures was mentioned in chapter two. These methods form the basis of emission reduction measures. However, for more reliable and detailed results, it was examined with the data in other studies and applicable techniques, within cost-benefit analysis was performed. In this section, the ways in IMO “MEPC 62 / INF.72” [70], TNO Report R11601 [34], ICCT [69] reports, and some published sources [81, 82] have been used. Details and importance of the methods are explained in detail in the following subtitles. The summary tables (Table 23-24-25) of all emission reduction potentials and costs can be accessed in section 3.3.6. These data are the primary data of this study.

The emission abatement methods are handled in two categories: Technical measures and Operational measures. While the first 9 methods refer to technical abatement measures, the 10 to 12 range shows operational measures.

3.3.3.1. Autopilot adjustment

It is an electronic device that automatically adjusts the rudder position to autopilot systems used in ships. The autopilot considers wind and currents, which helps to keep the route of the ships. These systems save fuel as small rudder angles keep the ship steady [69]. It has been widely used in recent years. This method is applicable for all ship types.

The abatement potential varies depending on the ship type and structure. According to references, the abatement potential is 0.5-3% [69, 70]. According to IMO-GloMEEP [81], this value is estimated to 0.25-1.5%. Thanks to technological developments and better adjustments, the autopilot abatement potential was used in calculations as 1.5% in this study. Although investment cost varies depending on the ship type [70], no investment cost was used, since most ships were assumed to have autopilot technology.

In the DNV GL Appraisal tool [82], the software update and training costs for "Voyage Execution" were marked as fixed, and the annual extra operational cost for this is applied to all ships as 5,000 USD or approximately 4,150 EUR [82]. The operational cost has been used as 4,000 EUR for all ship types. The autopilot's lifetime is estimated to be equivalent to the ship's lifetime (25 years).

3.3.3.2. Propeller upgrade

Propellers are one of the most important components of ships. It is possible to save fuel depending on the condition and type of propellers. The propeller converts the rotary motion into a driving force, allowing the ships to advance. Practically, high propeller efficiency can be achieved with a large propeller rotating at a low speed. Therefore, it is possible to get high efficiency from an optimized propeller [34, 69]. High efficiency can be obtained by updating/optimizing propellers with various methods. According to IMO “MEPC 62 / INF.72”, it can be between 0.5% to 10% [70]. On the other hand, optimizing the propeller is estimated to be 5% in the TNO Report R11601 [34]. Also, the new Propeller design developed by the Wartsila improves the efficiency of propeller is around 15% [80]. In this study, the CO_2 emission and Fuel consumption abatement potential of the propeller upgrade are assumed to be 8% due to technological developments. This method is applicable for all ship types. The lifetime of this system can be estimated for 25 years.

There is an investment cost to upgrade to the propellers of the ships and it depends on the type of ship. However, an average value shared by IMO-GloMEEP is between 400,000 USD to 500,000 USD to retrofitting propellers [81]. According to the ship size, propeller update prices were taken as between 330,000 EUR to 415,000 EUR in this study. According to the ship types and ship capacity values, the investment cost summary table can be accessed from section 3.3.6. The decision-making criteria used to decide investment cost was ship capacity/size (DWT).

3.3.3.3. High-Efficient lighting

Since using high-efficiency systems or optimization of lighting systems will decrease our energy consumption, it will reduce fuel consumption in ships. High-efficiency lighting systems can be achieved simply by optimizing halogen lamps, LED systems, or other lighting systems [69, 80]. This system increases energy efficiency on auxiliary engines. Generally, there is not a significant energy consumption for lighting systems on ships except cruise, passenger ships. Since new generation lighting systems are now used in most ship technology, the energy reduction potential can be estimated to be 1.5% for regular ships. However, these systems can be reduced to be 5% overall energy consumption for Passenger (Cruise) ships.

The investment cost of high-efficiency lighting systems is 50,000 to 200,00 EUR for regular ships [34]. However, this value is between 160,000 EUR and 830,000 EUR for passenger and cruise ships [81]. At the same time, the new generation lighting systems are durable, so the lifetime period of this system can be estimated for 25 years. This method is applicable for all ship types. In this study, costs between 50,000 and 200,000 EUR were taken according to the investment costs corresponding to reference ships in the TNO Report R11601. For passenger ships, the average investment cost has been taken 500,000 EUR.

3.3.3.4. Slender Design

The different studies have been carried out on propellers and hull improvement in previous years [58, 69, 70]. Such developments have been proven the potential to reduce CO_2 emissions. Related studies have also calculated the cost-benefit analysis according to these methods. Still, ways to increase ship efficiency with new designs have been explored, and ship designs that provide fewer carbon emissions are being developed.

The main focus of traditional ship designs is directly proportional to the load-carrying capacity of the ships, and the models of the ships are on maximum load carrying. For this reason, ships (cargo, bulk carrier, etc.) are in the form of shoeboxes. It does not matter what variable and fix costs are for such ships. However, the new type of ship design (Slender ship design) examined by Lindstad et al. (2014) has been shown to emit fewer emissions and reduce actual costs than existing ships [83].

It has been mentioned in related studies that the application of this method to existing ships is proportional to the investment cost of 10% of the new-built ship cost [34, 83]. Since the new-build ship prices are challenging to find on the internet, the prices were used by TNO are were used to our reference ships as approximately. Values between 1,000,000 and 5,000,000 EUR as investment costs were assumed to vary by ship size and type. In the related studies [34, 83], emission reduction potentials vary between 10% and 30% depending on the ship type. In this thesis study, the approximate values suitable for the ship type between these values were used in the calculations. The lifetime of the relevant investment is directly related to the ship's life and has been used in calculations as 25 years. This method is excluded from the passenger (cruise) ships.

3.3.3.5. Optimization of Trim/Draft

In maritime, the longitudinal balance of the ships is called trim. In ships, the longitudinal stability determines the positions of the ship's center of gravity and the ability to float the ship, just as in the transverse balance. Trim is the difference between the initial and aft draft of the ship. This difference is indicated in meters, not in degrees, as in transverse equilibrium [84].

The optimization of the Trim/draft of the ship directly affects the fuel consumption of the ship. Emissions can be reduced since the trim is generally engaged while actively the ship is loading, reducing the fuel consumption of the ship [81, 82].

This optimization is usually applied with the computer systems, and therefore an investment cost is required. Besides, an additional fee must be added to this investment cost to train employees. Total investment cost was calculated by IMO-GloMEEP [81] between 15,000 to 75,000 USD. According to the Appraisal Tool of DNV GL [82], this value is fixed for all ships and taken as 25,000 USD. In this thesis study, the fixed cost was used for all ships, and this value is taken as 25,000 EUR. Although it is an application system for all ships, it is more flexible to use in ships with exclusive designs such as passenger ships. Therefore, the emission reduction potential varies between 1% and 5%. For example, the value for container ships can be estimated at 5%, while for cruise ships, it can be calculated as 2%. While the investment lifetime is expected to be 25 years, there is no need for any operational cost.

3.3.3.6. Waste Heat Recovery

Electricity generation is possible using harmful gases originating from ships with Waste Heat Recovery (WHR) system. Thus, electricity is produced by using free fuel, and economic benefits are provided, and a significant contribution is made in terms of environmental awareness. Heat energy from ship exhaust gas can be used to reduce engine fuel consumption or the requirements of auxiliary engines thanks to the steam turbines and heat exchanger [34, 69]. Mainly, this system helps to reduce the fuel consumption of auxiliary engines [70].

The benefits of using this system on ships have been seen in previous examples [34, 69, 81]—the efficiency and size of the engine affect the ability of WHR. The emission reduction potential for the WHR systems is between 3% and 8%, according to IMO-GloMEEP [81]. Also, the ICCT shared the abatement potential as a 6-8%. In this study, the emission reduction potential is used to be 3-8%.

The WHR investment cost ranges from approximately 4,000,000 to 8,000,000 EUR, depending on the ship size [81, 82]. In the TNO Report R11601 [34], it is estimated that this value is between 1,250,000 and 6,300,000 EUR, depending on the ship type. Therefore, a wide range was used in this study; the investment costs were estimated at approximately 1,250,000 and 8,000,000 EUR by ship size and reference sources. It is a technology directly proportional to the engine type and size of the ship. There is also annual maintenance and operational maintenance cost for these systems. IMO-GloMEEP has estimated that this cost is between 10,000 and 30,000 USD [81]. For this study, the operational cost is taken as a fixed value, and the average of these two values is 20,000 USD per year, which is around 16,500 EUR.

3.3.3.7. Wind Power (Kite)

Nowadays, renewable energy sources are using in ships, which they need low power. Besides, it is seen that renewable energy sources are now used in ships that are in global shipping activities. It is possible to integrate wind energy into ships with wind engines, automatic kite systems, the Flettner rotor concept, and modern sail rigs. In this way, it can be used as forwarding propulsion by using wind energy [34, 69, 70].

In this study, the use of kites (automatic kite systems) for ships is mentioned as wind energy. Wind power (kite) can be used possibly for all ships. However, in the TNO [34] and DNV GL [82] studies, it was estimated that it did not apply to all ship types. The kite system does not apply to all ships in this thesis study as well. The appropriate ships showed in the section 3.3.6.

The kite systems are relative to the "size of the kite [m2]", which can be applied relative to the data shared by IMO and DNG VL [55, 81, 82]. The below table shows the approximate purchase cost, installation cost, and operational cost as a EUR. Original data can be accessed from the IMO-GloMEEP webpage [82].

Table 17. Details of the size of kite and cost elements, base data from [82]

Size of kite [m²]	Purchase cost [EUR]	Installation cost [EUR]	Operational cost [EUR]
160	230,000	17,500	9,300
320	400,000	30,000	24,000
640	760,000	57,500	61,300
1280	1,462,500	109,688	146,250
2500	2,158,333	161,875	259,000
5000*	2,850,000	213,750	399,000

** Assumed not to be available until 2020*

The above table values were converted to the Euro currency with 1.20 exchange rate (dollar to euro) because all analysis is calculated in the euro currency. The total purchase and installation costs of the equipment are used for investment costs that are taken for this study.

The efficiency in these systems varies according to the types of ships and rotation. Therefore, the potential emission abatement rate can be estimated between 5% and 10% depending on the ship type according to related studies [34, 55, 81, 82]. The investment lifetime is estimated to be 25 years [82].

3.3.3.8. Solar Power

Another renewable energy source that can be used in ships is the use of solar energy with the help of solar panels. Ships in the marine industry, electricity generated from solar energy, propulsion as the primary power source in the system, or other electrical can be used to meet your needs. The solar energy reduces the fuel consumption of its auxiliary engines. Solar power does not apply to all ship types because large areas are required to install panels [81]. Calculations for applicable ships have been made, and details of appropriate ships are shown in section 3.3.6.

According to IMO-GloMEEP technologies [81], the fuel consumption of auxiliary engines can be reduced by 0.5% to 2% with the help of solar panels. However, nowadays, the efficiency and frequency of use of solar panels are increasing. Therefore, the fuel or emission reduction potential can be assumed as 0.5% for the solar overall energy consumption of ships.

Compatible solar systems for ships should have different properties than land-based applications (e.g., more durable). Also, it is challenging to calculate solar efficiency in moving operations. For this reason, cost analysis has been made over some estimates. The assumptions are used in this thesis, as stated in the IMO-GloMEEP [81] and DNV GL [82] references. According to reference data, Solar modules rated at a test condition of 1000 W/m2 of radiation and 25 Co degrees (and 1.5 air mass). It means, for example, that a 200 W module will generate 200W at noon on a proper sunny day. Solar panels to be used for ships are generally taken as 40-50KW. These energy auxiliary engines (diesel generators) will be used to be supported [81, 82].

The installation cost of the system varies between 830,000 and 1,100,000 EUR for a 40-50kw system, according to reports [70, 81]. In the DNV GL appraisal tool, an average value in this range of values is taken from all ship types. This value is 1,370,000 USD [82]. A fixed investment cost of 1,150,000 EUR for all ship types, which is the euro equivalent of this value, can be used for all applicable values. However, this investment cost can be expected to decrease over time with innovations in solar panels. Besides, the lifetime of solar energy is taken as 25 years.

3.3.3.9. Hybridization

The use of hybrid systems in ships is increasing. In recent years, it has been studying that the use of Li-ion batteries has essential effects on the reduction of CO_2 emissions for ships [81, 87]. For hybrid ships, just like plug-in hybrid cars (PHEV), in this study, calculations for plug-in hybrid ships will be made. Batteries used for additional engines can be recharged using the coastal power and can increase the efficiency on the ships by reducing the energy used by the ships during maneuvering [81]. Besides, the use of hybrid systems for auxiliary vines increases the reduction of CO_2 emissions by allowing the main motors to be disconnected during low load times [87].

Calculations by TNO for hybrid systems are based on a 5% value for most ship types [34]. Besides, the reduction potential was estimated by IMO that it is between 15% and 30% for a total ship fuel consumption. These values depend on the ship model and engine type [81]. In the study conducted by Peralta et al. [87], It was estimated that there is an emission reduction potential between 5.7% and 8.9% on total CO2 emissions. Within this information, 7% abatement potential was taken in this study for all types of ships except passenger ships. According to the survey conducted by Ancona et al., A reduction in fuel consumption between 18% and 20% can be observed with the hybrid systems on cruise ships [95]. For this reason, 20% of reduction potential calculations are taken for Passenger (Cruise) ships.

According to IMO-GloMEEP Hybridization technology [81], the investment cost of the systems is between 1,800,000 to 3,000,000 USD, depending on the ship type. Also, hybridization methods in the TNO study ranged between 1,000,000 and 4,200,000 EUR according to the ship type [34]. According to the type of reference ships, the investment costs were used between 1,000,000 and 4,000,000 EUR. The investment cost for passenger (cruise) ships is taken as 7,000,000 EUR according to the value given in references [95].

3.3.3.10. Propeller Polishing

As mentioned in the propeller update section that it is possible to save fuel depending on the condition of propellers. Cleaning or polishing propellers on ships will help reduce fuel consumption by reducing friction. The propellers can be cleaned regularly without the need for any investment, or with automatic monitoring systems, this can be done at different intervals (investment required) [70].

