ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ
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Cruise shipping and emissions in Mediterranean ports

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Abstract

The control of SOx, NOx and CO2 exhaust emission from cruise ships is of particular importance because this type of ship is distinctively "fuel-thirsty" due to its generally very high auxiliary energy requirements, whilst its operational profile is consistent with frequent port calls to urban destinations (i.e. port-cities) which usually posses cultural and/or natural significance.

In this thesis a bottom-up methodology based on in-port ships activity has been applied to calculate the exhaust emissions of NOx, SO2 and CO2 produced during the stay (i.e. hoteling) of all the cruise ships at the top 10 cruise terminals within the Mediterranean Sea during 2019.

The results indicate that cruise ship traffic produces continuously increasing air pollution in ports over recent years, with top three cruise terminals, in terms of emissions, to be Barcelona, Palma de Mallorca and Venice. More importantly, however, the analysis of the ship emissions reveals that for any given ship traffic involving specific vessels using marine fuel of a given quality, the presence of other factors (e.g. seasonality etc) can also influence the ship emission levels. This is particularly evident in the case of the ports of Mediterranean Sea where Cruises is a common way of vacation, as the weather enhances this type of tourism, and at the same time increases air pollution and costs of associated damage.

An additional analysis will be presented, where the results that were found from MRV data base, which is a widely used inventory of entire shipping sector. In subject thesis, it will be used the data from MRV EMSA data base where data is only from European ports. For calculation purposes, it has been chosen passenger shipping only, so as to be compared with the data that have been collected for the subject study.

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1. Introduction

"Air pollution is now the world's largest single environmental health risk. Reducing air pollution could save millions of lives." (WHO, 25 March 2014)

Clean air is a basic requirement of human health and well-being. Air pollution, however, continues to pose a significant threat to health worldwide. According to an assessment of WHO for the burden of disease due to air pollution, more than two million premature deaths each year can be attributed to the effects of urban outdoor air pollution and indoor air pollution (from the burning of solid fuels) (WHO, 2005).

Air pollution has become a major threat to human health and the environment. The World Health Organization (WHO) considers the exposure to air pollution as the world's largest single environmental health risk, causing 4.2 million deaths every year occur as a result of exposure to ambient (outdoor) air pollution (WHO, 2014).

Maritime transport activities are contributors to air pollution problems especially with respect to air emissions resulting from the combustion process of marine engines. Hence, since the large portion of international ship traffic occurs not far from the coastline (Endresen et al., 2003) air pollution from ships can also have impacts on human health.

The maritime sector is becoming a more and more important role in the transport of goods and persons all over the world. Together with the growth of maritime traffic the attention towards the effect of ships on the environment is rising. The impact of ship emissions on air quality has different aspects (Toscano, 2019). It can be studied on a global or a local scale and in different sectors. The effect on the global scale depends mainly on emissions during navigation of ships between ports, while the local effects depend mainly on emissions while staying in ports or in their proximity. Emissions of CO_2 contribute significantly to the global warming effect while emissions of NOx, SOx, PM and VOCs impact mainly on human health and especially of port cities.

The future of tourism development is largely dependent on the natural environment and its preservation (Hall and Lew, 1998). Thus, environment is not only an important foundation for tourism sustainable development, but it can also be the foundation for unique attractions for tourists (Zi, 2015). Tourism by its very nature is a resource dependent industry and some commentators argue that sustainable tourism is unachievable given the industry's ability to pollute and consume resources (Johnson, 2002).

Public attention to the environmental impacts of the maritime industry has been especially focused on the cruise industry, in part because its ships are highly visible and in part because of the industry's desire to promote a positive image. It represents a relatively small fraction of the entire shipping industry worldwide. Also, it is well known that tourism and cruise are connected with a strong bond, as many people chose it as a method of vacations.

To the cruise ship industry, a key issue is demonstrating to the public that cruising is safe and healthy for passengers and the tourist communities that are visited by their ships. Cruise ships carrying several thousand passengers and crew have been compared to "floating cities," in part because the volume of wastes produced and requiring disposal is greater than that of many small cities on land. A passenger's carbon footprint triples in size when taking a cruise and the emissions produced can contribute to serious health issues (Forbes, 2019.)

Ports represent a source of atmospheric pollutants that can contribute significantly to jeopardize air quality of port cities. Carbon emissions and dangerous particulates emitted by cruise ships are caused by the quantity and quality of the fuel used by these floating "citadels" (Forbes, 2019.) NOx, SOx, PM and VOCs (Volatile Organic Compounds) are emitted by ships during maneuvering in ports at arrival or departure and during hoteling when moored at docks. The biggest issues with cruise emissions are the levels of nitrogen and sulphur oxides, which have been linked to acid rain, higher rates of cancer and other forms of respiratory diseases.

As such, all ship companies have been legislatively forced to switch to cleaner fuel alternatives of increasingly lower sulfur content and to implement design and operational energy efficiency measures.

However, the development of effective policy-making towards the control of ship exhaust emissions dictates the need for continuous delivery of reliable estimation and recording of emission inventories.

The current thesis attempts to make a valuable contribution towards meeting the above-mentioned objective, through reference to the exhaust emissions of cruise ships operating within the Mediterranean Sea. More specifically, the activity-based methodology is applied in order to estimate the ships' exhaust emissions during their stay (i.e. hoteling) at top Mediterranean cruise destinations.

Referrence will also be made at the MRV data base, where inventories will be used in order a comparison between data from entire Mediterranean Cruise shipping's emissions and from subject thesis data to be presented in graphical reproduction.

2. Literature review

"Climate change" and "global warming" are often used interchangeably but have distinct meanings. Similarly, the terms "weather" and "climate" are sometimes confused, though they refer to events with broadly different spatial and timescales.

"**If you don't like the weather in New England, just wait a few minutes.**"

- Mark Twain

Weather refers to atmospheric conditions that occur locally over short periods of time; from minutes to hours or days. Familiar examples include rain, snow, clouds, winds, floods or thunderstorms.

Climate, on the other hand, refers to the long-term regional or even global average of temperature, humidity and rainfall patterns over seasons, years or decades.

2.1 Global warming

Global warming is the long-term heating of Earth's climate system observed since the pre-industrial period (between 1850 and 1900) due to human activities, primarily fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere. The term is frequently used interchangeably with the term climate change, though the latter refers to both human- and naturally produced warming and the effects it has on our planet. It is most commonly measured as the average increase in Earth's global surface temperature.

Since the pre-industrial period, human activities are estimated to have increased Earth's global average temperature by about 1 degree Celsius (1.8 degrees Fahrenheit), a number that is currently increasing by 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade. Most of the current warming trend is extremely likely (greater than 95 percent probability) the result of human activity since the 1950s and is proceeding at an unprecedented rate over decades to millennia.

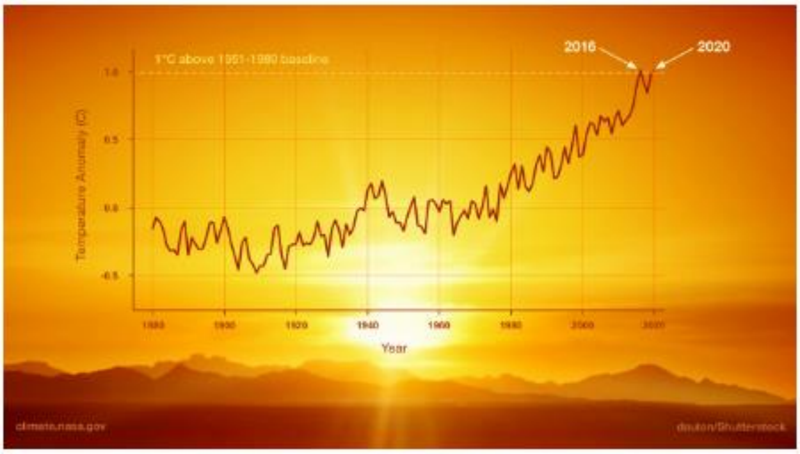


Figure 1 - Global Surface Temperature

Figure 1. *This graph illustrates the change in global surface temperature relative to 1951-1980 average temperatures, with the year 2020 tying with 2016 for warmest on record (Source: NASA's Goddard Institute for Space Studies).*

2.2 Climate change

Climate change is a long-term change in the average weather patterns that have come to define Earth's local, regional and global climates. These changes have a broad range of observed effects that are synonymous with the term.

Changes observed in Earth’s climate since the early 20th century are primarily driven by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth’s atmosphere, raising Earth’s average surface temperature. These human-produced temperature increases are commonly referred to as global warming. Natural processes can also contribute to climate change, including internal variability (e.g., cyclical ocean patterns like El Niño, La Niña and the Pacific Decadal Oscillation) and external forcings (e.g., volcanic activity, changes in the Sun’s energy output, variations in Earth’s orbit).

Scientists use observations from the ground, air and space, along with theoretical models, to monitor and study past, present and future climate change. Climate data records provide evidence of climate change key indicators, such as global land and ocean temperature increases; rising sea levels; ice loss at Earth’s poles and in mountain glaciers; frequency and severity changes in extreme weather such as hurricanes, heatwaves, wildfires, droughts, floods and precipitation; and cloud and vegetation cover changes, to name but a few. (NASA, Global Climate Change)

2.3 The Greenhouse Effect

Scientists attribute the global warming trend observed since the mid-20th century to the human expansion of the "greenhouse effect" (IPCC Fifth Assessment Report, 2014 , GSGCRP, 2009) — warming that results when the atmosphere traps heat radiating from Earth toward space.

Certain gases in the atmosphere block heat from escaping. Long-lived gases that remain semi-permanently in the atmosphere and do not respond physically or chemically to changes in temperature are described as "forcing" climate change. Gases, such as water vapor, which respond physically or chemically to changes in temperature are seen as "feedbacks."

Gases that contribute to the greenhouse effect include:

- Water vapor

The most abundant greenhouse gas, but importantly, it acts as a feedback to the climate. Water vapor increases as the Earth's atmosphere warms, but so does the possibility of clouds and precipitation, making these some of the most important feedback mechanisms to the greenhouse effect.

- Carbon dioxide (CO_2)

A minor but very important component of the atmosphere, carbon dioxide is released through natural processes such as respiration and volcano eruptions and through human activities such as deforestation, land use changes, and burning fossil fuels. Humans have increased atmospheric CO_2 concentration by 47% since the Industrial Revolution began. This is the most important long-lived "forcing" of climate change.

- Methane

A hydrocarbon gas produced both through natural sources and human activities, including the decomposition of wastes in landfills, agriculture, and especially rice cultivation, as well as ruminant digestion and manure management associated with domestic livestock. On a molecule-for-molecule basis, methane is a far more active greenhouse gas than carbon dioxide, but also one which is much less abundant in the atmosphere.

- Nitrous oxide

A powerful greenhouse gas produced by soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning.

- Chlorofluorocarbons (CFCs)

Synthetic compounds entirely of industrial origin used in a number of applications, but now largely regulated in production and release to the atmosphere by international agreement for their ability to contribute to destruction of the ozone layer. They are also greenhouse gases.

Consequences

The consequences of changing the natural atmospheric greenhouse are difficult to predict, but some effects seem likely.

- On average, Earth will become warmer. Some regions may welcome warmer temperatures, but others may not.
- Warmer conditions will probably lead to more evaporation and precipitation overall, but individual regions will vary, some becoming wetter and others dryer.
- A stronger greenhouse effect will warm the ocean and partially melt glaciers and ice sheets, increasing sea level. Ocean water also will expand if it warms, contributing further to sea level rise.
- Outside of a greenhouse, higher atmospheric carbon dioxide (CO_2) levels can have both positive and negative effects on crop yields. Some laboratory experiments suggest that elevated CO_2 levels can increase plant growth. However, other factors, such as changing temperatures, ozone, and water and nutrient constraints, may more than counteract any potential increase in yield. If optimal temperature ranges for some crops are exceeded, earlier possible gains in yield may be reduced or reversed altogether.

Climate extremes, such as droughts, floods and extreme temperatures, can lead to crop losses and threaten the livelihoods of agricultural producers and the food security of communities worldwide. Depending on the crop and ecosystem, weeds, pests, and fungi can also thrive under warmer temperatures, wetter climates, and increased CO_2 levels, and climate change will likely increase weeds and pests.

Finally, although rising CO_2 can stimulate plant growth, research has shown that it can also reduce the nutritional value of most food crops by reducing the concentrations of protein and essential minerals in most plant species. Climate change can cause new patterns of pests and diseases to emerge, affecting plants, animals and humans, and posing new risks for food security, food safety and human health (U.S.E.P.A, 2017)

2.4 Ship emissions and their impacts

The lower layer of the atmosphere consists mainly of nitrogen (78% v / v) and oxygen (21% v / v). The atmosphere also contains argon, carbon dioxide and other gases (The percentages of gases refer to dry atmosphere, i.e. atmosphere from which water vapor has been removed as the air content of water vapor varies depending on the place, time and season.) In a Main Engine, marine fuel is burned with oxygen in the air and the necessary mechanical energy is generated to move the ship, heat energy is emitted and exhaust gases are emitted.

Air emissions of cruise shipping may be grouped, subject to their general impact, to: emissions causing air pollution and emissions contributing to the climate change phenomenon. The first category includes emissions of SO_x, NO_x, PM, CO and VOC whereas the second one includes CO_2, HCFC, and CH_4.

Ship emissions having human health impacts may be further categorized in primary and secondary pollutants. The primary pollutants are emissions that have immediate effects in the proximity of the emission source (local/ port effects). Secondary pollutants derive when emissions are transformed during their distribution in the atmosphere to produce other pollutants. This transformation is subject to chemical reactions and may take place far away (some hundreds of kilometers) from the emission source.

Such significant amounts of emissions to air and discharges to sea, and can contribute to poor air quality locally and harmful effects on ecosystems in the sea, particularly in larger port areas.

The ship machinery consists of the main engines that provide the vessel's propulsion, and the auxiliary engines that are used to power functions on board not related to the propulsion, such as electricity for lighting, heating and similar. Marine diesel engines normally run on sulphurous heavy fuel oil, whereas start-up and maneuvering take place using marine diesel oil.

Marine fuels consist mainly of carbon and hydrogen (petroleum hydrocarbons). The content of marine oil in carbon ranges between 84.9% and 87.4% (MEPC, 2014). They also contain impurities, such as sulfur, the content of which varies according to the type of fuel (whether it is distillate - MDO, MGO - or residual fuel - HFO).

Exhaust gases from cruise ships mainly consist of carbon dioxide (CO_2), water vapor, nitrogen oxides (NO_x), Sulphur oxides (SO_x), particulate matter (PM), carbon monoxide (CO) and volatile organic compounds (VOC), including unburned hydrocarbons (UHC) (V. Eyring, 2005), see below illustration and explanation in Figure 2.

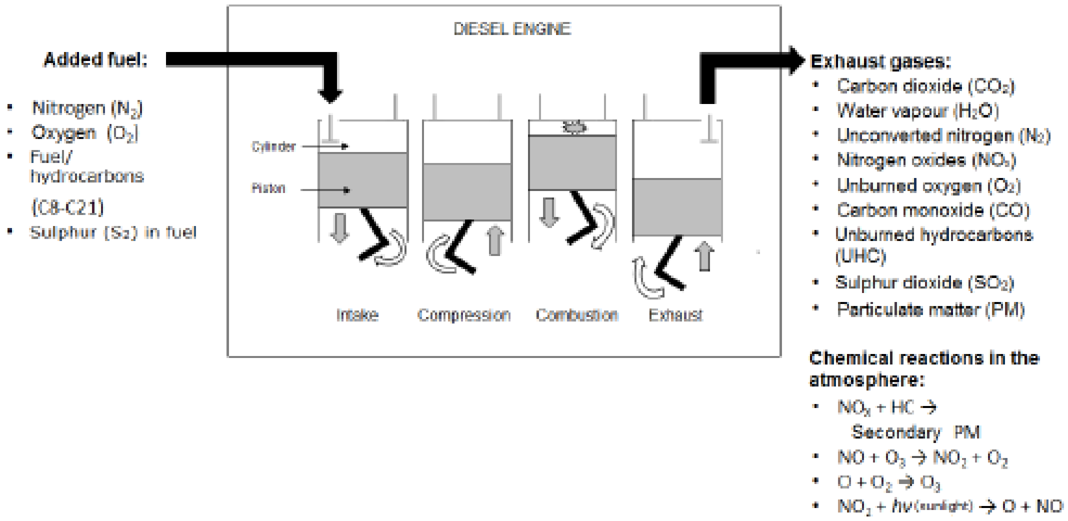


Figure 2 - Schematic presentation of a marine diesel engine

Figure 2. Illustration showing a schematic presentation of the manner of operation of a marine diesel engine, and an overview of added fuel, exhaust gases and atmospheric chemistry.

> *"In a combustion engine, the fuel's energy content is converted to mechanical power by combustion inside the engine's combustion chamber. The thermal energy liberated during the combustion pushes down a piston. Diesel engines have a high compression pressure in the combustion chamber, and a temperature that is so high that the fuel self-ignites upon intake. Clean air is fed to the cylinders. The combustion leads to an expansion, which pushes the piston downwards.*
>
> *The exhaust gases released to the air consist of products of combustion, mainly carbon dioxide (CO_2) and water vapor (H_2O). The most important pollutants with regard to local air quality are nitrogen oxides (NO_x), Sulphur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO) and unburned hydro-carbons (UHC). Some of the*

compounds in the exhaust gases form part of a number of chemical reactions in the atmosphere. NO_x and hydrocarbons form secondary particulate matter. Nitrogen monoxide (NO) and nitrogen dioxide (NO_2) form part of a cyclic process where ozone (O_3) is central, and this equilibrium varies depending on atmospheric conditions such as irradiance and ozone concentration."

Various pollutants released to the air may have negative effects on the earth's climate, ecosystems and human health. Emissions of greenhouse gases such as carbon dioxide (CO2) from cruise shipping and contributions to global warming will be estimated in this dissertation. Harmful effects on ecosystems in the sea and on land will be mentioned, but the main emphasis will be on concentrations of relevant air pollutants and potential harmful effects on people's living, by cruise ships' staying in Mediterranean ports and especially from heavy cruise traffic in such areas.

Air pollution is one of the most important causes of premature death and damage to health on a global scale, and harmful effects have been established at low concentrations in air (S. S. Lim, 2012). Nitrogen oxide (NO2), particulate matter (PM10 and PM2.5) and Sulphur dioxide (SO2) are considered the most important pollutants in air in areas with a high percentage of ship traffic. This is based on the size of the emissions, typical concentrations in the atmosphere and potential damage to health (J. J. Corbett, 2007). These components will therefore be examined more closely in this report.

2.4.1 Particulate matter (PM)

Particulate matter (PM) emissions represent the most significant air pollutant of shipping which produces health damage costs (Rabl, 2001). PM emissions are found in various types and components; however, they are usually divided in $PM_{2.5}$ and PM_{10} subject to the particle size (diameter). Airborne particulate matter has a very complex and varying composition, and forms part of a number of chemical reactions and physical processes in the atmosphere. The source of particulate matter may be both natural and anthropogenic. The burning of fossil fuels is one of the most significant sources of emission. Road traffic on land will also contribute to the emission of particulate matter, both in the form of combustion particles in exhaust gases from vehicles and by dust being stirred up into the air through wear of brake pads, tires and asphalt.

Particulate matter may divide into size fractions based on the size of the particles. Commonly used size fractions when evaluating outdoor air quality include particles with diameters smaller than 10 µm, 2.5 µm and 1 µm (PM_{10}, $PM_{2.5}$ and PM_1), and particles with a diameter of less than 0.1 µm, or ultrafine particles ($PM_{0.1}$). The rough particle fraction ($PM_{2.5-10}$) of particulate matter in city air mainly comes from road surface wear, whereas the fine ($PM_{0.1-2.5}$) and ultrafine fractions mostly originate from combustion.

There is sufficient evidence that there exists a link between particle levels and hospital admissions and emergency room visits, even death from heart or lung diseases (Denisis, 2009). Particle size is considered a decisive factor for potential adverse effects of particulate matter on health. WHO (2014) concluded that ''the evidence for a causal link between $PM_{2.5}$ and adverse health outcomes in humans have been confirmed and strengthened and, thus, clearly remain valid". PM emissions are mostly primary pollutants and their impact on human health is experienced in the proximity of the source hence they are important contributors to local impacts. Studies indicate that PM_{10} is mainly associated with effects on the pulmonary system, whereas $PM_{2.5}$ is associated with adverse effects on the cardiovascular system.