In this study, it is taken as a reference that the propellers are cleaned twice a year. The estimated cost for this is approximately 4,100-6,600 EUR per propeller pear year [81]. The abatement potential depends on different variables, but it has been estimated at around 1%. This method is applicable for all ship types. The propeller polishing cost was considered constant for all vessels two times per year and have taken as 10,000 EURO.

3.3.3.11. Speed reduction

It is known that speed reduction on ships has a direct effect on fuel consumption. Therefore, it can be said that it has an impact on CO_2 emissions. It is also known to have an exponential relationship between fuel consumption and speed [34, 69, 70]. According to the data shared on IMO “MEPC 62 / INF.7” [70], the ratio between speed reduction, engine power, and fuel consumption shown in the following figure.

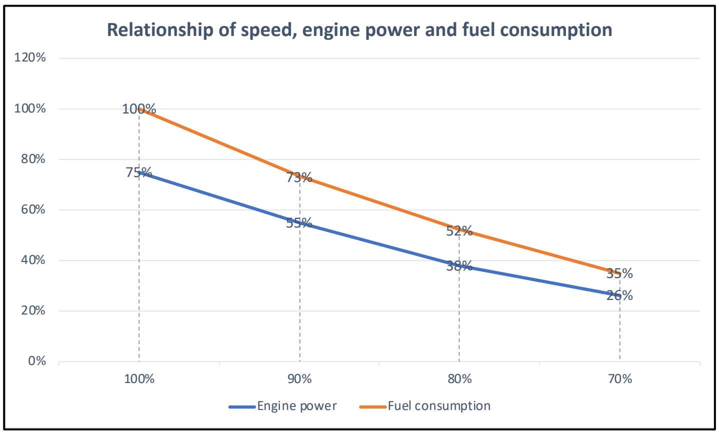

Figure 20. Relationship of speed, engine power, and fuel consumption, base data from [70]

According to the figure, the effect of a 10% decrease in ship speed on fuel consumption is 27 percent. Likewise, the reduction in rate helps the engine power to decrease (approximately %20). However, there are some limits to speed reduction. Ships' engines must work on specific engine power. Therefore, the speed reduction below accurate rates are not technically appropriate [70]. These analyzes should be aware of when making analyzes. Speed reduction can be applied in 2 ways: speed planning or slow Steaming. In this study, it was preferred for slow steaming (ECO speed) for the cost-benefit analysis.

The below figure shows the relationship standard oil tanker speed and costs in USD per tonne transported. When speed is reduced compared to the design speed; fixed cost per nautical mile (nm) increases, fuel cost per nm decreases [96].

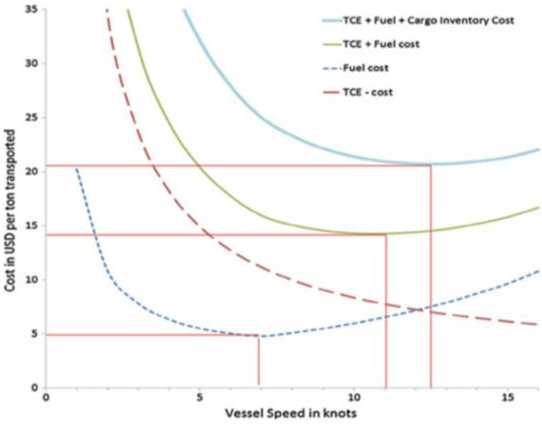

Figure 21. Cost per tonne carried as a function of speed and cost for a standard oil tanker [96]

According to the above figure, for the first reduction bellow design speed, the decrease in fuel cost is more substantial than the increase in fixed cost per nm, but when the rate drops below around 11 – 12,5 knots, the reduction in fuel cost is less than the rise of the fixed cost for oil tankers. Time charter equivalent (TCE) value shows some financial losses, such as operational cost, depreciation, and other expenses. This cost is simplified, and slow steaming is assumed to be used unless we increase the total cost per nm by the authors in the TNO Report R11601 [34]. For this thesis study, the investment cost was assumed on investment zero modeling in the cost-benefit analysis.

The duration of time the ships stay at sea due to slow steaming may increase. Thus, it may increase operational costs and other expenses as well. Dr. Lindstad's report [96] also appears to have a cost of around 15,000 EUR for the TCE. Although TCE costs are according to the type and structure of the ship, it was assumed in this thesis that the operational cost has increased at this rate while the ships are at sea. The total time spent at sea is available in the EU MRV report for reference ships. According to the values given in the abatement potentials of the ships, it is assumed that the ships' sea duration increases in direct proportion. Accordingly, the operational cost calculation has been made for reference ship.

Emission reduction potential is used according to the reference values in the TNO Report R11601 [34]. The range of reduction potential is between 2% and 18%. The total time spent day was taken as the average for reference ships (see Appendix 2). The increases in time the ships stay at sea were calculated the right proportion with the emission reduction potential.

Table 18. Speed reduction CO_2 emission potentials and time spent at sea

	Container	Oil Tanker	Bulk Carrier	General Cargo	Chemical Tanker	Passenger (Cruise) Ship	LNG Carrier	Ro-Ro & Vehicle Carrier	Ro-Pax ship
Speed Reduction Abatement Potential %	2	18	17	11	17	n/a	n/a	16	n/a
Anual average total time spent at sea day [day]	140	115	75	128	120	175	97	150	183
Increase in the time spent at sea [day]	3	21	13	14	20	n/a	n/a	24	n/a

The "Increase in the time spent at sea" in Table 18 is multiplied by TCE, and operational cost is calculated according to the ship type.

3.3.3.12. Advanced route planning

The advanced route planning system is directly related to the characteristics of the ships, and these systems not only plan the ship's route but also allow the ships to reach the destination point most efficiently according to the weather, current, and wave information [34]. Generally, systems such as weather planning, voyage execution are considered as part of this system [82].

According to the TNO Report R11601 [34], the emission reduction potential was estimated between 5% and 10% by ship type. The emission reduction potential can be expected between 5% and 10% according to the ship type for this study as well. In terms of investment cost, there is a cost ranging between 50,000 EUR and 100,000 EUR depending on the ship type. The lifetime of the system is thought to be 25 years in our study. In addition, the operational cost (approximately 4,000 EUR) used for voyage execution technology in the DNV DL application was taken as the operational cost for advanced route planning in this study [82]. The system is expected to give better results in the future with the developing technologies.

3.3.4. Alternative technology: exhaust gas cleaning system (Scrubber)

Scrubber systems are one of the essential methods used to clean exhaust gases. These systems have the most considerable advantage in preventing Sulphur Oxides (SOx), Nitrogen Oxides (NOx), Particulate matter (PM), and other exhaust gases IMO limit in emission control areas (ECAs, SECAs) while still using HFO [88]. However, recent studies have emphasized the importance of systems on GHG emissions [86]. The following four different types of scrubber systems are generally used in ships [85].

1. Open Loop system; seawater is used in the open-loop system due to its alkalinity. If there is low alkalinity water, Sodium Hydroxide mixture is added to the system.
2. Closed Loop system; the system is circulated in itself, and Sodium Hydroxide is added to the system. The washing water used is cleaned in its system and used again in the system.
3. Hybrid system; the system contains both methods described above.
4. Dry Scrubbers system; it doesn't use any liquids process. The emissions are cleaned with hydrated lime-treated granulates.

The open-loop systems are using more common than other systems. However, these rates may differ depending on the ship type and route [88]. The usage examples and calculations of scrubber systems today are mostly on SOx and other harmful gases. However, a CSNOx scrubber system, which had developed by Ecospec, can use for reduction for CO_2 emissions. There is no analysis result on all ships related to this system; however, it is possible to see new examples in the coming years. The CSNOx is the world's first hybrid emission abatement system, and it is like the open-loop system scrubber. These systems help to reduce CO_2 emissions in addition to SOx and NOx significantly [81, 89].

Investment costs are essential to cost for scrubber systems. Generally, the investment cost of scrubber systems is based on the type of ship according to the exclusive agreement between the companies. The investment cost is estimated between 200 and 400 EUR/kW by CE Delft for open-loop systems [85]. In addition to the investment cost, there is an annual maintenance and operational cost expense. It was estimated to be between 1% and 3% of the value range given by CE Delft for the open-loop system [85].

Appropriate investment and operating costs have been calculated to be an example of the reference ships. The investment cost was taken 300 EUR/kW, and the operational cost was taken 2% of investment cost which is the average of the range given by CE Delft. The below shows the reference ships average engine powers, investment, and operational cost of the scrubber system.

Table 19. The reference ship average engine power, investment and operational cost of scrubber system

	Container	Oil Tanker	Bulk Carrier	General Cargo	Chemical Tanker	Passenger (Cruise) Ship	LNG Carrier	Ro-Ro & Vehicle Carrier	Ro-Pax ship
Average reference ships Engine Power [kW]	44805	17530	13320	4090	7730	16300	35500	11700	26700
Investment Cost (x1000 Euro)	13442	5259	3996	1227	2319	4890	10650	3510	8010
Operational Cost (x1000 Euro)	269	105	80	25	46	98	213	70	160

As seen in the table above, scrubber systems have high investment and operational costs. Still, according to the IMO Sulfur 2020 regulation, it is imperative to use such methods for ships that are using high sulfur fuels.

Despite the high costs, they significantly reduce the spread of harmful gases to the environment. In the brochure prepared by the Ecospec [89], the emission reduction rates are shared as follows for a 100,000-tonnes oil tanker for the CSNOx system.

Table 20. Ecospec, CSNOx system emission abatement potential [89]

	SO_2	NOx	CO_2
Ecospec, CSNOx	99%	66%	77%

According to the table above, it is seen that the potential to reduce CO_2 emissions besides SO_2 and NOx is quite high. These values were shared for 100,000 DWT oil tankers.

In the study by Dr. Lindstad, the potential of scrubber systems to reduce greenhouse gas emission has been shown to be between 15% and 20% for other ship types [97]. Scrubber systems can be applied to all ships and their investment life can be estimated to be 25 years. The effects of scrubber systems are not used in this study, but in further studies, the results of these systems on CO_2 emissions can be studied.

3.3.5. The reference ships

The reference ships are the ships in EU MRV public data in this study [40]. However, there is a need to create a different sampling model for some abatement technologies. For this model, based on the ship capacities expected to be in 2030 in the TNO Report R11601 [34], reference ships were selected upon an estimation. TNO estimated 2030 according to the increase between 2002 and 2015. The capacity of the ships in 2050 (2050E) was calculated at the same increase rate. Since ships suitable for some values in the increase could not be found, ships with appropriate values between TNO 2030 and 2050E values calculated in this study were used. Investment costs and operational costs were estimated according to these reference ships.

The Third IMO GHG study 2012 data (IMO2012) [35], TNO study 2030 estimation (TNO2030) [34] and the estimate of 2050 (2050E), which calculated in this study, ship size/capacity values available in the below;

Table 21. Average vessel sizes/capacity estimation, 2012 – 2050

Ship Type	Ship Size/Capacity in dwt			Increase
	IMO2012	TNO2030E	2050E	
Bulk carrier	68569	98000	138180	41%
Oil tanker >80'dwt	182700	189000	192780	2%
Container	41638	77000	133210	73%
LNG & LPG	27622	46000	72680	58%
Chemical tanker	17982	29000	44370	53%
Vehicle	16165	11000	13640	24%
General cargo	5333	7000	7490	7%
Passenger (Cruise)	3743	4800	6000	25%
Ro-Ro	3539	11000	13640	24%
Ferry-RoPax	1580	2300	2967	29%

The reference ships were found according to the ship capacity/size close to the 2050E values in the table above. Sample ships were used calculation; for instance, the investment cost of Scrubber or operational cost for speed reduction/slow steaming.

Table 22. The reference ships

Ship Type	Average Size	Average Fuel Consumption [tonnes/year]	IMO Number	
			Sample 1	Sample 2
Container	126650	15000	9705081	9806055
Oil tanker 80' dwt	153995	4000	9593012	9817494
Bulk carrier	115233	5400	9615121	9620566
General Cargo	13785	1700	9721657	9742417
Chemical Tanker	39649	3500	9617650	9712606
Passenger (Cruise) Ship	5300	20000	9636955	9704130
LNG Carrier	91450	22600	9666998	9737187
Ro-Ro & Vehicle Carrier	17932	5900	9762534	9784037
Ro-Pax ship	3761	9300	9665437	9773064

The reference ships were specified according to the MarineTraffic [98] and EU-MRV data [40]. The average fuel consumption [tonnes/year] values from DNV GL [82] and IMO [35] references. Details of the ships can be found in the Appendix 2.

3.3.6. Summary tables of emission savings and cost per abatement measure

Summary tables of potential abatement measures described in the previous sections are presented in this section. The abatement potentials applied to the reference ships are shown in Table 23, investment costs Table 24, and operational costs Table 25, respectively.