2.4.2 Nitrogen emissions

Most nitrogen oxides (NO_x) emitted in the form of NO which is rapidly oxidized in the atmosphere to NO_2 and then to nitric acid and other nitrates. NO is usually considered harmless as it is a reducing and not an oxidizing agent (Rabl, 2001). NO_2 primary affects the respiratory system (EEA, 2013). Nitrogen oxides (NO_x) are formed by combustion of fuel at high temperatures. Marine diesel engines in particular have a high level of NO_x emissions. The actual emissions mainly consist of nitrogen monoxide (NO) and smaller amounts of nitrogen dioxide (NO_2). In addition to depending on the type of fuel, the percentage of NO_2 in ambient air will also depend on atmospheric conditions, as NO can oxidize in air to nitrogen dioxide (NO_2) in the presence of ozone (O_3). Furthermore, NO can be reformed from NO_2 by absorption of energy from sunlight. The free oxygen atoms (O) formed thereof react with oxygen in the atmosphere to form ozone. NO_x compounds also form part of a number of other chemical reactions in the atmosphere. Conditions such as irradiance, precipitation, ozone concentration and distance to the source of emission will therefore be decisive for the distribution between NO and NO_2 in the air in various areas and at various times.

NO_2 is the most relevant compound to consider when it comes to health damage in humans (FHI, 2015). Limit values for human health have therefore been laid down for the component NO_2. Short-term exposure to NO2 can change the lung function in sensitive population groups and long-term exposure can lead to more serious effects such as increased susceptibility to respiratory infection (EEA, 2013). Epidemiological studies have shown that long-term exposure to NO2 is possibly associated with an increase of symptoms of bronchitis in asthmatic children (EEA, 2013). There isn't sustainable evidence for direct health impacts of NO2 except maybe for morbidity of children and therefore it seems that the main damage of NO_x is the result of its second pollutants, O_3 and nitrates (Rabl, 2001). Nitrate particles can be transported long distances by winds and inhaled deep into people's lungs increasing illness and premature death (from asthma and bronchitis).

2.4.3 Sulphur emissions

Oxidation of SO_2 produces acidic deposition (Holleman and Wiberg, 2001) called acid rain, which can cause adverse effects on aquatic ecosystems in rivers and lakes, damage to forests, and acidification of soils (EEA, 2013). Regarding to health impacts, sulfate particles which are secondary pollutants of SO_2 can be transported long distances by winds and inhaled deep into people's lungs increasing illness and premature death from heart and lung disorders, such as asthma and bronchitis. Moreover, SO_2 as a primary pollutant can contribute to respiratory problems, particular in children and elderly, and aggravate existing heart and lung diseases (Denisis, 2009). However, the concentration of SO_2 in the air must be relatively high in order to produce such effects. The emissions and concentrations in outdoor air of SO_2 have been considerably reduced in the Western world over the last decades.

Emissions from ships from the combustion of sulphurous fuel have been a significant contribution to the total emissions of Sulphur oxides (SO_x) in Europe. However, new emission requirements have contributed to reducing these emissions. This particularly applies within emission control areas defined by IMO (ECAs) and for operation in ports, where ships are currently using fuels with low Sulphur content or pollution-reducing technology in order to satisfy the emission requirements.

2.4.4 More ship air pollutants

Apart from the aforementioned emissions there are other ship air pollutants having health effects, such as carbon monoxide (CO), volatile organic compounds (VOC) and ozone (O_3). For CO, there is evidence that its direct impacts appear to be statistically significant, however the estimated damage costs are low, even for the transport sector (Rabl, 2001). VOC contain hydrocarbons (HC), some of which are carcinogenic. Other harmful components of VOC are the polycyclic aromatic hydrocarbons (PAHs) which are ubiquitously distributed human mutagens and carcinogen (Choi et al., 2006).

In response to the effects of ship air pollution, the International Maritime Organization (IMO) which is the formal regulating body of the maritime sector has adopted (2010 and 2011) specific regulations for reducing air pollution from PM (IMO, 2015) as well as sulfur and nitrogen oxides in specific areas around the world, the so-called Emission Control Areas (ECA). European counties have also put in force specific measures for the reduction of ship air pollution in harbor areas (European Commission, 2015).

3. Regulations

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

IMO ship pollution rules are contained in the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78. On 27 September 1997, the MARPOL Convention has been amended by the “1997 Protocol”, which includes Annex VI titled

“Regulations for the Prevention of Air Pollution from Ships”. MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances from ships of 400 gross tonnage and above engaged in voyages to ports or offshore terminals under the jurisdiction of states that have ratified Annex VI.

The IMO emission standards are commonly referred to as Tier I...III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008, as follows:

- 1997 Protocol (Tier I)—The “1997 Protocol” to MARPOL, which includes Annex VI, becomes effective 12 months after being accepted by 15 States with not less than 50% of world merchant shipping tonnage. On 18 May 2004, Samoa deposited its ratification as the 15th State (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden, and Vanuatu). At that date, Annex VI was ratified by States with 54.57% of world merchant shipping tonnage.

  Accordingly, Annex VI entered into force on 19 May 2005. It applies retroactively to new engines greater than 130 kW installed on vessels constructed on or after January 1, 2000, or which undergo a major conversion after that date. The regulation also applies to fixed and floating rigs and to drilling platforms (except for emissions associated directly with exploration and/or handling of sea-bed minerals). In anticipation of the Annex VI ratification, most marine engine manufacturers have been building engines compliant with the above standards since 2000.

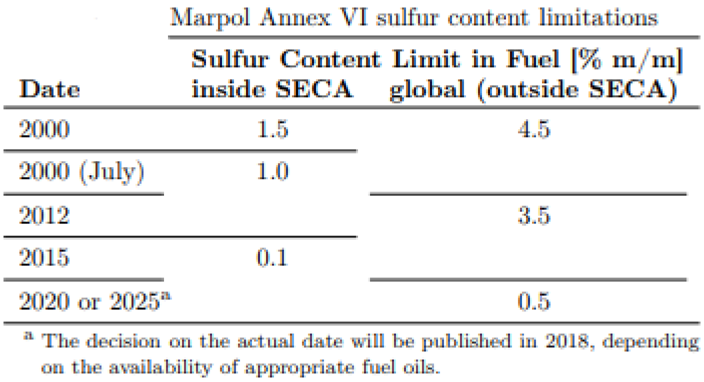
- 2008 Amendments (Tier II/III)—Annex VI amendments adopted in October 2008 introduced (1) new fuel quality requirements beginning from July 2010, (2) Tier II and III NOx emission standards for new engines, and (3) Tier I NOx requirements for existing pre-2000 engines.

  The revised Annex VI entered into force on 1 July 2010. By October 2008, Annex VI was ratified by 53 countries (including the Unites States), representing 81.88% of tonnage.

This Annex was added in 1997 and entered into force in 2005. A revision with more stringent emission limits was adopted in 2008 and went into force 2010. MARPOL Annex VI aims for the minimization of exhaust gas emissions from ships (SO2, NOx, VOCs, ozone depleting substances (ODS)). Also, the contribution of shipping emissions to local and global environmental problems as well as air pollution should be minimized. It sets limits on sulfur content in heavy oil fuels (Table 1) globally as well as establishes local Sulfur Emission Control Areas (SECA) with more stringent restrictions and controls.

Table 1 - MARPOL Annex VI Sulphur Content Limitations

(Source:https://www.researchgate.net/figure/MARPOL-Annex-VI-Fuel-sulphur-limits_tbl2_271561267)



Marpol Annex VI sulfur content limitations

	Sulfur Content Limit in Fuel [% m/m]	
Date	**inside SECA**	**global (outside SECA)**
2000	1.5	4.5
2000 (July)	1.0	
2012		3.5
2015	0.1	
2020 or 2025[a]		0.5

[a] The decision on the actual date will be published in 2018, depending on the availability of appropriate fuel oils.

3.1 Emission Control Areas

Two sets of emission and fuel quality requirements are defined by Annex VI: (1) global requirements, and (2) more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SOx and PM, or NOx, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI.

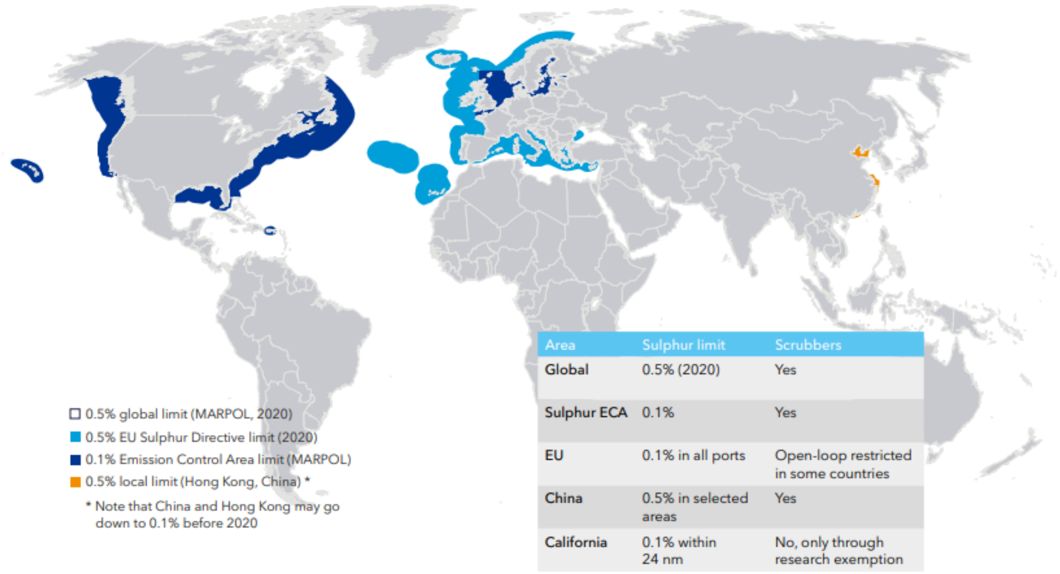
Existing Emission Control Areas include:

- Baltic Sea (SOx: adopted 1997 / entered into force 2005; NOx: 2016/2021)
- North Sea (SOx: 2005/2006; NOx: 2016/2021)
- North American ECA, including most of US and Canadian coast (NOx & SOx: 2010/2012).

- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NOx & SOx: 2011/2014)

The Baltic Sea was the first SECA, later the North Sea as well as two SECAs in North America followed. Later, the SECAs were changed into general Emission Control Areas (ECA), which can be seen in Figure 3. In the North Sea and Baltic Sea only sulfur content is regulated, in the North American and United States Caribbean Sea area also NOx and PM are limited.

After a review of the outlook of the availability of compliant low Sulphur fuel oil in 2020, the IMO has decided that the global fuel Sulphur limit of 0.5% should enter into force in 2020. This requirement is in addition to the 0.1% Sulphur limit in the North American, US Caribbean, North Sea and Baltic Emission Control Areas (SECA).



Area	Sulphur limit	Scrubbers
Global	0.5% (2020)	Yes
Sulphur ECA	0.1%	Yes
EU	0.1% in all ports	Open-loop restricted in some countries
China	0.5% in selected areas	Yes
California	0.1% within 24 nm	No, only through research exemption

Figure 3 - Map of the established ECAs

Map of the established Emission Controlled Areas (ECA). (Source: https://safety4sea.com/wp-content/uploads/2016/11/DNV-GL-Global-sulphur-cap-2020-2016_11.pdf)

A complicating factor is the regional and local regulations, which in some cases stipulate stricter requirements and in others, prohibit certain compliance options. The European Union Sulphur Directive stipulates a maximum of 0.10% sulphur content for ships in EU ports. In certain EU countries, the Water Framework Directive constrains the discharge of scrubber water. Belgium and Germany have prohibited the discharge of scrubber water in many areas, constraining the operation of open-loop scrubbers. Other EU countries may follow suit, with no common EU practice likely to be agreed.

In China, as of 1 January 2020 vessels operating in the Inland ECAs (Yangtze and Xijiang River) shall use fuel with a sulphur content not exceeding 0.10% sulphur. The same will apply within the Hainan Coastal ECA from 1 January 2022. In addition, discharging wastewater from scrubbers is banned within inland Emission Control Areas (ECAs), port waters and the Bohai Bay waters.

California's Air Resources Board (ARB) enforces a 0.10% sulphur limit within 24 nautical miles of the California coast. The regulation does not allow any other compliance options than low-sulphur marine gas or diesel oil (DMA or DMB). A temporary research exemption may be granted, allowing the use of a scrubber. The application must be sent before entering California waters. After a formal review of the regulation, California legislators have decided to retain it as an addition to the ECA requirements. Both sets of regulations must be complied with when calling at port in California (Global Sulphur Cap, 2020).

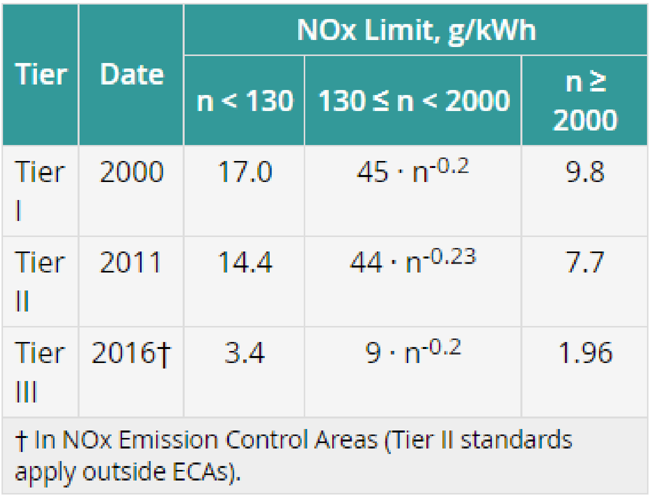
There is a general global trend of stricter local air pollution regulations that will come into force the next years.

3.2 NOx Emission Standards

The NOx emission limits of Regulation 13 of MARPOL Annex VI apply to each marine diesel engine with a power output of more than 130 kW installed on a ship. A marine diesel engine is defined as any reciprocating internal combustion engine operating on liquid or dual fuel. There are two exceptions: engines used solely for emergencies and engines on a ship's operating solely within the waters of the state in which they are flagged. The later exception only applies if these engines are subject to an alternative NOx control measure.

Table 2- MARPOL Annex VI NOx emission limits

(Source:https://www.semanticscholar.org/paper/Exhaust-Gas-Cleaning-Systems%3A-A-Maritime-Study-Comden-Cavanaugh/d8546eca05e84dd04aa56100a8a4238accfa560d/figure/1)



Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

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

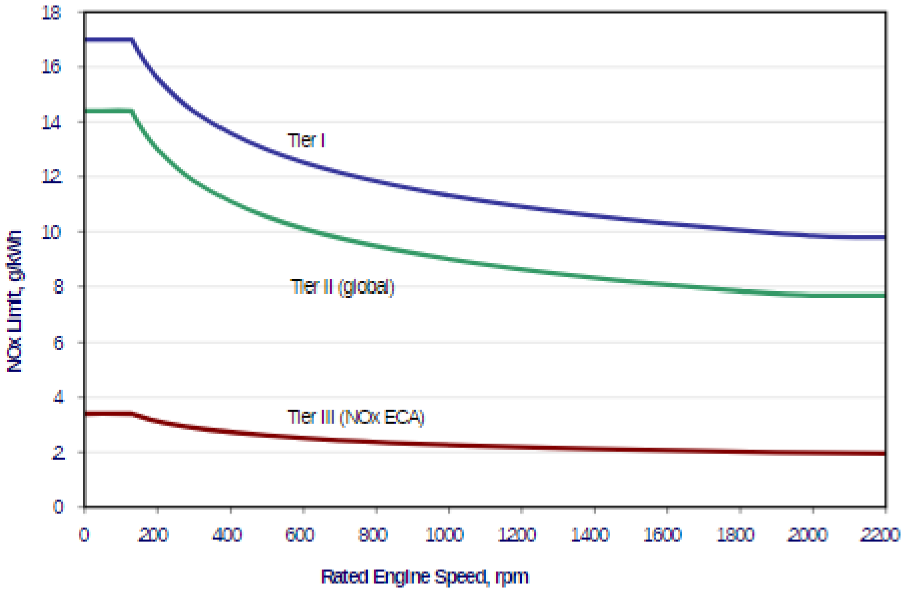


Figure 4 - MARPOL Annex VI NOx emission limits

(Source:https://www.researchgate.net/figure/MARPOL-Annex-VI-NOx-emission-limits-wwwdieselnetcom_fig2_320451548)

NOx emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 2 and presented graphically in Figure 4. Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas.

Tier II standards are expected to be met by combustion process optimization. The parameters examined by engine manufacturers include fuel injection timing, pressure, and rate (rate shaping), fuel nozzle flow area, exhaust valve timing, and cylinder compression volume.

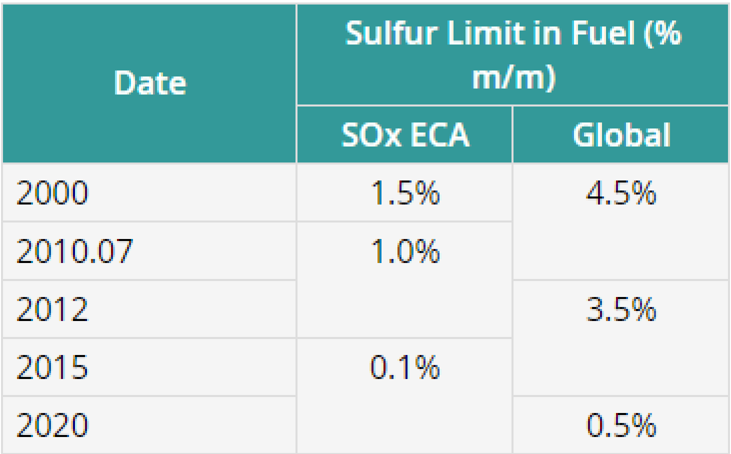
Tier III standards are expected to require dedicated NOx emission control technologies such as various forms of water induction into the combustion process (with fuel, scavenging air, or in-cylinder), exhaust gas recirculation, or selective catalytic reduction.

3.3 Sulfur Content of Fuel

Annex VI regulations include caps on sulfur content of fuel oil as a measure to control SOx emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SOx Emission Control Areas (SOx ECA or SECA). The sulfur limits and implementation dates are listed in Table 3 and illustrated in Figure 5 and 6.

Table 3 - MARPOL Annex VI fuel sulfur limits

(Source:https://www.researchgate.net/figure/MARPOL-Annex-VI-Fuel-sulphur-limits_tbl2_271561267)



Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020		0.5%

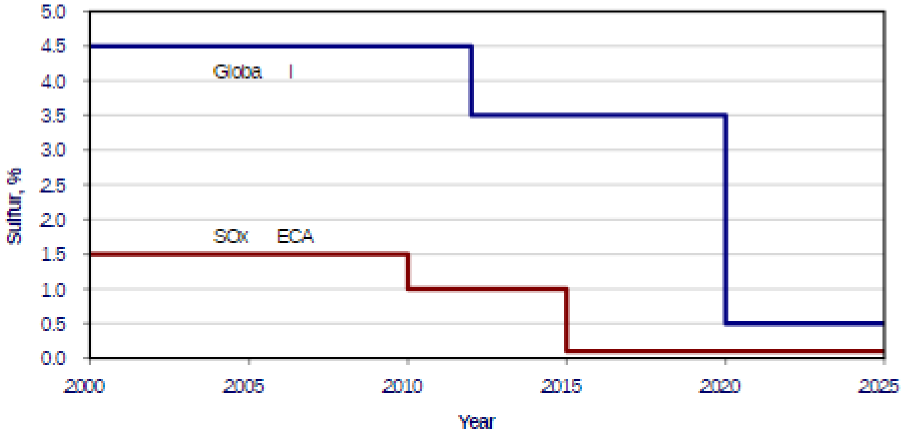


Figure 5 - MARPOL Annex VI fuel sulfur limits

(Source: https://www.researchgate.net/figure/Fuel-sulphur-limits-and-implementation-dates-under-MARPOL-Annex-VI_fig2_312948938)