Table 23. Overview of CO_2 abatement potential (%) for different abatement measures

Abatement Potential (%)	Container	Oil Tanker	Bulk Carrier	General Cargo	Chemical Tanker	Passenger (Cruise) Ship	LNG Carrier	Ro-Ro & Vehicle Carrier	Ro-Pax ship
Autopilot adjustment	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Propeller upgrade	8	8	8	8	8	8	8	8	8
High-efficient lighting	1.5	1.5	1.5	1.5	1.5	5	1.5	1.5	1.5
Slender Design	10	20	30	20	20	n/a	10	15	10
Optimization of Trim/Draft	5	1.5	1.5	3	1.5	2	2	4	2
Waste Heat Recovery	8	5	3	3	3	5	3.5	3.5	5
Wind Power (Kite)	n/a	8	8	5	7.5	n/a	n/a	5	n/a
Solar Power	n/a	0.5	0.5	n/a	0.5	0.5	0.5	0.5	n/a
Hybridization	7	7	7	7	7	20	7	7	7
Propeller Polishing	1	1	1	1	1	1	1	1	1
Speed Reduction	2	18	17	11	17	n/a	n/a	16	n/a
Advanced Route Planning	5	10	10	5	5	n/a	5	5	n/a

Table 24. Investment costs for different abatement measures (x1000 Euro)

Investment Cost (x1000 Euro)	Container	Oil Tanker	Bulk Carrier	General Cargo	Chemical Tanker	Passenger (Cruise) Ship	LNG Carrier	Ro-Ro & Vehicle Carrier	Ro-Pax ship
Autopilot adjustment	0	0	0	0	0	0	0	0	0
Propeller upgrade	415	415	415	330	372,5	330	415	372,5	330
High-efficient lighting	200	200	100	50	100	500	100	100	200
Slender Design	2500	3000	3000	1150	1500	n/a	2000	1200	1000
Optimization of Trim/Draft	25	25	25	25	25	25	25	25	25
Waste Heat Recovery	8000	7000	6500	4200	4500	4000	2500	5500	3000
Wind Power (Kite)	n/a	1572	1572	430	817,5	n/a	n/a	1572	n/a
Solar Power	n/a	1150	1150	n/a	1150	1150	1150	1150	n/a
Hybridization	4000	2000	1700	1100	1300	7000	2200	1750	2500
Propeller Polishing	0	0	0	0	0	0	0	0	0
Speed Reduction	0	0	0	0	0	n/a	n/a	0	n/a
Advanced Route Planning	100	75	100	50	50	n/a	50	50	n/a

Table 25. Operational costs for different abatement measures (x1000 Euro)

Annual Operational Cost (x1000 Euro)	Container	Oil Tanker	Bulk Carrier	General Cargo	Chemical Tanker	Passenger (Cruise) Ship	LNG Carrier	Ro-Ro & Vehicle Carrier	Ro-Pax ship
Autopilot adjustment	4	4	4	4	4	4	4	4	4
Propeller upgrade	-	-	-	-	-	-	-	-	-
High-efficient lighting	-	-	-	-	-	-	-	-	-
Slender Design	-	-	-	-	-	n/a	-	-	-
Optimization of Trim/Draft	-	-	-	-	-	-	-	-	-
Waste Heat Recovery	16,5	16,5	16,5	16,5	16,5	16,5	16,5	16,5	16,5
Wind Power (Kite)	n/a	146,25	146,25	24	61,3	n/a	n/a	146,25	n/a
Solar Power	n/a	-	-	n/a	-	-	-	-	n/a
Hybridization	-	-	-	-	-	-	-	-	-
Propeller Polishing	10	10	10	10	10	10	10	10	10
Speed Reduction	45	315	195	210	300	n/a	n/a	360	n/a
Advanced Route Planning	4	4	4	4	4	n/a	4	4	n/a

In the next section, the results of the cost-benefit analysis were calculated according to these tables and reference vessels.

3.4. The cost-benefit analysis with MAC curves

Details about MAC curves were explained in chapter two. In summary, Marginal Abatement Cost (MAC) Curves show the maximum abatement cost (EUR/tonne CO_2 emissions) versus yearly abatement potential tonnes of CO_2 emissions. The cumulative effect is displayed on the x-axis since there will be a cumulative effect due to the use of more than one abatement technology on the same system. MAC curves take into account the cost of reducing emissions with the next tonne of CO_2, given the reduction achieved with the technology that has already been applied. The results of the cost-benefit analysis targeted in this thesis will be shown in this section with MAC curves.

Individual abatement costs were calculated for the measures to be used in the analyzes, and the most appropriate method was listed to be used first—the abatement costs are calculated according to the type of ship calculated individually. The details are available in the Appendix 6.

Twelve different measures were used for nine different ship types in this thesis. MAC curves show only applicable methods, as not all actions are suitable for all ship types. The use of these technologies will help reduce CO_2 emissions in future ships.

The figures below show the marginal abatement cost curves according to the ship type. All graphics were created according to the specifications of the ships, which means the engine power, design, etc. of the ships. In all calculations, fuel price (HFO price) 250 euro per tonne was taken. This value is also the predicted reference value in future modeling. In Chapter 4, sensitivity analysis of the effect of the fuel price is also shown. The discount rate was calculated as 6% for NPV calculations. At the same time, considering that operational expenses will change over the years, a 2% inflation value is used only to operational costs in cash flow calculations.

Twelve different emission reduction measures were determined for MAC calculations. Not all of these methods are applicable to all ships, but they are available for energy efficiency. The EU-MRV data was used for the selection of reference ships, and when this data was analyzed, it was observed that nine different ship types caused 95% of the total emissions.

Calculator based on ship types had been prepared in Microsoft Excel for marginal abatement cost analysis. This calculator shows the values of NPV, MAC, CO_2 abatement potential, etc. Summary values calculated for all ship types can be found in Appendix 4.

The MACC Builder Pro tool [78] was used for MAC curves. The tool licensed by Enright Niall (founder of SustainSuccess) and used exclusively for this study.

Figure 22 shows the values of abatement measures (except Wind Power (Kite) and Solar Power) applied for Container ships larger than 8000 TEU. The x-axis of the graph represents the total cumulative CO_2 emissions abatement potential within a year. The y-axis represents the Marginal Abatement Cost (MAC) which means the cost of reducing each tonne of CO_2 emission (EUR/tonne CO_2 Emissions). The fact that some measures have negative cost indicates that the NPV value is positive. In other words, using this method will reduce the cost of the shipowners (decrease fuel consumption). Thus, CO_2 and other emissions will be reduced. The MAC value of each measure is in parentheses.

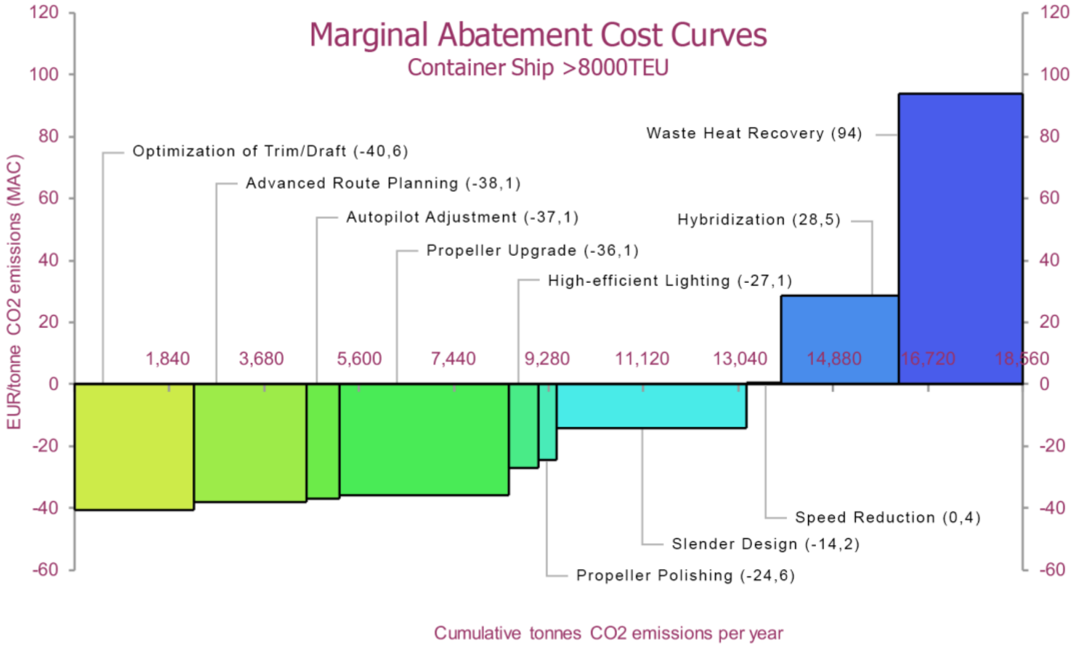

Figure 22. MAC curves for Container Ship (>8000TEU)

It is assumed that there is an annual fuel consumption of 15000 tons for container ships in Figure 22. Considering the fuel type is HFO, it is expected to emit 46710 (fuel consumption x carbon factor (3.114)) tonne CO_2 emissions annually. When all technologies are applied, the maximum emission reduction potential is about 40%. When only measures with positive NPV are involved, an annual emission reduction of 28.2% is expected.

Figure 23 is prepared for the oil tanker (80' DWT). Annual fuel consumption for these ship types was assumed 4000 tonnes. All abatement measures can be applied. The maximum abatement potential is about 58.4%. Only 19.7% CO_2 reduction can be achieved when measures with positive NPV are used.

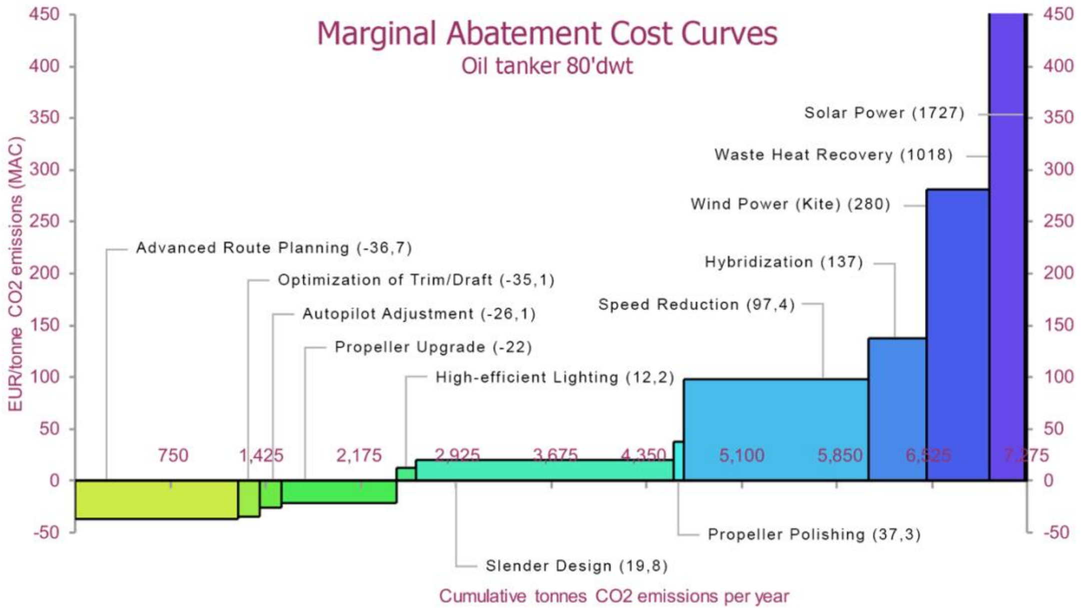

Figure 23. MAC curves for Oil Tanker (80’dwt)

The abatement costs for waste heat recovery and solar panels are 1,018 and 1,727 euros per tonne CO_2 emissions, respectively in Figure 23. However, it is limited at 450 euros per tonne CO_2 emissions to simplify the above curves.

Figure 24 is prepared for the bulk carrier. Annual fuel consumption for these ship types were assumed 5400 tonnes. All abatement measures can be applied. The maximum abatement potential is about 62.4%. When measures with positive NPV are applied, 44.6% CO_2 emissions savings can be achieved.

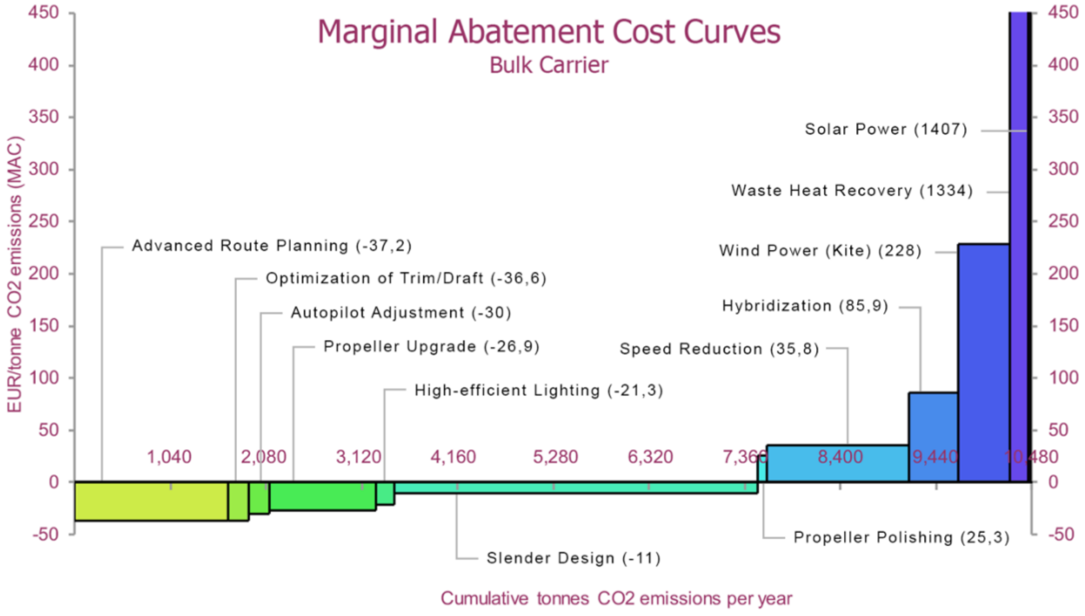

Figure 24. MAC curves for Bulk Carrier

The abatement costs for waste heat recovery and solar panels are 1,334 and 1,407 euros per tonne CO_2 emissions, respectively. However, it is limited at 450 euros per tonne CO_2 emissions to simplify the above curves.

Figure 25 is prepared for the General Cargo ships. Annual fuel consumption for these ship types were assumed 1700 tonnes. All abatement measures can be applied except solar panels. The maximum abatement potential is about 50.3%. When measures with positive NPV are applied, 17.7% CO_2 emissions savings can be achieved.