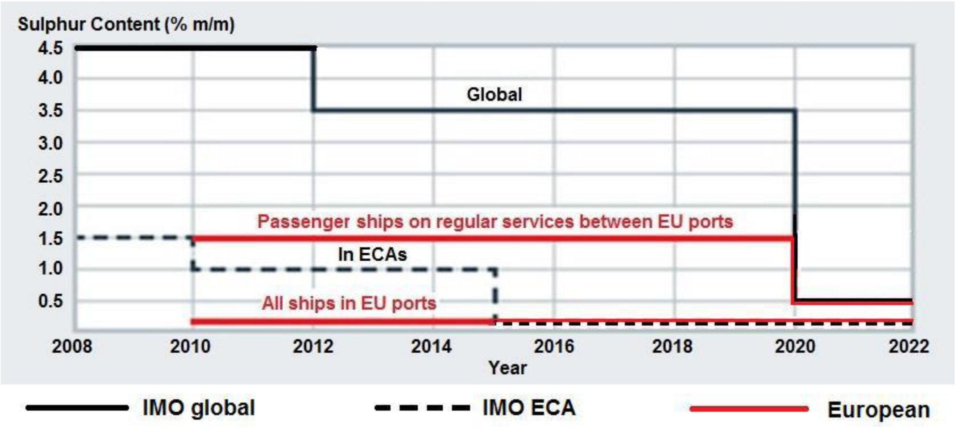


Figure 6 - Sulphur Content limits Globally, in ECAs and in EU ports

(Source: Tzannatos E., Ship Efficiency (presentation slide 119)

Heavy fuel oil (HFO) was allowed provided it was meeting the applicable sulfur limit. Alternative measures are also allowed (in the SOx ECAs and globally) to reduce sulfur emissions, such as through the use exhaust gas cleaning systems (EGCS), also known as scrubbers. For example, instead of using the 0.5% S fuel (2020), ships can fit an exhaust gas cleaning system or use any other technological method to limit SOx emissions to ≤ 6 g/kWh (as SO_2)

3.4 New amendments ban high Sulphur fuels without using scrubbers

A significant amendment to the regulation is the carriage ban for HSFO as of 1 March 2020, from which ships equipped with scrubbers are exempted. While it’s still permitted to carry HSFO as a cargo, it's no longer permitted to have HSFO in fuel tanks unless scrubbers are installed. This enables port state control (PSC) to detain ships carrying non-compliant fuel without having to determine if it has been used or not. Certain ports have banned the use of open-loop scrubbers within their areas.

3.5 Greenhouse Gas Emissions

MARPOL Annex VI, Chapter 4 introduces two mandatory mechanisms intended to ensure an energy efficiency standard for ships:
(1) the Energy Efficiency Design Index (EEDI), for new ships and
(2) the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

The EEDI is a performance-based mechanism that requires a certain minimum energy efficiency in new ships. Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements in a specific ship design.

The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships. The regulations apply to all ships of 400 gross tonnage and above and enter into force from 1 January 2013. Flexibilities exist in the initial period of up to six and a half years after the entry into force, when the IMO may waive the requirement to comply with the EEDI for certain new ships, such as those that are already under construction.

Essentially, the EEDI requires new ships to emit less CO_2 per unit of “transport work,” typically described as g CO_2/dwt-nm. Ships built between 2015 and 2019 are required to be 10% more efficient than a baseline of ships built between 1999 and 2009. Subsequently, ships built between 2020 and 2024 must be 20% more efficient, and those built in 2025 or later must be 30% more efficient than the baseline.

Evidence suggests that these EEDI targets can be further strengthened for key ship types because the EEDI baseline was artificially weak (Faber & ‘t Hoen, 2015). IMO member states have proposed tightening the existing EEDI standards. In April 2018, the IMO adopted an Initial Strategy on the reduction of GHG emissions from ships, with a target to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008. The strategy calls for strengthening the EEDI requirements and a number of other measures to reduce emissions, such as operational efficiency measures, further speed reductions, measures to address CH_4 and VOC emissions, alternative low-carbon and zero carbon fuels, as well as market-based measures (MBM). This strategy was proposed to be done in phases. Some had advocated for moving up the implementation date of Phase 3 (30%) EEDI standards from 2025 to 2022 and introduce a new more strict “Phase 4” EEDI standard for 2025.

The IMO had not agreed to change the EEDI yet. In any case, because the EEDI only applies only to new ships, it cannot meaningfully decrease GHGs from the shipping sector in the short term. Even in the long-term, the EEDI, as currently designed, is expected to reduce shipping’s cumulative CO_2 emissions by only 3% over the period 2010 to 2050 (Smith et al., 2016). Unfortunately, the EEDI alone is not enough to reverse the trend of increasing CO_2 and GHG emissions from ships (IEA, 2017; Smith et al., 2015, 2016).

3.6 IMO STRATEGY TO REDUCE GHG EMISSIONS FROM SHIPS

IMO member states and organizations are developing a roadmap to determine the amount of GHG emissions that need to be reduced from the shipping sector, by when, and by what means. The IMO delivered an initial comprehensive strategy to reduce GHG emissions from shipping in 2018, with a final strategy in 2023. Opinions differ on the level of ambition and implementation mode (aspirational vs. binding targets) to be included in the strategy. In their submission to the 71st meeting of IMO’s Marine Environmental Protection Committee (MEPC), the Marshall Islands and Solomon Islands (2017) called for a high level of ambition to be incorporated into IMO's GHG strategy, including an overall "fair share" global target for shipping. In contrast, other countries opposed IMO adopting a sectoral emissions target for international shipping. A third approach, supported by Japan (2017), calls for aspirational short- and long-term goals for international shipping. Specifically, Japan calls for a reduction in CO_2 emissions per unit transport work of 40% by 2030, and a reduction of net CO_2 emissions from international shipping by 50%, both from 2008 levels.

IMO member states are still debating what the strategy will look like, but we do know that the strategy will include short-, mid-, and long-term measures to reduce GHGs. Given that existing ship energy-efficiency policies that apply only to new ships (the EEDI) will take a long time to work their way through the in-service fleet, it will be particularly important to reduce emissions from the existing fleet. In the short term, limiting ship speeds can immediately reduce GHG emissions. Main engine power demand is proportional to the cube of the speed; as the ship's speed decreases, its main engine power demand falls even more rapidly, reducing fuel consumption and emissions. Various studies (Faber, Nelissen, Hon, Wang, & Tsimplis, 2013; Maddox Consulting, 2012; Yuan, Ng, & Sou, 2016) found that slowing down is a cost-effective way to reduce GHG emissions.

In the mid- and long-term, new marine propulsion technologies and low-carbon and zero carbon fuels will be needed to decarbonize the sector. At the moment, existing regulations provide little incentive to invest in research and development of new technologies and fuels. DNV-GL's recent study Low Carbon Shipping Towards 2050 (Chryssakis et al., 2017), highlights that although scrubbers might be a financially attractive option for complying with the upcoming 0.5% global fuel sulfur cap in 2020, such a strategy will not allow significant reductions in GHG emissions because ship owners will be "locked in" to using carbon-intensive bunker fuels over the life of the ship. Moreover, the study also recommends biofuel as one of the least carbon-intensive fuels, and proposes developing future market-based measures (MBMs) to counter their price differentials to fossil fuels.

At Bouman, Lindstad, Rialland, & Strømman (2017)'s article similar opinions are found as above mentioned. In this case it is stated that biofuels should be the key to decarbonizing the marine transportation system. The Institute of Marine Engineering, Science and Technology

(IMarEST) and the Royal Institution of Naval Architects (RINA) (2017) assessed that the operational efficiency, as measured by the Energy Efficiency Operational Index (EEOI), of ships in 2015 can be reduced (enhanced) by 7.5% to 19.4% from 2010 levels using available technologies, but that advanced wind technologies and low-carbon fuels would be needed to achieve large (54% to 90%) reductions. Thus, there needs to be some driver to encourage a shift toward low-carbon technologies and fuels. Some sort of MBM could be used to accelerate decarbonization and research and development of alternative technologies and fuels.

3.7 MRV data base - IMO Data Collection System

International shipping is a large and growing source of greenhouse gas emissions. The EU supports global action to tackle these emissions and has put in place EU-wide data collection measures.

Maritime transport emits around 940 million tonnes of CO2 annually and is responsible for about 2.5% of global greenhouse gas (GHG) emissions (3rd IMO GHG study).

These emissions are projected to increase significantly if mitigation measures are not put in place swiftly. According to the 3rd IMO GHG study, shipping emissions could under a business-as-usual scenario increase between 50% and 250% by 2050, undermining the objectives of the Paris Agreement.

At the same time, there is significant untapped potential to reduce shipping emissions cost-effectively. Many technical and operational measures, such as slow steaming, weather routing, contra-rotating propellers and propulsion efficiency devices, can deliver more fuel savings than the investment required.

Although a global approach to address GHG emissions from international shipping led by the International Maritime Organisation (IMO) would be the most effective and thus preferable, the relatively slow progress in the IMO has triggered the EU to take action.

EU strategy

Shipping emissions represent around 13% of the overall EU greenhouse gas emissions from the transport sector (2015).

In 2013, the Commission set out a strategy towards reducing GHG emissions from the shipping industry.

The strategy consists of **3 consecutive steps**:

- **Monitoring, reporting and verification** of CO_2 emissions from large ships using EU ports
- **Greenhouse gas reduction targets** for the maritime transport sector
- **Further measures**, including market-based measures, in the medium to long term.

The contribution of the shipping sector to emission reductions consistent with the temperature goals of the Paris Agreement remains an important issue in the EU.

The recent amendment to the EU Emissions Trading System (ETS) Directive, by Directive (EU) 2018/410 of the European Parliament and the Council, emphasises the need to act on shipping emissions as well as all other sectors of the economy.

The Directive also states that the Commission should regularly review IMO action and calls for action to address shipping emissions from the IMO or the EU to start from 2023, including preparatory work and stakeholder consultation.

On 14 July 2021, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the EU by 2050, including the intermediate target of an at least 55% net reduction in greenhouse gas emissions by 2030. The package proposes to revise several pieces of EU climate legislation, including the EU ETS, Effort Sharing Regulation, transport and land use legislation, setting out in real terms the ways in which the Commission intends to reach EU climate targets under the European Green Deal.

First step: monitor, report and verify CO_2 emissions

From 1 January 2018, large ships over 5 000 gross tonnage loading or unloading cargo or passengers at ports in the European Economic Area (EEA) are to monitor and report their related CO_2 emissions and other relevant information.

Monitoring, reporting and verification (MRV) of information shall be done in conformity with Regulation 2015/757 (as amended by Delegated Regulation 2016/2071).

Four other legal acts are also relevant:

- Delegated Regulation (EU) 2016/2072 on the verification activities and accreditation of verifiers
- Delegated Regulation (EU) 2016/2071 as regards the methods for monitoring carbon dioxide emissions and the rules for monitoring other relevant information
- Implementing Regulation 2016/1927 on templates
- Implementing Regulation 2016/1928 further defining cargo carried for some ship categories

Main obligations for companies eligible under the EU MRV Regulation:

- **Monitoring:** From 1 January 2018, companies shall – in line with their respective monitoring plans – monitor for each of their ships CO_2 emissions, fuel consumption and other parameters, such as distance travelled, time at sea and cargo carried on a per voyage basis, so as to gather annual data into an emissions report submitted to an accredited MRV shipping verifier.

- **Emissions report:** From 2019, by 30 April of each year, companies shall, through THETIS MRV, submit to the Commission and to the States in which those ships are registered ('flag States') a satisfactorily verified emissions report for each ship that has performed maritime transport activities in the European Economic Area in the previous reporting period (calendar year).

- **Document of compliance:** From 2019, by 30 June of each year, companies shall ensure that all their ships that have performed activities in the previous reporting period and are visiting ports in the European Economic Area carry on board a document of compliance issued by THETIS MRV. This obligation might be subject to inspections by Member States' authorities.

Every year, the Commission publishes a report to inform the public about the CO_2 emissions and energy efficiency information of the monitored fleet:

Global action

IMO Data Collection System

Following the adoption of the EU MRV Regulation, the IMO established an IMO Data Collection System.

The system requires owners of large ships (above 5 000 gross tonnage) engaged in international shipping to report information on fuel consumption of their ships to the flag States of those ships. The flag States then report aggregated data to the IMO, which shall produce an annual summary report to the IMO Marine Environment Protection Committee.

The IMO system entered into force in March 2018 and the collection of fuel consumption data started on 1 January 2019.

As a result, from 2019, ships calling into EEA ports will have to report under both the EU MRV Regulation and the IMO Data Collection System.

The EU MRV Regulation (Article 22) anticipated this situation as it foresees that the Commission should, in the event of an international agreement on a global MRV system for shipping emissions, review the regulation and, if appropriate, propose amendments to ensure alignment with that international agreement.

In February 2019, the European Commission made a proposal to amend the EU MRV Regulation to take appropriate account of the global data collection system.

Initial IMO greenhouse gas strategy

After considerable efforts over recent years, the IMO agreed in April 2018 on an initial greenhouse gas emissions reduction strategy.

In line with the internationally agreed temperature goals under the Paris Agreement, the strategy includes objectives to:

- reduce total annual GHG emissions from shipping by **at least 50% by 2050** compared to 2008 levels
- pursue efforts to **phase them out** as soon as possible in this century.

However, short-, mid- and long-term emission reduction measures, as well as research and innovation, necessary to achieve the objectives under the strategy remain to be developed and agreed.

In October 2018, the IMO Marine Environment Protection Committee agreed on a programme of follow-up actions to implement the initial strategy, with timelines for consideration and agreement on GHG reduction measures:

- Short-term measures are to be decided between 2020 and 2023.
- Proposals for mid- and long-term measures are to be considered, without mentioning the timelines for agreement.

The strategy will be **revised in 2023**, taking into account

- data from the IMO Data Collection System
- other data, such as reports by the Intergovernmental Panel on Climate Change.

<u>EU support to IMO energy efficiency project</u>

The European Commission contributes €10 million funding to an EC-IMO energy efficiency project.

As part of the 4-year project, Maritime Technology Cooperation Centres have been set up in 5 regions: Africa, Asia, the Caribbean, Latin America and the Pacific.

Through technical assistance and capacity-building, the centres will promote the uptake of low carbon technologies and operations in maritime transport in less developed countries.

This will also support the implementation of the internationally agreed **energy efficiency rules and standards** – Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP).

3.8 Clean Air Act

The Clean Air Act of 1963 (42 U.S.C. § 7401) is a United States federal law designed to control air pollution on a national level. It is one of the United States' first and most influential modern environmental laws, and one of the most comprehensive air quality laws in the world. As with many other major U.S. federal environmental statutes, it is administered by the U.S. Environmental Protection Agency (EPA), in coordination with state, local, and tribal governments. Among other things, this law authorizes EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and public welfare and to regulate emissions of hazardous air pollutants.

3.9 Ports and Cruise ships emissions

The port areas are the most recognizable receptors of pollutants emitted from ships. The emissions from ships may threaten the air quality while berthing or maneuvering and in coastal communities while transiting along the coast. Approximately 80% of the world fleet are either harbored (55% of the time) or near a coast (25% of the time) (ICCT, 2007). This means that ships spend about 20% of the time far from land (Corbett J., 1999).

Involving non-optimal engine loads, maneuvering can generate much more pollution (3–6 times) than cruising and hoteling phases (Petzold et al., 2010; Moldanova et al., 2013; Lack and Corbett, 2012). When at berth, most ships supply their services by means of auxiliary diesel engines. Depending on ship type, the energy needed during hoteling ranges between 30% and 50% of the one employed at cruising (e.g., Tzannatos, 2010). Overall, in-port emissions of NOx and SO2 represent 5–6% of the total generated by ships in all their navigation phases (Whall et al., 2002).

All these elements point out that in both port areas and port cities important fractions of air pollutants can originate from ships (Tzannatos, 2010, Cullinane et al., 2014, Viana et al., 2014). To evaluate and reduce risks associated with atmospheric pollution, it is therefore important to know both amount and type of pollutants attributable to shipping, particularly in port-cities.

There are many local studies about estimating the shipping emissions in gulfs and port regions in the literature. It was estimated that the shipping emissions were approximately 1.725 Mt, 1.246 Mt SO2, 0.147 Mt CO, and 0.035 Mt HC in the Mediterranean Sea and the Black Sea regions based on ship movements (LR). The International Institute for Applied Systems Analysis (IIASA) estimated that the shipping emissions of CO2, SO2, and HC were 77.140 Mt, 1.818 Mt, 1.278, and 0.062 Mt, respectively, in the Mediterranean Sea.

Air pollution from cruise ships is generated by diesel engines that burn high sulfur content fuel, producing sulfur dioxide, nitrogen oxide, and particulate matter, in addition to carbon monoxide, carbon dioxide, and hydrocarbons. Diesel exhaust has been classified by EPA as a likely human carcinogen. EPA recognizes that emissions from marine diesel engines contribute to unhealthy air and failure to meet air quality standards, as well as visibility degradation, haze, acid deposition, and eutrophication and nitrification of water (U.S.E.P.A, 2009). Emissions from marine diesel engines can be higher on a port-specific basis. Ships are also an important source of greenhouse gas (GHG) pollutants.

One source of environmental pressure on maritime vessels came from states and localities, as they assessed the contribution of commercial marine vessels to regional air quality problems when ships are docked in port. A significant portion of vessel emissions occur at sea, but they can impact areas far inland and regions without large commercial ports, according to EPA. Once more, there is little cruise-industry specific data on this issue. They comprise only a small fraction of the world shipping fleet, but cruise ship emissions may exert significant impacts on a local scale in specific coastal areas that are visited repeatedly.

Shipboard incinerators also burn large volumes of garbage, plastics, and other waste, producing ash that also should be disposed.

Most shipping emissions in ports will grow fourfold up to 2050. This is the case for CH_4, CO, CO_2 and NOx-emissions. This would bring CO_2 emissions from ships in ports to approximately 70 million tons in 2050 and NOx emissions up to 1.3 million tons. The level of PM_{10} and $PM_{2,5}$-emissions from ships in ports remains at the level of 2011 emissions and SOx emissions decline slightly compared to the 2011 level as shown in Figure (7).

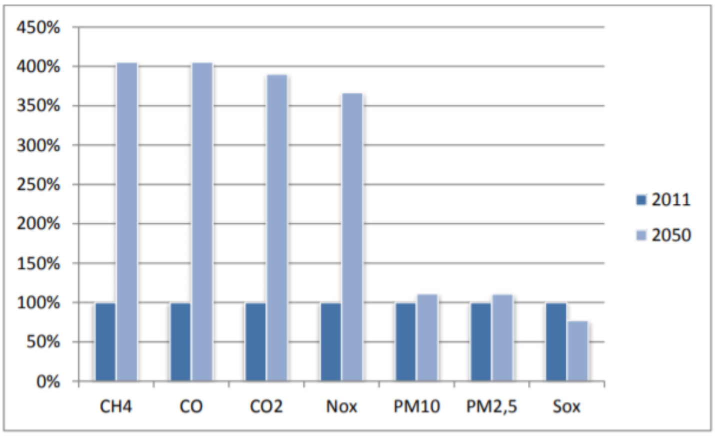


Figure 7 - Increase of shipping emissions in ports 2011-2050

Increase in shipping emissions in ports 2011-2050 based on data from Lloyds Marine Intelligence Unit.

A “Mediterranean Emission Control Area” webinar (SAFETY4SEA, 2020) held recently by Nabu, MEPs and activists from local groups across Europe, focused on how to fight air pollution and tackle shipping’s climate impact around the Mediterranean Sea. About the subject matter, it was highlighted that the use of fuel for marine ships with high sulfur content, or low quality in general, cause relevant harmful emissions (particulate matter, sulfur dioxides etc.). Considering the situation, it was explained that there is an immediate need for improvement of air quality of ports and cities of the Mediterranean Sea, by using better-quality fuels or alternative fuels and new, greener technologies.