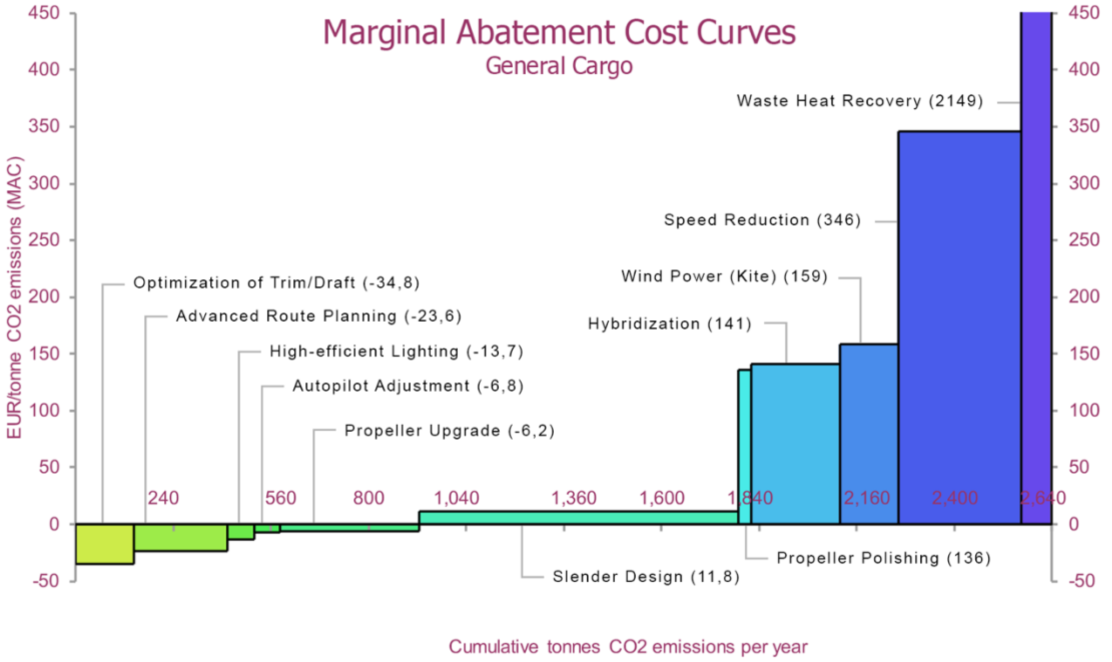

Figure 25. MAC curves for General Cargo

The abatement costs for waste heat recovery is 2,149 euros per tonne CO_2 emissions. However, it is limited at 450 euros per tonne CO_2 emissions to simplify the above curves.

Figure 26 is prepared for the chemical tanker ship. Annual fuel consumption for these ship types was assumed 3500 tonnes. All abatement measures can be applied. The maximum abatement potential is about 54.4%. When measures with positive NPV are applied, 33.2% CO_2 emissions savings can be achieved.

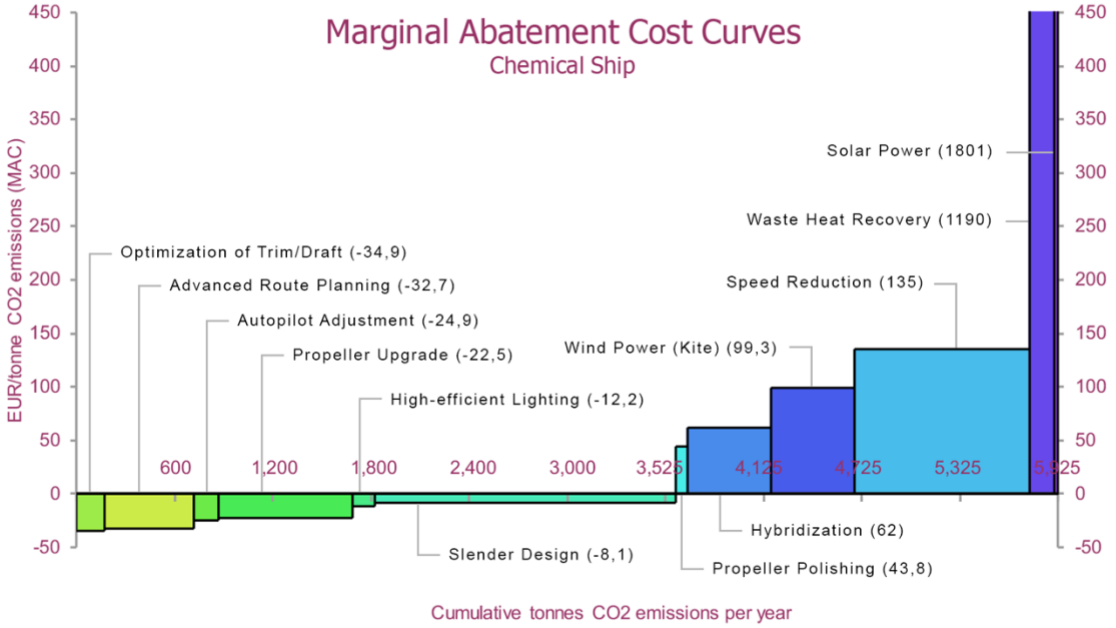

Figure 26. MAC curves for Chemical ship

The abatement costs for waste heat recovery and solar panels are 1,190 and 1,801 euros per tonne CO_2 emissions, respectively. However, it is limited at 450 euros per tonne CO_2 emissions to simplify the above curves.

Figure 27 is prepared for the Passenger (cruise) ships. Annual fuel consumption for these ship types is assumed 20000 tonnes. The Slender Design, Wind Power (Kite), Speed Reduction, Advanced Route Planning measures are assumed not applicable for passenger ships according to references. The maximum abatement potential is about 36.8%. When measures with positive NPV are applied, 33.2% CO_2 emissions savings can be achieved.

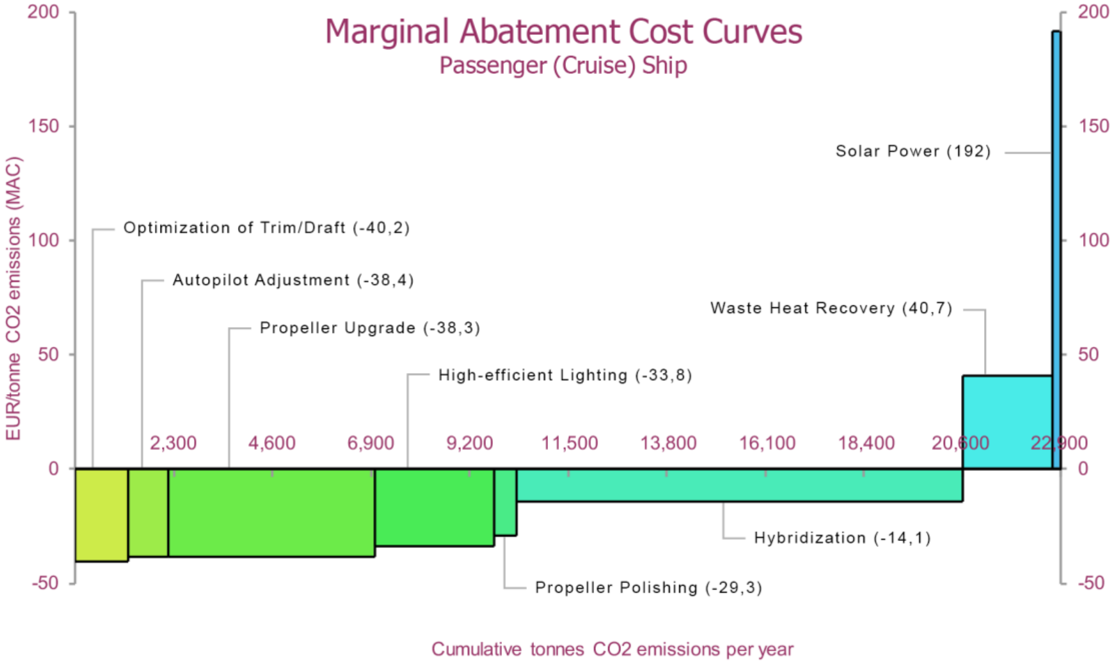

Figure 27. MAC curves for Passenger (Cruise) Ship

Figure 28 is prepared for the LNG carrier ships. Annual fuel consumption for these ship types was assumed 22600 tonnes. The Wind Power (Kite), Speed Reduction, measures are assumed not applicable for LNG carrier according to references. The maximum abatement potential is about 33.9%. When measures with positive NPV are applied, 31.1% CO_2 emissions savings can be achieved.

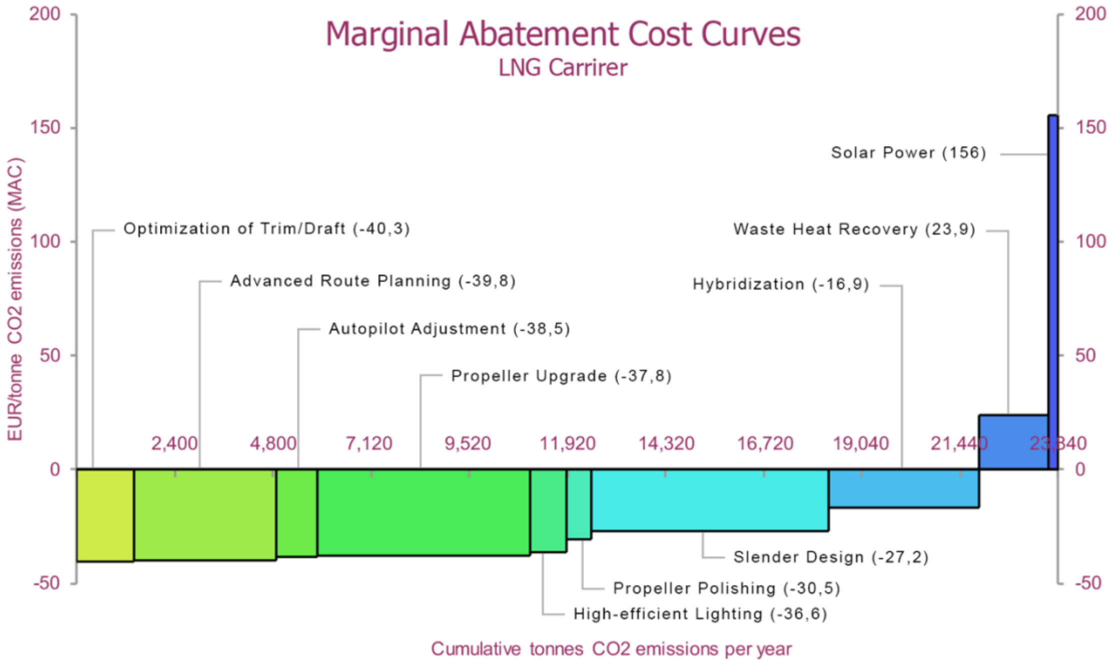

Figure 28. MAC curves for LNG Carrier

Figure 29 is prepared for the Ro-Ro & Vehicle Carrier ships. Annual fuel consumption for these ship types was assumed 5900 tonnes. All abatement measures can be applied. The maximum abatement potential is about 51.2%. When measures with positive NPV are applied, 30.8% CO_2 emissions savings can be achieved.

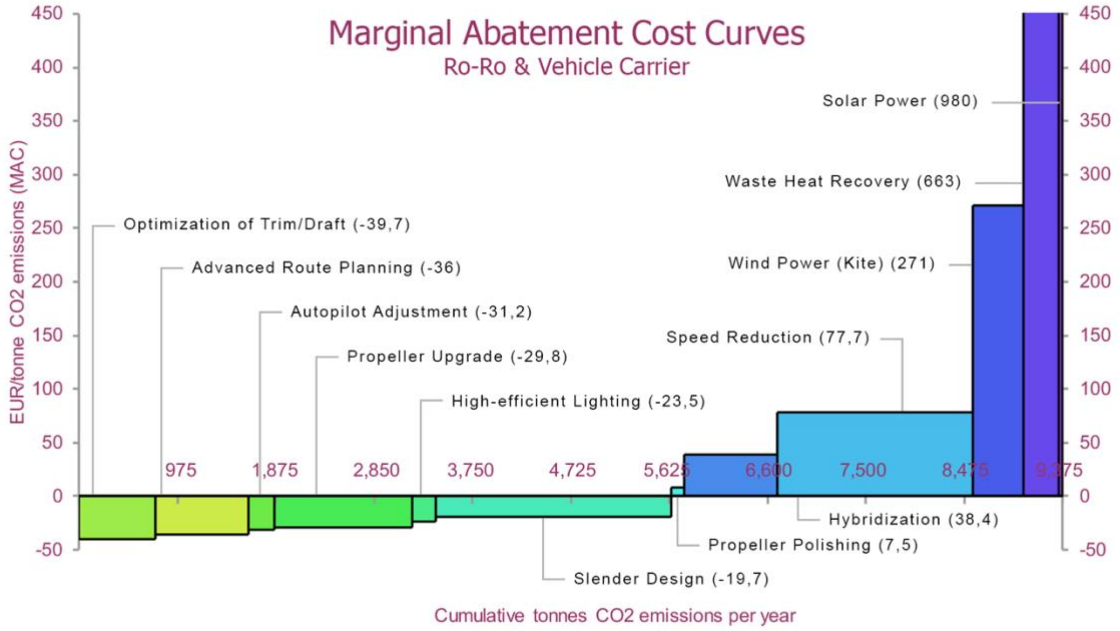

Figure 29. MAC curves for Ro-Ro & Vehicle Carrier

The abatement costs for waste heat recovery and solar panels are 663 and 979 euros per tonne CO_2 emissions, respectively. However, it is limited at 450 euros per tonne CO_2 emissions to simplify the above curves.

Figure 30 is prepared for the Ro-Pax ships. Annual fuel consumption for these ship types was assumed 9300 tonnes. The Solar power, Wind Power (Kite), Speed Reduction, Advanced Route Planning measures are assumed not applicable for Ro-Pax ships according to references. The maximum abatement potential is about 31.1%. When measures with positive NPV are applied, 22.1% CO_2 emissions savings can be achieved.

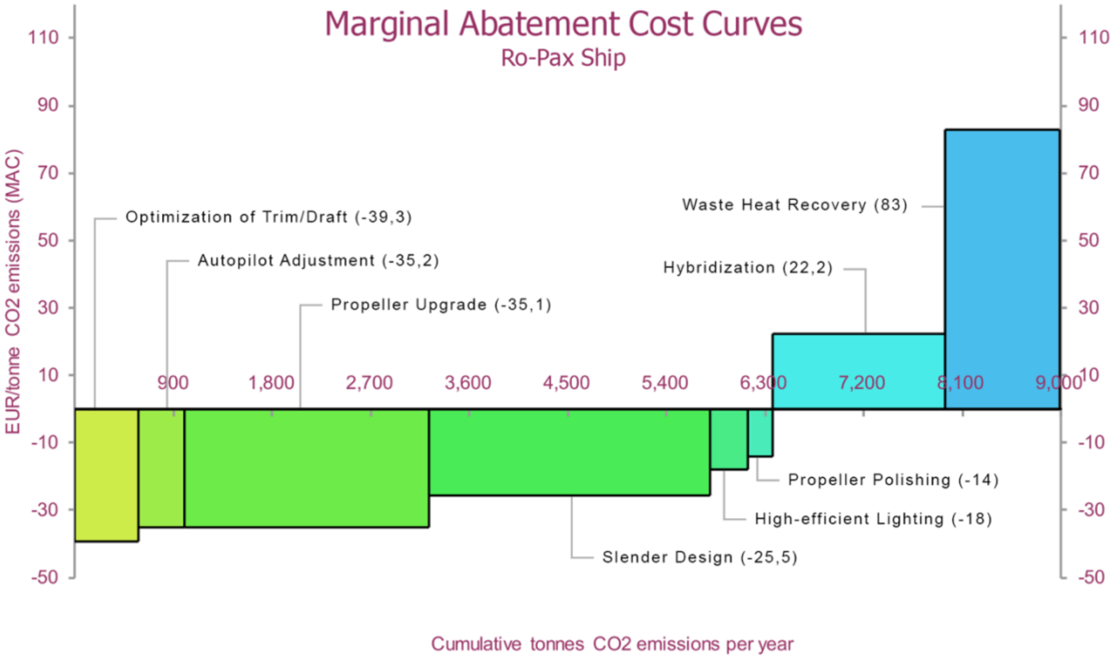

Figure 30. MAC curves for Ro-Pax Ship

The Net Present Value (NPV), Marginal Abatement Costs (MAC), and annual CO_2 abatement potentials calculated for all ship types can be reached from Appendix 4. In summary, the figures show that for most ship types, measures with negative MAC, or positive NPV, can be easily implemented by fleets.

4. Evaluation Analysis of Data and Suggestions

This thesis aims to calculate the marginal abatement cost of measures that can be taken to reduce CO_2 emissions from shipping and to examine the potential of these measures to reduce CO_2 emissions from ships. It is also to calculate the investment costs required for these reductions. MAC curves show the cost per ton. Based on the MAC curves, an assessment is made for each of the reference ships and two different scenarios:

- Cost-Effective measures (NPV+) abatement potential: Only cost-effective CO_2 emissions abatement measures are applied to ships. The NPV value is greater than zero in these technologies. This also means that marginal abatement costs are negative. The reference value for fuel price is 250 EUR per tonne. However, for sensitivity analysis, the emission reduction potentials for 150 EUR per tonne (low price scenario) and 400 EUR per tonne (High price scenario) values are also shown in the table below.
- Maximum Abatement: CO_2 reduction potential to be achieved by all abatement measures that can be applied according to ship types. The maximum reduction potential is the same for all fuel prices. There will be differences in NPV and MAC values. These values can be accessed from Appendix 4.

The CO_2 abatement potentials for the scenarios mentioned above are given in Table 26.

Table 26. CO_2 emissions reduction potential (%) for new-built ships for the different scenarios

CO_2 Abatement Potential (%)		**Cost-Effective Measures (NPV+) abatement, with different fuel prices**			**Maximum Abatement**
Fuel Price [EUR/tonne]		**150**	**250**	**400**	
Ship Types	Container	20	28	30	40
	Oil Tanker	19	20	37	58
	Bulk Carrier	21	45	45	62
	General Cargo	8	18	34	50
	Chemical Tanker	15	33	33	54
	Passenger (Cruise) Ship	17	33	33	37
	LNG Carrier	31	31	34	34
	Ro-Ro & Vehicle Carrier	31	31	32	51
	Ro-Pax ship	21	22	28	31
	Other Ships (Average)*	20	29	34	46

*Average abatement potential values were taken for other ship types in EU-MRV dataset

In this study, analyzes were made for 9 types of ships. It is available on different types of ships in EU-MRV data. The abatement potentials of 9 ship types are averaged for other ships types (Other Ships (Average) values). According to Table 26; the abatement potential ranges from 18% to 45% for reference fuel price (250 EUR / tonne). Likewise, an abatement potential of 8% to 31% for low price estimation is available only for the cost-effective scenarios which means NPV positive scenarios. For high price estimation, this value varies between 28% and 45%. Since the increase in fuel price will make NPV positive, its effect on emission reduction potential is also increasing. There is a large percentage of differences between almost all ship types between low price estimation and high price estimation. Although reference price values are close to high price scenarios values, it is seen that it does not change for some ship types. The maximum abatement potential is the same for all ship types. However, for maximum abatement potentials, NPV and MAC values will vary according to the fuel price.

The values given in Table 26 can be used to calculate the CO_2 emissions of future ships if all ships have these systems. However, it is not possible to apply all methods to existing vessels such as slender design, waste heat recovery. Table 26 was calculated based on this information. Table 27 assumes that in 2050 freight works will increase in direct proportion to the increase in GDP compared to today's ships, and CO_2 emissions in 2050 are estimated with a rise of 52%. Scenarios are assumed that 50 percent of the ships have systems with all technologies, and the other half will have only applicable operational reduction measures. Also; since there is data for ships larger than 5000 gross tons in EU-MRV data, no calculations have been made for ships originating from ship types such as Yacht, Offshore, Service, Fishing, and other (unspecified).

Table 27. 2050 Europe CO_2 emissions in thousand tonne, per ship types for the different abatement scenarios

Ship Type	**# of Ship**	**Total CO_2 emissions [thousand tonnes] (2018)**	**Total CO_2 emissions [thousand tonnes] (2050)**	**Cost-Effective Technologies (NPV+) with diffirent Fuel Prices [thousand Tonnes] (2050)**			**Maximum Abatement [thousand tonnes] (2050)**
				150 [EUR/tonne]	**250 [EUR/tonne]**	**400 [EUR/tonne]**	
Container	1750	44204	66988	56840	52820	52067	46992
Oil tanker	1821	18061	27370	23532	23326	19837	15382
Bulk carrier	3701	17977	27243	22973	18130	18130	14493
Ro-pax ship	350	13829	20957	17609	17483	16635	16069
Chemical tanker	1314	9184	13918	12331	10452	10452	8239
Passenger ship	148	6368	9650	8456	7247	7247	6986
Ro-Ro ship	260	6047	9164	7047	7047	6999	5645
General cargo	1088	5970	9047	8511	7846	6727	5634
LNG carrier	198	5467	8285	6353	6353	6204	6179
Vehicle carrier	448	5103	7734	5947	5947	5907	4764
Other Ships	651	6983	10583	8972	8285	7901	6894
Total	**11729**	**139194**	**210939**	**178571**	**164937**	**158104**	**137278**
Average CO_2 Emission Reduction Potential				**15%**	**22%**	**25%**	**35%**

Based on Table 27, we can compare the results with the reference scenario. Thus, the following conclusions can be deduced from CO2 emissions from European maritime transport in 2050:

- The emission reduction potentials of the scenarios are 15, 22, 25, and 35 percent, respectively. Here, the reduction potential between 250 EUR/tonne fuel price and 400 EUR/tonne appears to be very close to each other.
- Emission reduction potential has also been observed to decrease NPV positive measures for low fuel prices. Therefore, it can be said that the Fuel price has an important effect.
- As a result of the implementation of 12 reduction measures, which are CO_2 reduction measures, this thesis is expected to have a maximum CO_2 abatement potential of 35%. In other words, CO_2 emissions expected to be 211 million tons in 2050 are likely to fall to 138 million tons or below.

Based on Table 27, the potentials of CO_2 abatement were calculated for the EU-MRV data and presented in Figure 31. This is done for the reference fuel price which is 250 EUR/tonne.

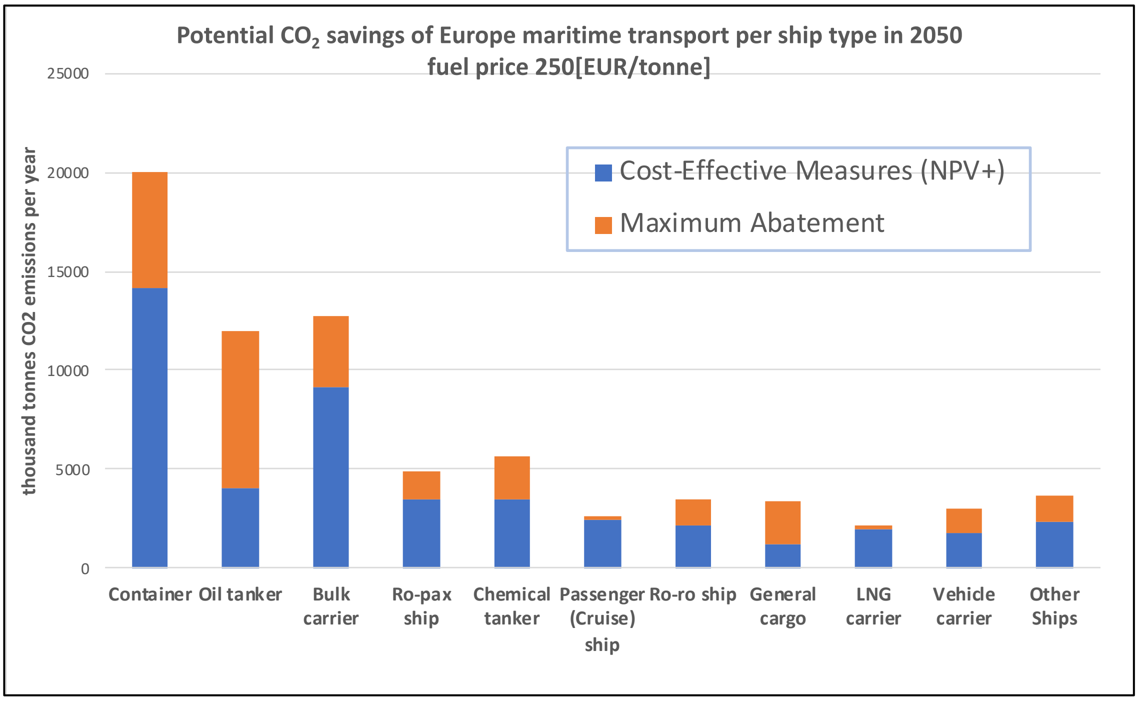

Figure 31. Potential CO_2 savings of Europe maritime transport per ship type in 2050, fuel price 250[EUR/tonne]

4.1. Abatement scenarios for Europe

In Section 3.2.4, estimates for 2050 are made for EU MRV data and various references. For Europe, a baseline was created based on the GDP growth rate of 1.35%, and in the light of this baseline, it is estimated that freight works will increase by approximately 52%. It is estimated that there will be a total of 211 million tons of CO_2 emissions. When the results are calculated with the reduction scenarios in this study, the following results are obtained. Table 28 shows these results.

Table 28. Estimation of CO_2 emissions with abatement scenarios up to 2050 in Europe

Year [million tonnes]	2018	2020	2030	2040	2050
Baseline	139	141	161	184	211
EEDI & SEEMP	139	141	139	151	164
Cost-Effective Measures (NPV+)	139	141	143	154	165
Maximum Abatement	139	141	133	136	137
EEDI & SEEMP + Cost-Effective Measures (NPV+)	139	141	123	128	128
EEDI & SEEMP + Maximum Abatement	139	141	114	114	107

The EEDI+SEEMP predictions were made by using the analysis from previous studies. The new projections were made using operational and technical reduction measures. As a result of the application of all emission reduction technologies (Maximum Abatement), it is seen that emissions will fall below the 2018 values despite the increase in freight works. At the same time, EEDI and SEEMP, which are mandatory for all ships, and the use of technologies in this study will help to reduce emissions to almost 107 million tonnes, which in turn, shows a 50% decrease. If EEDI and SEEMP and NPV positive technologies are used, emissions in 2050 are expected to be around 128 million tons, while this has shown a 39% reduction compared to baseline.