As explained in the webinar, it has finally come the time for shipping players, national governments and the European Commission to act and take drastic measures such as the designation of the Mediterranean Sea, as an Emission Control Area both for:

- SECA (sulphur): low sulphur fuel.
- NECA (nitrogen): low NOx emissions.

Unfortunately, experts considered that the plan for the Mediterranean lacks in tempo and scope of content, while foresees only Sulphur dioxide, and will not be effective before 2024. Shipping is the main source of air pollution among many places around the Mediterranean Sea. It is absolutely intolerable that people around the Mediterranean Sea have to wait for clean air, while northern Europe but also China and North America already forced the industry to switch to cleaner fuels. Emission control areas moreover incentives new technologies that help to reduce air pollutant but also climate emissions.

In a call to action, speakers at the online conference advised all relevant industries and organizations to take into consideration the following:

- Assist air quality measurements in the Mediterranean Sea, especially for cruise ships.
- Organize meetings and seminars for the education of the involved local governments, competent authorities, industry representatives and stakeholders on the MedECA agenda, for the final endorsement and realization.
- Promote the MedECA idea and benefits through local communication portals, such as news publications, radio shows etc.
- Contact scientific bodies and promoting scientific research and evidence-based policy making for the MedECA designation.
- Interconnect with local groups and movements for the improvement of quality of life in the Med ports.
- Make the Mediterranean a better place to live

Designation of the Mediterranean Sea as an ECA would socioeconomically benefit both the health and quality of life of the European citizens and the economy.

3.10 Current and Future Handling of Emissions

While cruise ships comprise less than 1% of the global maritime community, cruise lines are at the forefront in developing responsible environmental practices and innovative technologies, which benefit the entire shipping industry. The cruise industry has invested over $23.5 billion into a variety of onboard and portside technologies as well as cleaner fuel sources to reduce its environmental impact while providing a unique tourism experience to a growing cohort of travelers.

Cruise ship companies’ constituents are addressing air emissions by transitioning to cleaner-burning fuels such as Liquified Natural Gas (LNG), biofuels, and synthetic fuels while installing Exhaust Gas Cleaning Systems (EGCS) on ships that rely on legacy fuel sources. Presently, LNG is the primary alternative fuel source being implemented due to its strong environmental performance, growing land-based infrastructure, and established technological viability. Burning LNG produces virtually zero sulfur emissions, 85% fewer nitrogen oxide emissions, 95-100% fewer particulate emissions, and the industry estimates up to 20% fewer greenhouse gas emissions. The industry is working closely with partners to mitigate the potential risk associated with burning LNG and methane slip. Natural gas extraction, refinement, and distribution operations have grown, aided by both environmental and economic efficiency, enabling cruise ships to refuel at ports worldwide.

Currently there are 25 ships on order or under construction committed to relying on LNG for primary propulsion, representing 49% of new passenger capacity. Investment, development, and adoption of still cleaner-burning biofuels and synthetic fuels face key hurdles such as fuel density, safe storage, and global availability. However, the contemporary engine technology enables LNG-reliant ships to transition to future fuel sources with minimal structural intervention required.

Providers of LNG as bunker fuel to the shipping industry enable operators of cruise liners, tankers, ferries, container liners, and more to improve their environmental performance by moving away from conventional fuels. LNG outperforms key legacy fuel sources such as Heavy Fuel Oil (HFO), which composes around 84% of marine bunker fuel utilization, and Marine Gas Oil (MGO)1. The latter can be utilized in its Low Sulfur (LS-MGO) form to meet ECA standards for sulfur content below 0.1%; however, its performance still falls short of LNG's complete elimination of SOx emissions (Marquard & Bahls 2015).

Outside of the cruise industry, LNG has faced longer-than-expected adoption times primarily due to falling overall oil prices and a decades-long shipping crisis. The shipping crisis revolves around widespread over-capacity amid moderating shipping demand. Concurrently, recent demand growth has aided shipyards to continue building LNG-enabled vessels. Presently, two well-known shipping companies, among others, have announced adoption of LNG in their container shipping businesses and have brought renewed positive signals to the broader market.

The longevity of cruise ships and their engines tempers the pace of transition to alternative fuel sources but does not impede the goal of fleetwide emissions reduction. Exhaust Gas Cleaning Systems are currently installed on ships that comprise 69% of global passenger capacity, reflecting a 25% increase over 2018 ETP inventory levels, and 95% of new ships not relying on LNG as their primary fuel source will have EGCS installed. These systems reduce exhaust sulfur oxide levels by as much as 98%, typical total particulate matter levels by 50% or more, and nitrogen oxide levels by up to 12%. The future cruise fleet will leverage EGCS technology and LNG fuel to lessen air emissions.

Alongside EGCS, Water Fuel Emulsion treatments further limit the air emissions of heavy fuels and diesel oil. By mixing water with the fuel using various methods, emulsified fuels are able to simultaneously reduce nitrogen oxide emissions by as much as 50% and particulate matter emissions by up to 90%5. In addition to fewer emissions, WFE technology grants a 5% savings on fuel consumption (Hielscher Ultrasound Technology, 2020). Currently, over one-quarter of global passenger capacity is equipped with WFE technology.

EGCS and WFE empowers cruise ships to meet or exceed MARPOL requirements using existing engine technology and demonstrates the value of implementing auxiliary technologies that produce desired environmental outcomes in retrofitting initiatives.

Data analysis, optimization, and automation have long played key roles in the broader shipping industry, and the cruise industry has been among the leaders. Multiple shipbuilders have entered this market, offering digital solutions that operate alongside upgraded or improved ship components. These digital solutions broadly operate on two levels: optimizing internal functions such as engine and fuel type utilization and optimizing vessel-level decisions such as route and trim. Digital solutions are available both for new builds and for retrofitting jobs and are flexible to account for the pace of adoption of newer physical components.

In 2018, Cruise companies committed to a 40% reduction in the rate of carbon emissions across the cruise industry’s global fleet by 2030 as an initial step towards their goal of being carbon-free by the end of the century. Some of them have demonstrated their commitment to carbon reduction through optimizing energy efficiency through conservation and energy management.

This reduction will be fueled by innovative technologies and optimized procedural practices. Some such technological improvements on this front that are being implemented include:

- The advent and widespread use of ecological, non-toxic, slick hull paint coatings, which have been estimated to improve fuel efficiency by five percent.
- More bulbous bow designs that reduce fuel usage for propulsion upwards of 15 percent when compared to the traditional V-shape.
- The use of advanced materials in ship applications, such as advanced strength-enhanced steel, that provide energy savings through reducing ship weight and providing a more hydrodynamic surface.
- The installation of tinted windows, high efficiency appliances and HVAC systems, and windows that capture and recycle heat reduce energy use from heating and air conditioning.

- Switching to LED lights which use 80 percent less energy and last 25 times longer than previous lighting systems.
- Installation of solar panels for emissions-free energy.

Cruise lines are investing heavily in implementing these carbon reduction technologies along with continual funding for research and development of further carbon reducing technologies, such as zero-carbon fuels. There are a number of zero-carbon fuels being researched and developed, such as ammonia used in internal combustion engines, fuel cells, and electric motors combined with batteries.

Procedurally, the cruise industry has been performing data analytics for itineraries to maximize fuel efficiency. Findings in this field have led to reductions in fuel consumption through optimized speed, routs, and distances travelled.

Many cruise lines have set and achieved ambitious company carbon reduction goals. Some of these goals include designing energy efficient hulls to help reduce CO2 emissions of new ships by 20 percent when compared to ships built just a few years ago to refitting older ships with improved propulsion technology that is 10% more energy efficient. One member of cruise lines starting on January 1, 2020 became carbon-neutral. This has been accomplished through the implementation of carbon reducing technologies that have helped reduce their carbon emission rate 29%, well on their way to meeting the 40% reduction goal by 2030, along with blue carbon credits for the conservation and restoration of coastal and marine ecosystems.

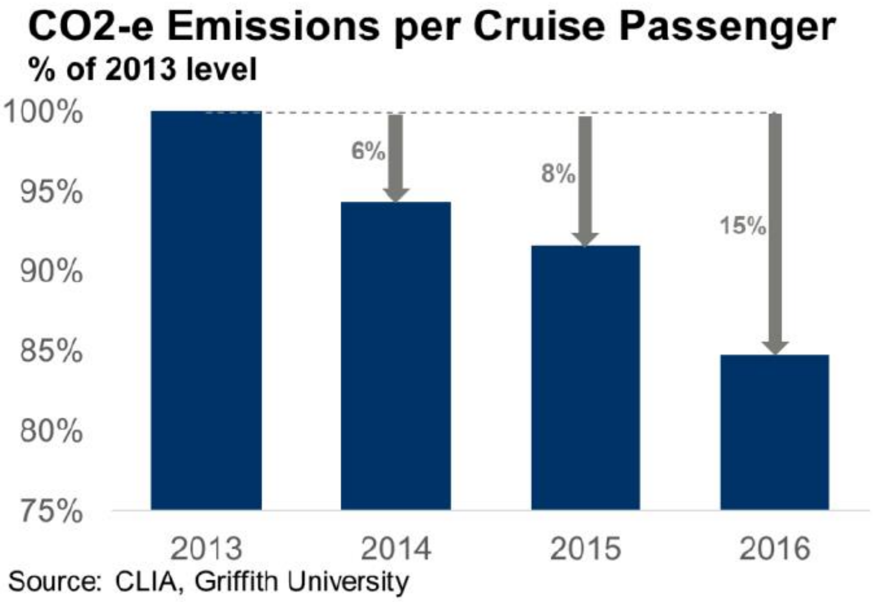


Figure 8 - CO2 Emissions per Cruise Passenger

Alongside these new technologies to meet carbon reduction goal, cruise lines continue to implement shore-side electricity (SSE), also known as cold-ironing, which allows cruise ship operators to turn off the ship engines while in port and rely on more efficient municipal power systems when available, to reduce overall emissions. When measured in the Port of Charleston, CO2 emissions are reduced by an estimated 36% (Corbett and Comer, 2013) and another study found that SSE offers the potential to reduce CO2 emissions by over 800,000 tons in Europe alone (Winkel et al., 2016).

The objective of expanding SSE availability at ports presents a valuable opportunity for advocacy and cooperation with port operators that could have influence on the broader adoption of SSE capabilities by other shipping industry participants.