The graphical representation of the values in Table 28 is as follows;

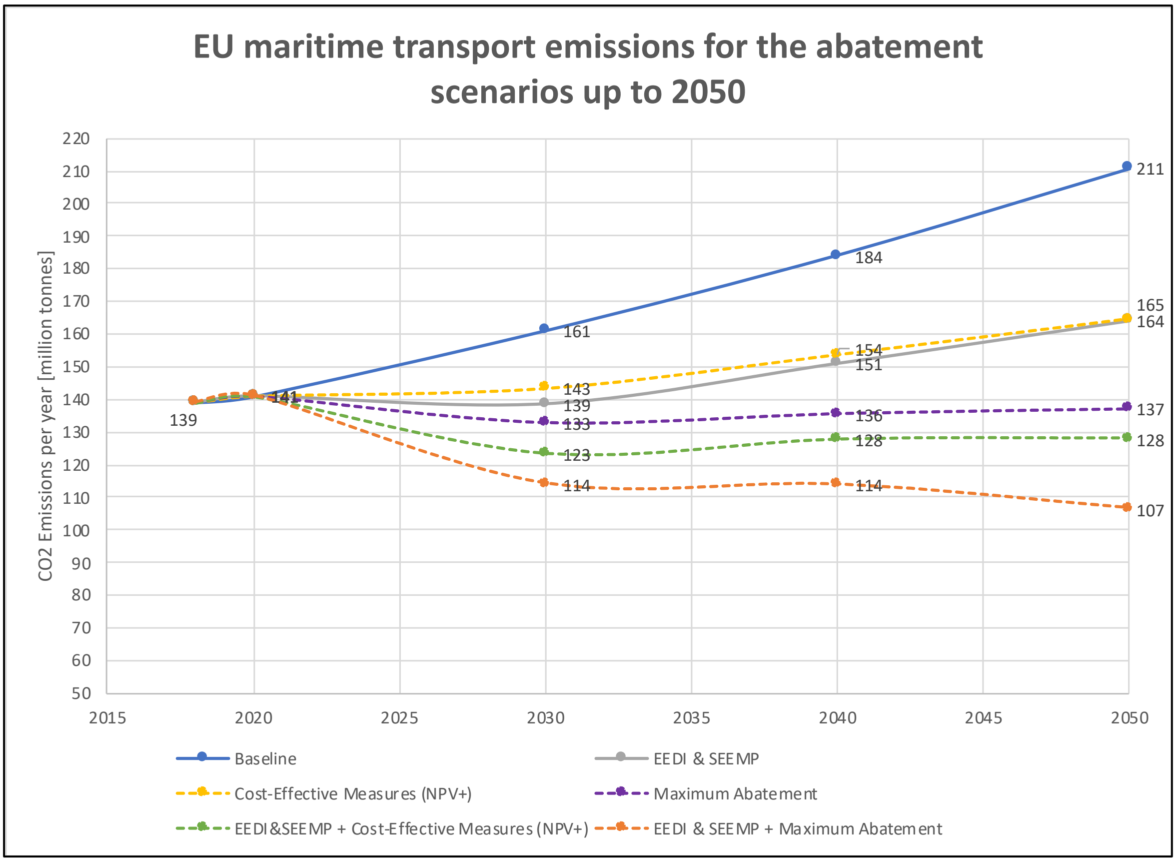

Figure 32. EU maritime transport emissions for the abatement scenarios up to 2050

4.2. Suggestions for further studies

The use of the systems in this study on new ships has been about reducing CO_2 emissions from ships. Besides, calculations were made based on some reference values, and a vision was created for the future. More effects can be observed with new technologies. The analysis results here are not made for any investment purpose. Today, actions that can be taken to reduce the increasing greenhouse gas emissions have been tried to be shown.

Further studies, emission values that may occur in the use of ships with different fuel types can be examined, and cost-benefit analyzes of these techniques can be made with varying types of fuel. Besides, the effects of technologies on CO_2 emissions can be reviewed on a ship basis by making analyzes. The values taken in this study are based on general estimates created by observations of IMO and other references.

The reference source in this study is EU-MRV. Emission reduction estimates for ships larger than 5000 gross tons have been found in EU MRV data. However, apart from the ships that are referenced in this study, analysis for ships such as Yacht, Offshore, Service, Fishing, and other (unspecified) can be done in future studies.

Also, the effects of using these systems together with an exhaust gas cleaning system (Scrubber) can be examined in later studies. Especially the impact of hybrid scrubber systems on CO2 emissions was observed in previous studies.

Conclusion

One of the most critical problems of recent years is global warming. The most important reason for global warming is the increase in greenhouse gas (GHG) emissions in the atmosphere. Scientists have been aware of the effects of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere for many years. Burning fuel oils mostly cause emissions. An essential share of emissions belongs to the transport sector. The transport sector consists of several industries, including airlines, maritime, road and rail, transportation infrastructure, and freight and logistic services.

According to the European Environment Agency report; In 2016, the transport sector contributed 27% of the total EU-28 GHG emissions. Europe, which is responsible for approximately 10% of global GHG emissions, is playing a leading role concerning the shift to an economy with net-zero GHG emissions.

Ships are one of the essential vehicles used in freight works and passenger transportation. For this reason, emissions from the maritime industry are continuously increasing. There are many different studies to reduce emissions from ships. The International Maritime Organization aims to reduce CO_2 emissions like other harmful gases. The most important of these are methods such as the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), and Energy Efficiency Operational Indicator (EEOI). The European Union (EU) has set up strategies to reduce these gases through various regulations. One of these strategies is EU-MRV Shipping Regulation 2015/757 (Directive 2009/16 / EC). EU-MRV applies to larger ships over 5000 gross tonnages on all voyages to or from EU ports. Thanks to MRV regulation, it is possible to monitor CO_2 emissions for ships traveling to European ports. According to EU-MRV data used in this study, it is seen that total CO_2 emissions are 139 million tons in 2018 to 2019. These emissions are expected to increase rapidly with increasing freight works. This thesis aims to calculate the marginal abatement cost of measures that can be taken to reduce CO_2 emissions from maritime transport and to examine the potential of these measures to reduce CO_2 emissions from ships.

The increase in emissions from ships was estimated in this study according to GDP, OECD freight works estimation, and the Third IMO GHG projections. Five different scenarios were used for these estimations. A baseline is estimated with the GDP rate, which is calculated at 1.35% annually for the European Union (EU-28). The CO_2 emissions from ships will be expected at 211 million tonnes in 2050, that is, an increase of 52% compared to the 2018-2019 period for the baseline estimation. If IMO actions (EEDI & SEEMP) are implemented, CO_2 emissions from ships will estimate to be approximately 164 million tonnes.

Reducing CO_2 emissions from ships is primarily possible by increasing the efficiency of the ships, and there are different methods for this. The effects of these methods can be easily intelligible with Marginal Abatement Costs (MAC) curves. Marginal abatement cost and MAC curves are frequently used in kind of environmental, economic analysis.

The MAC curves are defined as a curve that usually shows the cost in terms of currency per tonne CO_2 emissions (e.g., EUR/tonne CO_2 emissions), depending on the amount of emission reduction (yearly cumulative tonnes of CO_2 emissions) and the marginal cost. Therefore, such the MAC curves compare the marginal abatement cost on the Y-axis and the emission reduction level on the X-axis.

Various emission abatement measures should be determined for the MAC curves, and these should be calculated according to the lifetime of actions. Net Present Value (NPV) for MAC accounts can be found by dividing total decreased CO_2 emissions. If NPV is positive, it is expected that the mac value will be negative, which means that the applied measures will provide us with a net profit throughout the life of the project. Measures with negative NPV show that investment cannot be met throughout the ship's lifetime. All of the measures have the potential to reduce CO_2 emissions.

There are two essential factors for MAC calculation; Fuel Price and Discount Rate. Fuel price is critical for the accuracy of NPV and MAC calculations. The CME group's future oil price estimation (55 dollars per barrel) value was used for calculations. In this thesis, it was assumed that ships use the most common type of ship fuel, which is Heavy Fuel Oil (HFO). The Carbon Factor (CF) is 3.114 (t-CO_2/t-fuel) for HFO. The correlation between crude oil price and HFO is assumed approximately five times (Crude Oil Price*5.209+ 1.392). Accordingly, the HFO reference price used in the calculations is taken as 250 EUR/tonne. Besides, 150 EUR/tonne and 400 EUR/tonne HFO prices were used for sensitivity analysis.

The second essential component is the discount rate. Typical discount rates could be 3% in the public sector and 9% in the private sector. However, these values vary by sector type. An exclusive discount rate account for the Shipbuilding & Marine industry will provide more reliable results in MAC curves analysis. Therefore, the cost of capital was calculated for the European Shipbuilding & Marine industry, and the cost of capital (EUR) value, which is 6%, was used as a discount rate for the MAC calculation.

The measures must be determined for marginal abatement cost calculations. Twelve different technical or operational measures are assessed in 3 chapters. The abatement potential, investment, and operational costs of these technologies were also explained in the same section. Furthermore, alternative technology (exhaust gas cleaning system (Scrubber)) has mentioned the end of the chapter. This system is not only used for reducing CO_2 emissions but also to reduce SOx and NOx emissions. However, this system was not taken as a reference method because it did not increase energy efficiency. The effects of this method can be examined in further studies. Most techniques used in this study have been calculated as applicable to new ships. However, operational methods can also be applied to existing ships.

After all assumptions and measures were determined, the ship types had been identified. The EU-MRV data was used for the selection of reference ships, and when this data was analyzed, it was observed that nine different ship types caused 95% of the total emissions. These nine types of ships were taken as reference ships and were predicted Deadweight tonnage (DWT) values, which are expected to be in 2050 with increased shipping. Main engine power (kWh), DWT, and speed values are essential for calculations. Average fuel consumption, which is consumed annually for ship types, was obtained from the data shared by DNV GL.

Appropriate methods were determined for the ships, and MAC calculations were made. Marginal abatement cost curves for each ship type were obtained at the end of the three sections. Curves are ranked from the most cost-effective method to the least, which means the most cost-effective measure used first. The individual effects of all measures were calculated separately, and the order of the technologies in the MAC values was determined based on the results from these calculations (see appendix 6).

During the last section, the results obtained from MAC curves are discussed in two different scenarios. The first is the situation where only cost-effective measures are applied to ships, and the second is the expected emission reduction potentials if all abatement methods are used. The cost-effective measures, which means NPV positive measures, were analyzed how much CO_2 emissions from ships decreased when applied. These methods were also calculated separately for three different fuel price estimations for sensitivity analysis. The maximum abatement potential had been calculated as the potential of reducing the maximum CO_2 emissions as a result of applying all applicable measures to the type of ships.

Finally, future CO_2 emissions scenarios were estimated thanks to emission abatement potentials. A model has been developed for estimations. As previously mentioned, all abatement measures can be applied for new-built ships but cannot to existing ships. Therefore, it had been assumed that existing vessels use only 50% of these measures. For example; Total CO_2 emissions in 2050 will be expected to be approximately 9 million tonnes for the General Cargo ships. If all abatement measures are applied, existing vessels (50% of ships) will have an impact of 50% of the abatement potential. The remaining ships are considered as new-built ships, and the maximum abatement potential is applied as 100%. As a result, CO_2 emissions from general cargo ships were calculated to decrease to about 5.6 million tonnes in 2050. As a result of these calculations, the expected new average emission reduction potentials were determined.

In 2050, the potential CO_2 saving fuel price of EU maritime shipping per ship type was calculated with 250 [EUR/tonne]. The results were shared with the effect of the emissions estimated by the previous GDP on the future forecast. The baseline was created for GDP, and it was estimated at 211 million tonnes in 2050. If only cost-effective measures (NPV +) are used, emissions are expected to decrease by 22% and are expected to be around 165 million tonnes. If all emission reduction measures are applied (Maximum Abatement), emissions will be reduced by 35% and will be reduced to 137 million tonnes. This value is below the reference year CO_2 Emissions. If cost-effective measures (NPV+) and maximum abatement scenarios are applied with the IMO EEDI & SEEMP strategies, CO_2 emissions are expected to drop 128 million tonnes and 107 million tonnes respectively despite a 52% increase in freight works.

In summary, the results show that it is possible to keep the emissions at the desired levels or even below with emission abatement measures. Also, these methods will not only reduce CO_2 emissions but also help minimize other harmful gases from ships. With cost-effective ways (NPV +), shipowners will have more efficient ships, and at the same time, the emissions caused by the ships will be reduced.

The results obtained in the thesis study may be affected by possible socio-economic changes in the future. Also, types of fuels could be replaced, or more efficient ships can be built with new technologies by 2050. In calculations, estimates have been made for ships larger than 5000 gross tonnages, but analysis may be made for other types of ships in future studies. The effects of different measures can also be observed.

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Appendices

Appendix 1: European Union Member States (28 Countries), (EU-28),

(based on data from [13])

#	Country	Abbreviation of Country
1	Austria	(AT)
2	Belgium	(BE)
3	Bulgaria	(BG)
4	Croatia	(HR)
5	Cyprus	(CY)
6	Czechia	(CZ)
7	Denmark	(DK)
8	Estonia	(EE)
9	Finland	(FI)
10	France	(FR)
11	Germany	(DE)
12	Greece	(EL)
13	Hungary	(HU)
14	Ireland	(IE)
15	Italy	(IT)
16	Latvia	(LV)
17	Lithuania	(LT)
18	Luxembourg	(LU)
19	Malta	(MT)
20	Netherlands	(NL)
21	Poland	(PL)
22	Portugal	(PT)
23	Romania	(RO)
24	Slovakia	(SK)
25	Slovenia	(SI)
26	Spain	(ES)
27	Sweden	(SE)
28	United Kingdom	(UK)

Appendix 2: The Reference Ships

Details for the reference ships were found online on the MarineTraffic [98]. These ships were selected in the EU-MRV data [40].

IMO Number	Year Built	Name	Type	Details	Gross Tonnage	DWT	Speed [knot]	Main Engine Power [kW]
9705081	2015	CMA CGM VOLGA	Container	9002 TEU	95793	113800	22	47430
9806055	2018	ONE COLUMBA	Container	14052 TEU	145647	139500	-	42180
9593012	2015	ISTANBUL	Oil tanker	Crude oil tanker (~80'dwt)	83377	149989	14.8	18660
9817494	2018	MORVIKEN	Oil tanker	Crude oil tanker (~80'dwt)	83000	158000	14.5	16400
9615121	2012	YUE DIAN 102	Bulk carrier		64654	115169	14.3	13560
9620566	2014	MA LIAN HAI	Bulk carrier		64654	115297	14.3	13080
9721657	2016	SYMPHONY SEA	General Cargo		6749	10600	13.5	2999
9742417	2016	THORCO LOGIC	General Cargo		13110	16969	16.3	5180
9617650	2015	STOLT LARIX	Chemical Tanker	Oil/Chemical	22424	30297	14.8	8280
9820295	2018	MARVIN CONFIDENCE	Chemical Tanker	Oil/Chemical	30000	49000	14.5	7180
9636955	2016	AIDAPRIMA	Passenger (Cruise) Ship	Big Size	125572	9200	14	28000
9704130	2015	LE LYRIAL	Passenger (Cruise) Ship	Normal Size	10992	1400	16	4600
9666998	2015	LNG JUROJIN	LNG Carrier		136739	86121	21.1	26000
9737187	2016	CHRISTOPHE DE MARGERIE	LNG Carrier		128806	96779	19.5	45000
9762534	2017	SIEM CICERO	Ro-Ro & Vehicle Carrier	Vehicle	56677	17416	18.5	11200
9784037	2017	GRANDE BALTIMORA	Ro-Ro & Vehicle Carrier	Ro-Ro	62134	18447	19	12200
9665437	2014	LOCH SEAFORTH	Ro-Pax ship	SmalL Size	8680	1442	19.2	12800
9773064	2017	MEGASTAR	Ro-Pax ship	Big Size	49134	6080	27	40600

Appendix 3: Third IMO GHG Study (2012) data summary

(based on data from [35,101])

Average speed [knot], Average Installed Power [kW] and, Average Capacity of ships IMO 2012

Ship Type	Average Speed [knot]	Average Capacity	Capacity Unit	Average Installed Power [kW]
Bulk carrier	14,8	68569	DWT	9390
Oil tanker	13,2	59094	DWT	7551
Container	21,3	41638	TEU	26820
Liquefied gas tanker	15,6	27622	CBM	10147
Chemical tanker	13,6	17982	DWT	4918
Vehicle	19,5	16165	Vehicle	12505
Refrigerated bulk	16,8	5695	DWT	5029
General cargo	12,4	5333	DWT	2259
Cruise	17,2	3743	GT	21681
Ro-Ro	12,6	3539	DWT	4126
Ferry-RoPax	16,6	1580	GT	7351
Other liquids tankers	9,8	670	DWT	558
Other Ship Type	12,2	491	-	2089
Ferry-pax only	22,5	170	GT	1991

Appendix 4: Marginal Abatement Costs (MAC) and NPV Results

Fix Values		Unit
Discount Rate	6%	-
Fuel Price	250	[EUR/tonne]
Inflation Rate	2%	-
Carbon Factor (HFO)	3,114	[tonne-CO_2/tonne-fuel]

Details of the graphics drawn in 3 sections are shared in this appendix. Lifetime is 25 years for all technologies. For the MAC account, the annual CO_2 saving values should be multiplied by 25, and the formula (9) should be applied.

Container ship >8000TEU				
Technology	MAC [EUR/Tonne]	NPV [EUR]	CO_2 Saving Yearly [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(40,62)	2.371.879,28	2.336	2.336
Advanced Route Planning	(38,13)	2.115.261,21	2.219	4.554
Autopilot adjustment	(37,14)	587.180,96	632	5.187
Propeller upgrade	(36,05)	2.994.177,27	3.322	8.508
High-efficient lighting	(27,09)	388.083,08	573	9.081
Propeller Polishing	(24,63)	231.739,29	376	9.458
Slender Design	(14,21)	1.323.128,10	3.725	13.183
Speed Reduction	0,41	(6.795,62)	671	13.854
Hybridization	28,52	(1.639.600,71)	2.300	16.153
Waste Heat Recovery	94,02	(5.746.050,94)	2.445	18.598
Wind Power (Kite)	n/a	n/a	-	-
Solar Power	n/a	n/a	-	-

Oil Tanker 80' DTW				
Technology	MAC [EUR/tonne]	NPV [EUR]	Annual CO_2 Saving [tonne]	Annual Cumulative CO_2 Saving [tonne]
Advanced Route Planning	(36,66)	1.141.561,51	1.246	1.246
Optimization of Trim/Draft	(35,10)	147.575,31	168	1.414
Autopilot adjustment	(26,13)	108.212,57	166	1.579
Propeller upgrade	(21,97)	477.996,68	870	2.450
High-efficient lighting	12,25	(45.958,07)	150	2.600
Slender Design	19,82	(976.916,01)	1.971	4.571
Propeller Polishing	37,29	(73.511,90)	79	4.650
Speed Reduction	97,43	(3.422.656,50)	1.405	6.055
Hybridization	137,49	(1.540.144,92)	448	6.503
Wind Power (Kite)	280,70	(3.342.043,45)	476	6.979
Waste Heat Recovery	1.018,66	(6.973.781,03)	274	7.253
Solar Power	1.727,17	(1.123.301,47)	26	7.279

Bulk Carier				
Technology	MAC [EUR/tonne]	NPV [EUR]	Annual CO_2 Saving [tonne]	Annual Cumulative CO_2 Saving [tonne]
Advanced Route Planning	(37,20)	1.563.978,98	1.682	1.682
Optimization of Trim/Draft	(36,65)	207.976,67	227	1.909
Autopilot adjustment	(30,00)	167.707,91	224	2.132
Propeller upgrade	(26,92)	790.545,52	1.175	3.307
High-efficient lighting	(21,31)	107.956,60	203	3.509
Slender Design	(10,99)	1.096.745,08	3.992	7.501
Propeller Polishing	25,27	(58.844,54)	93	7.594
Speed Reduction	35,79	(1.402.695,83)	1.568	9.162
Hybridization	85,87	(1.150.171,75)	536	9.698
Wind Power (Kite)	228,05	(3.246.414,83)	569	10.267
Waste Heat Recovery	1.334,32	(6.553.204,02)	196	10.464
Solar Power	1.407,33	(1.117.405,71)	32	10.495

General Cargo				
Technology	MAC [EUR/Tonne]	NPV [EUR]	CO_2 Saving Yearly [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(34,75)	137.987,79	159	159
Advanced Route Planning	(23,64)	151.722,82	257	416
High-efficient lighting	(13,72)	25.096,62	73	489
Autopilot adjustment	(6,77)	12.196,07	72	561
Propeller upgrade	(6,19)	58.589,99	379	939
Slender Design	11,77	(256.243,03)	871	1.810
Propeller Polishing	136,28	(118.684,98)	35	1.845
Hybridization	141,22	(852.250,57)	241	2.087
Wind Power (Kite)	158,66	(636.068,22)	160	2.247
Speed Reduction	346,01	(2.899.175,82)	335	2.582
Waste Heat Recovery	2.149,35	(4.371.328,57)	81	2.663
Solar Power	n/a	n/a	-	-

Chemical Ship

Technology	MAC [EUR/tonne]	NPV [EUR]	Annual CO_2 Saving [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(34,93)	142.781,55	163	163
Advanced Route Planning	(32,72)	439.108,65	537	700
Autopilot adjustment	(24,90)	95.227,48	153	853
Propeller upgrade	(22,51)	452.281,66	804	1.657
High-efficient lighting	(12,20)	42.274,84	139	1.796
Slender Design	(8,10)	368.542,85	1.821	3.616
Propeller Polishing	43,77	(79.693,55)	73	3.689
Hybridization	61,98	(782.039,92)	505	4.194
Wind Power (Kite)	99,27	(1.248.077,94)	503	4.697
Speed Reduction	134,71	(3.550.946,78)	1.054	5.751
Waste Heat Recovery	1.190,46	(4.596.320,73)	154	5.905
Solar Power	1.801,34	(1.124.376,25)	25	5.930

Passenger Ship

Technology	MAC [EUR/tonne]	NPV [EUR]	Annual CO_2 Saving [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(40,25)	1.253.335,62	1.246	1.246
Autopilot adjustment	(38,35)	877.802,57	916	2.161
Propeller upgrade	(38,31)	4.605.909,48	4.810	6.971
High-efficient lighting	(33,82)	2.338.147,95	2.765	9.736
Propeller Polishing	(29,29)	384.812,85	525	10.262
Hybridization	(14,14)	3.677.112,59	10.404	20.665
Waste Heat Recovery	40,74	(2.119.395,66)	2.081	22.746
Solar Power	191,66	(947.134,86)	198	22.944
Slender Design	n/a	n/a	-	-
Wind Power (Kite)	n/a	n/a	-	-
Speed Reduction	n/a	n/a	-	-
Advanced Route Planning	n/a	n/a	-	-

LNG Carrier				
Technology	MAC [EUR/tonne]	NPV [EUR]	Annual CO_2 Saving [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(40,34)	1.419.519,25	1.408	1.408
Advanced Route Planning	(39,75)	3.427.298,05	3.448	4.856
Autopilot adjustment	(38,54)	946.861,46	983	5.839
Propeller upgrade	(37,84)	4.883.698,83	5.163	11.002
High-efficient lighting	(36,56)	814.025,55	891	11.892
Propeller Polishing	(30,49)	445.774,85	585	12.477
Slender Design	(27,23)	3.942.080,08	5.790	18.267
Hybridization	(16,93)	1.543.510,45	3.648	21.915
Waste Heat Recovery	23,91	(1.014.085,82)	1.696	23.611
Solar Power	155,68	(910.027,61)	234	23.845
Wind Power (Kite)	n/a	n/a	-	-
Speed Reduction	n/a	n/a	-	-

Ro-Ro & Vehicle Carrier				
Technology	MAC [EUR/Tonne]	NPV [EUR]	CO_2 Saving Yearly [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(39,69)	729.218,01	735	735
Advanced Route Planning	(35,98)	793.287,51	882	1.617
Autopilot adjustment	(31,22)	196.168,46	251	1.868
Propeller upgrade	(29,77)	982.558,25	1.320	3.188
High-efficient lighting	(23,49)	133.747,55	228	3.416
Slender Design	(19,66)	1.102.413,35	2.243	5.660
Propeller Polishing	7,54	(23.965,17)	127	5.787
Hybridization	38,40	(845.842,28)	881	6.668
Speed Reduction	77,70	(3.637.688,46)	1.873	8.541
Wind Power (Kite)	270,65	(3.326.283,70)	492	9.032
Waste Heat Recovery	663,09	(5.419.312,38)	327	9.359
Solar Power	979,64	(1.103.748,13)	45	9.404

Ro-Pax				
Technology	MAC [EUR/Tonne]	NPV [EUR]	CO_2 Saving Yearly [tonne]	Annual Cumulative CO_2 Saving [tonne]
Optimization of Trim/Draft	(39,32)	569.426,06	579	579
Autopilot adjustment	(35,25)	375.129,05	426	1.005
Propeller upgrade	(35,15)	1.965.197,91	2.236	3.241
Slender Design	(25,50)	1.639.477,59	2.572	5.813
High-efficient lighting	(18,01)	156.329,48	347	6.160
Propeller Polishing	(13,96)	79.554,43	228	6.388
Hybridization	22,24	(878.451,46)	1.580	7.968
Waste Heat Recovery	82,99	(2.177.646,65)	1.050	9.018
Wind Power (Kite)	n/a	n/a	-	-
Solar Power	n/a	n/a	-	-
Speed Reduction	n/a	n/a	-	-
Advanced Route Planning	n/a	n/a	-	-

Appendix 5: Statistical Analysis of EU-MRV data with Python

The EU-MRV has 11729 different ships [40]. However, since not all ships have Fuel consumption value, ships with fuel consumption value of zero (0) and empty are not used in the analysis below. The following analyzes were made for 11085 ships.

```
df_MRVData = pd.read_excel (‘Data_path /DataName.xlsx')

cols_to_include = ['Name', 'Ship type', 'Technical efficiency', 'Total fuel consumption [m tonnes]',

               'Total CO₂ emissions [m tonnes]', 'Annual Total time spent at sea [hours]',

           'Annual Total time spent at sea [Days]']

df_MRVData = df_MRVData.loc[:, cols_to_include]
```

```
# Sum of 'Total CO₂ emissions [m tonnes]'

#metric tonnes = m Tonnes = tonnes

Sum_of_CO2_All_Ship =  df_MRVData['Total CO₂ emissions [m tonnes]'].sum()

print('Total CO₂ emissions for all Ship types = ', Sum_of_CO2_All_Ship , '[m tonnes]')
```

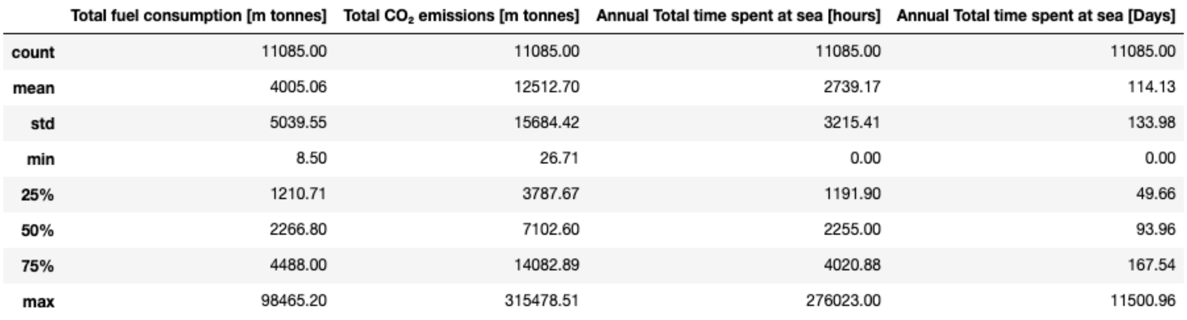
Result;

```
Total CO₂ emissions for all Ship types =  138703265.92000002 [m tonnes]
Total CO₂ emissions for all Ship ≈  139.0 [million tonnes]
```

Appendix 5.1. Summary of EU-MRV data

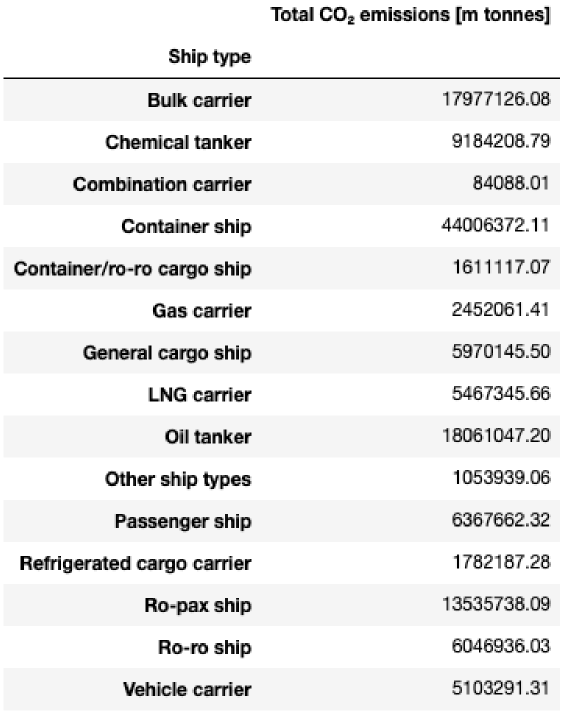
```
# Statistical Analysis of EU-MRV

df_MRVData.describe().round(2)
```

Result;

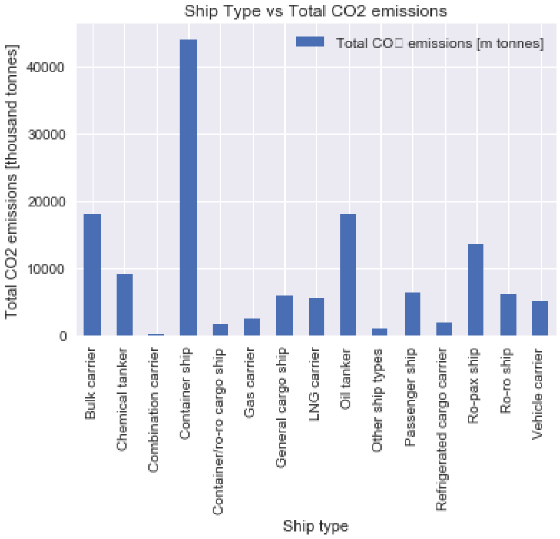


	Total fuel consumption [m tonnes]	Total CO₂ emissions [m tonnes]	Annual Total time spent at sea [hours]	Annual Total time spent at sea [Days]
count	11085.00	11085.00	11085.00	11085.00
mean	4005.06	12512.70	2739.17	114.13
std	5039.55	15684.42	3215.41	133.98
min	8.50	26.71	0.00	0.00
25%	1210.71	3787.67	1191.90	49.66
50%	2266.80	7102.60	2255.00	93.96
75%	4488.00	14082.89	4020.88	167.54
max	98465.20	315478.51	276023.00	11500.96

```
# Pivot Table of CO2 emissions vs Ship Types [Values Metric Tonnes]
table = pd.pivot_table(df_MRVData, values='Total CO₂ emissions [m tonnes]', columns=['Ship
type'],aggfunc=np.sum)
PivotTable = round(table.T) #numbers are rounded

#Creating bar graphs from Pivot Table [Values are thousand Tonnes]
(PivotTable/1000).plot(kind='bar')   #  /1000 => tonnes converted thousand tonnes
plt.title('Ship Type vs Total CO2 emissions')
plt.ylabel('Total CO2 emissions [thousand tonnes]')
plt.show() plt.show()
```

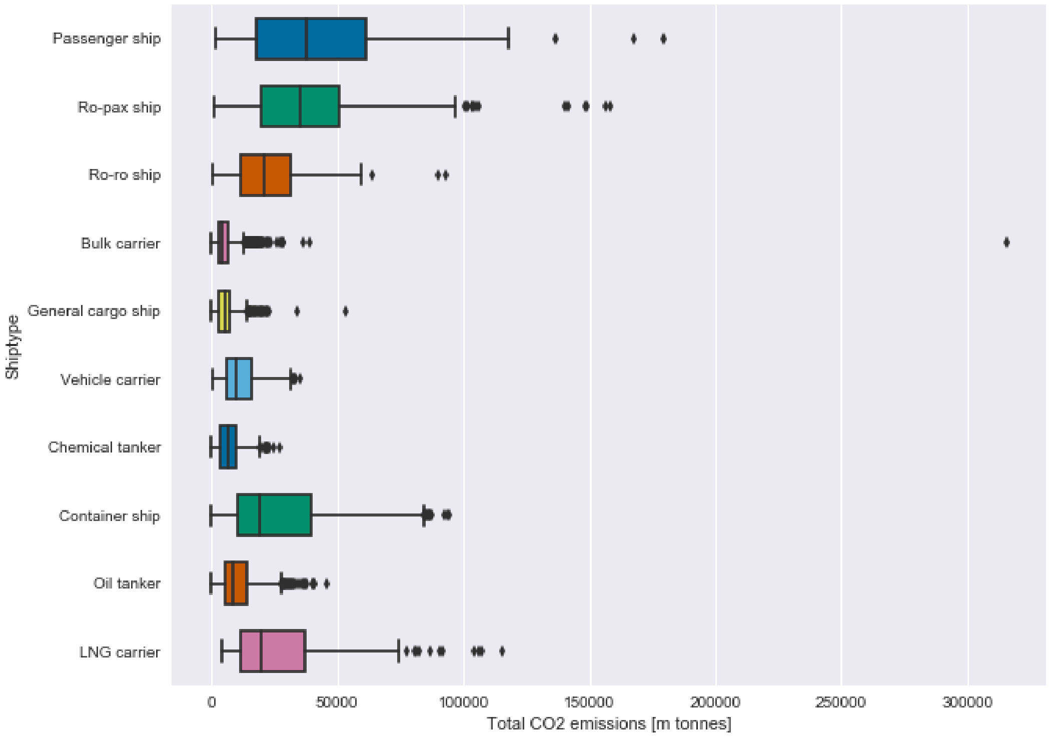


Ship type	Total CO$_2$ emissions [m tonnes]
Bulk carrier	17977126.08
Chemical tanker	9184208.79
Combination carrier	84088.01
Container ship	44006372.11
Container/ro-ro cargo ship	1611117.07
Gas carrier	2452061.41
General cargo ship	5970145.50
LNG carrier	5467345.66
Oil tanker	18061047.20
Other ship types	1053939.06
Passenger ship	6367662.32
Refrigerated cargo carrier	1782187.28
Ro-pax ship	13535738.09
Ro-ro ship	6046936.03
Vehicle carrier	5103291.31



Appendix 5.2. CO$_2$ emissions by Ship Type with Boxplot

```
#search references ships
searchreferenceShips = ['Oil tanker', 'Container ship','Chemical tanker', 'Ro-pax ship', 'General
cargo ship',  'Bulk carrier', 'Passenger ship', 'Ro-ro ship', 'Vehicle carrier', 'LNG carrier']

df_ReferenceShips =
df_MRVData[df_MRVData.Shiptype.str.contains('|'.join(searchreferenceShips))]

#Creating Boxplot with Python Pandas

bplot = sns.boxplot(y='Shiptype', x='Total CO2 emissions [m tonnes]',

data=df_ReferencesShips,

width=0.6,

palette="colorblind")
```


Passenger ship
Ro-pax ship
Ro-ro ship
Bulk carrier
General cargo ship
Vehicle carrier
Chemical tanker
Container ship
Oil tanker
LNG carrier
Shiptype
0
50000
100000
150000
200000
250000
300000
Total CO2 emissions [m tonnes]

Appendix 6: CO_2 Emission abatement technologies Individual MAC and NPV Values

Fix Values		Unit
Discount Rate	6%	-
Fuel Price	250	[EUR/tonne]
Inflation Rate	2%	-
Carbon Factor (HFO)	3,114	[tonne-CO2/tonne-fuel]

The fixed values used in the MAC and NPV accounts below are in the table above. The characteristics of the reference ships can be accessed from Table 21. and Appendix 2. The tables below show the expected MAC and NPV values for individual emission abatement technologies. So, the previous technology has no effect on the next technology, the results of individual effects are shared. these tables were used to find the cumulative effect.

Container Ship	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (40,62)	€ 2.371.879,28
Advanced Route Planning	€ (38,28)	€ 2.235.105,17
Autopilot adjustment	€ (37,52)	€ 657.289,68
Propeller upgrade	€ (36,04)	€ 3.366.727,03
High-efficient lighting	€ (29,63)	€ 519.063,78
Propeller Polishing	€ (27,83)	€ 324.940,59
Slender Design	€ (19,64)	€ 2.293.758,56
Speed Reduction	€ (11,29)	€ 263.793,03
Hybridization	€ 7,88	€ (644.369,01)
Waste Heat Recovery	€ 47,31	€ (4.419.811,34)
Wind Power (Kite)	n/a	n/a
Solar Power	n/a	n/a

Oil Tanker	Output	
Technology	MAC	NPV
Advanced Route Planning	€ (36,66)	€ 1.141.561,51
Optimization of Trim/Draft	€ (35,70)	€ 166.750,34
Autopilot adjustment	€ (27,83)	€ 129.976,24
Propeller upgrade	€ (23,82)	€ 593.460,54
High-efficient lighting	€ 1,77	€ (8.249,66)
Slender Design	€ 7,12	€ (443.328,77)
Propeller Polishing	€ 8,54	€ (26.601,70)
Speed Reduction	€ 45,74	€ (2.563.706,66)
Hybridization	€ 50,70	€ (1.105.165,07)
Wind Power (Kite)	€ 112,72	€ (2.808.135,22)
Waste Heat Recovery	€ 424,90	€ (6.615.650,38)
Solar Power	€ 697,55	€ (1.086.083,22)

Bulk Carier	Output	
Technology	MAC	NPV
Advanced Route Planning	€ (37,20)	€ 1.563.978,98
Optimization of Trim/Draft	€ (37,09)	€ 233.862,96
Autopilot adjustment	€ (31,25)	€ 197.088,86
Propeller upgrade	€ (28,14)	€ 946.421,73
High-efficient lighting	€ (25,19)	€ 158.862,96
Slender Design	€ (17,26)	€ 2.177.259,24
Propeller Polishing	€ (4,32)	€ 18.140,05
Speed Reduction	€ 1,09	€ (77.707,38)
Hybridization	€ 16,72	€ (491.972,84)
Wind Power (Kite)	€ 72,86	€ (2.450.201,25)
Waste Heat Recovery	€ 494,55	€ (6.237.092,26)
Solar Power	€ 506,06	€ (1.063.712,35)

General Cargo	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (34,75)	€ 137.987,79
Advanced Route Planning	€ (24,16)	€ 159.872,21
High-efficient lighting	€ (15,86)	€ 31.493,90
Autopilot adjustment	€ (9,93)	€ 19.719,79
Propeller upgrade	€ (9,31)	€ 98.595,73
Slender Design	€ 2,40	€ (63.414,73)
Propeller Polishing	€ 75,64	€ (100.106,00)
Hybridization	€ 77,69	€ (719.695,15)
Wind Power (Kite)	€ 79,94	€ (528.998,31)
Speed Reduction	€ 181,72	€ (2.645.518,61)
Waste Heat Recovery	€ 1.080,97	€ (4.291.830,39)
Solar Power	n/a	n/a

Chemical	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (34,93)	€ 142.781,55
Advanced Route Planning	€ (32,85)	€ 447.497,73
Autopilot adjustment	€ (25,94)	€ 106.007,44
Propeller upgrade	€ (23,39)	€ 509.902,97
High-efficient lighting	€ (16,58)	€ 67.781,55
Slender Design	€ (13,53)	€ 737.087,33
Propeller Polishing	€ 15,63	€ (42.580,90)
Hybridization	€ 27,11	€ (517.019,44)
Wind Power (Kite)	€ 45,28	€ (925.280,41)
Speed Reduction	€ 58,97	€ (2.731.533,65)
Waste Heat Recovery	€ 540,63	€ (4.419.255,08)
Solar Power	€ 803,06	€ (1.094.072,82)

Passenger Ship	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (40,25)	€ 1.253.335,62
Autopilot adjustment	€ (38,41)	€ 896.977,61
Propeller upgrade	€ (37,83)	€ 4.712.302,70
High-efficient lighting	€ (34,63)	€ 2.695.839,04
Propeller Polishing	€ (31,13)	€ 484.732,55
Hybridization	€ (18,57)	€ 5.783.356,16
Waste Heat Recovery	€ 13,60	€ (1.058.979,14)
Solar Power	€ 106,67	€ (830.416,10)
Slender Design	n/a	n/a
Wind Power (Kite)	n/a	n/a
Speed Reduction	n/a	n/a
Advanced Route Planning	n/a	n/a

LNG Carrier	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (40,34)	€ 1.419.519,25
Advanced Route Planning	€ (39,78)	€ 3.499.524,01
Autopilot adjustment	€ (38,71)	€ 1.021.615,33
Propeller upgrade	€ (37,53)	€ 5.282.802,06
High-efficient lighting	€ (37,26)	€ 983.389,43
Propeller Polishing	€ (32,27)	€ 567.824,36
Slender Design	€ (29,68)	€ 5.222.596,23
Hybridization	€ (23,19)	€ 2.855.817,36
Waste Heat Recovery	€ 3,68	€ (226.909,50)
Solar Power	€ 89,67	€ (788.870,19)
Wind Power (Kite)	n/a	n/a
Speed Reduction	n/a	n/a

RoRo & Vehicle	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (39,69)	€ 729.218,01
Advanced Route Planning	€ (36,18)	€ 830.998,41
Autopilot adjustment	€ (32,09)	€ 221.057,65
Propeller upgrade	€ (30,34)	€ 1.114.979,30
High-efficient lighting	€ (26,54)	€ 182.831,76
Slender Design	€ (23,63)	€ 1.628.317,55
Propeller Polishing	€ (7,43)	€ 34.119,24
Hybridization	€ 13,38	€ (430.118,48)
Speed Reduction	€ 34,60	€ (2.542.797,40)
Wind Power (Kite)	€ 125,75	€ (2.888.031,20)
Waste Heat Recovery	€ 316,92	€ (5.094.877,42)
Solar Power	€ 459,69	€ (1.055.722,75)

Ro-Pax	Output	
Technology	MAC	NPV
Optimization of Trim/Draft	€ (39,32)	€ 569.426,06
Autopilot adjustment	€ (35,36)	€ 384.045,44
Propeller upgrade	€ (34,78)	€ 2.014.670,76
Slender Design	€ (27,24)	€ 1.972.130,31
High-efficient lighting	€ (22,64)	€ 245.819,55
Propeller Polishing	€ (19,72)	€ 142.777,77
Hybridization	€ 8,28	€ (419.508,79)
Waste Heat Recovery	€ 48,86	€ (1.768.753,03)
Wind Power (Kite)	n/a	n/a
Solar Power	n/a	n/a
Speed Reduction	n/a	n/a
Advanced Route Planning	n/a	n/a