Cruise terminals have begun regular operations of the onshore power station, supplying cruise ships with eco-friendly power from ashore. With ship's own generators shut down completely, and instead being powered by emissions-free energy from its berth, SSE technology has significantly contributed to emissions reduction for instance in the Port of Hamburg. Despite only one of its three terminals having an operational shore power station, in 2018 this was estimated to have reduced CO2 emissions by over 650 tons.

While Hamburg's Altona terminal is already equipped with SSE capability, a new project expanding shore power supply to all terminals with an alternative marine power station is underway and is expected to be completed in 2022. Switching the energy source from the ship's main and auxiliary engines to a municipal power system reduces emissions but having the shore-side power grid be reliant on renewable power will eliminate all existing CO2 and pollutant emissions at berth.

4. Research objectives

An evaluation of the total external cost due to estimated air emissions in port areas will be presented at the subject area of this thesis. Thus, the current study should provide a unique inventory allowing a detailed approach in addressing the issue of air pollution generated by cruise ships at the busiest touristic areas in the Mediterranean Sea.

Simultaneously, it will be presented an analysis from data that retrieved from EU MRV data base in comparison with the above-mentioned estimations of the study.

5. Methodology and Data

To reduce emissions across the maritime sector, national authorities need to first quantify those emissions and then develop a strategy to reduce them. A new set of toolkits to assess and address emissions from ships and ports is now available from the International Maritime Organization (IMO), the global regulatory body for shipping.

The Ship Emissions Toolkit and Port Emissions Toolkit have been developed under the GEF-UNDP-IMO Global Maritime Energy Efficiency Partnerships (GloMEEP) Project, in collaboration with its strategic partners, the Institute of Marine Engineering, Science and Technology (IMarEST) and the International Association of Ports and Harbors (IAPH).

5.1 Port Emissions Toolkit

As more attention is focused on reducing emissions from the entire marine shipping sector, ports are driven to understand the magnitude of the air emissions impact from their operations on the local and global community and to develop strategies to reduce this impact. Port emissions inventories provide the basic building block to the development of a port emissions reduction strategy. The Port Emissions Toolkit includes two guides:

- Guide No.1: Assessment of port emissions: The guide is intended to serve as a resource guide for ports intending to develop or improve their air pollutant and/or GHG emissions assessments. It incorporates the latest emission inventory methods and approaches. It recognizes that ships do not operate independently from shore-based entities in the maritime transportation system, and that port emission considerations must extend beyond the ships themselves to include all port-related emission sources including: seagoing vessels, domestic vessels, cargo handling equipment, heavy-duty vehicles, locomotives, and electrical grid.

- Guide No.2: Development of port emissions reduction strategies: The guide is intended to serve as a resource guide for ports intending to develop an emissions reduction strategy (ERS) for port-related emission sources. It describes the approaches and methods that can be used by ports to develop, evaluate, implement, and track voluntary emission control measures that go beyond regulatory requirements (IMO, 2018).

5.2 Ship Activity Model

The activity-based estimation of ship emissions involves the application of emission factors to a particular ship activity, where an emission factor is a representative value that attempts to relate the emitted quantity with the operational status of the ship's engines during that activity. For port emissions, a ship activity profile is a breakdown of a ship's movements into modes of operation (i.e. maneuvering or at berth), with a representative engine type and size, engine load factor, type of fuel consumed and time spent in each mode. Maneuvering refers to the slow speed movement of the ship between the port's breakwater (entry/exit) and point of berth, whereas berthing refers to the dockside mooring of the ship.

For every ship call, each of the NOX, SO2 and CO2 emissions produced during the ship's inbound and outbound maneuvering and while at berth are estimated through the application of the following expressions:

$$\mathbf{E_M = T_M * [(ME * LF_{ME} * EF_{ME}) + (AE * LF_{AE} * EF_{AE})] * 10^{-6}}$$

and

$$\mathbf{E_B = T_B * [(ME * LF_{ME} * EF_{ME}) + (AE * LF_{AE} * EF_{AE})] * 10^{-6}}$$

Where,

E_M or E_B = Ship Emissions during maneuvering or at birth respectively (tons).
T_M = Time spent during maneuvering (h).
T_B = Time spent at berth (h).
ME = Main engine power (kW).
AE = Auxiliary engine power (kW).
$LF_{ME\text{-}M}$ or $LF_{ME\text{-}B}$ = Load factor of main engine in maneuvering or at berth, respectively.
$LF_{AE\text{-}M}$ or $LF_{AE\text{-}B}$ = Load factor of auxiliary engine in maneuvering or at berth, respectively.
EF_{ME} = Emission factor of main engine for each of the emitted species (g kWh^{-1}).
EF_{AE} = Emission factor of auxiliary engine for each of the emitted species (g kWh^{-1}).

In subject case, it will be examined only the emissions' production while cruise ships are at berth. For this reason, in all calculations it is assumed that:

1. Auxiliary (installed) power=30% of total (installed) power.
2. Average loading factor of propulsion power at port= 0%.
3. Average loading factor of auxiliary power at port= 50%.

5.3 Port traffic statistics

In order to estimate the ships' emissions in Mediterranean Ports, there was a need to select thirty cruise ships that were active in both big and small Mediterranean ports and consequently to end up with all calculations of an average representative cruise ship. After research, it was decided to be chosen two ports from each five Mediterranean Countries, either big or small. Therefore, those five countries that have been selected to be studied are Italy, Greece, Croatia, Spain, Malta and Slovenia.

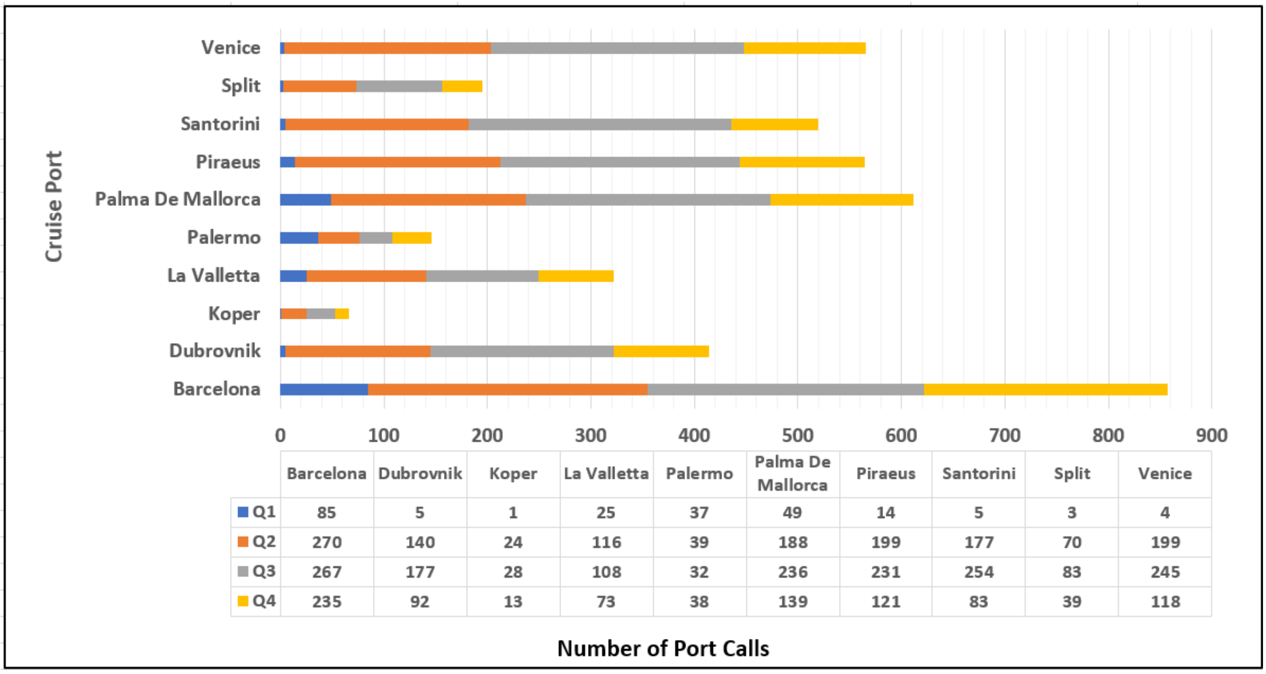
Shipping activity within ports such as Barcelona, Dubrovnik, Koper, La Valletta, Palermo, Palma de Mallorca, Piraeus, Santorini, Split and Venice, as shown below, is comprised by the daily itineraries of cruise ships' calls across the Mediterranean Sea.

Figure 9 - Ports of the Case Study

Map has been utilized from netpas and ports have been marhed by the author.

The Crew Centre (www.crew-center.com) provided all the information relevant to cruise ship calls for the above-mentioned ports, involving the date of call, the vessel's name, as well as the call's duration (i.e. arrival and departure time).

Records of cruise shipping within those ten ports covered almost a sixteen-month period, namely between the 30th of Dec 2018 and the 23rd of March 2020. The total Number of Port Calls during this period is 4246, which have been analyzed per quarter for better understanding of traffic condition through the year. Also, the record data was further divided into quarterly intervals in order to be captured the influence of seasonality in cruise and consequently in emissions' production.



	Barcelona	Dubrovnik	Koper	La Valletta	Palermo	Palma De Mallorca	Piraeus	Santorini	Split	Venice
■ Q1	85	5	1	25	37	49	14	5	3	4
■ Q2	270	140	24	116	39	188	199	177	70	199
■ Q3	267	177	28	108	32	236	231	254	83	245
■ Q4	235	92	13	73	38	139	121	83	39	118

Figure 10 - Ship traffic statistics at ten passenger ports of Mediterranean Sea (Quarterly analysis of 2019)

[a]Q1= January – February – March, Q2= April – May – June, Q3= July – August – September, Q4= October – November -December

Figure 10 shows the number of cruise ships that involved in our research and their seasonal and overall number of calls (or departures) at subject ports.

It is clearly revealed (Figure 10) that the cruise ships' activity is higher during Q2 and Q3 of the year than during Q1 and Q3, which explains that Mediterranean cruise activity depends mainly on seasonality.

In order to find out the amount of emissions, it has additionally been calculated the average port stay of cruise ships on each Mediterranean port, as it is shown at the below figure (11).

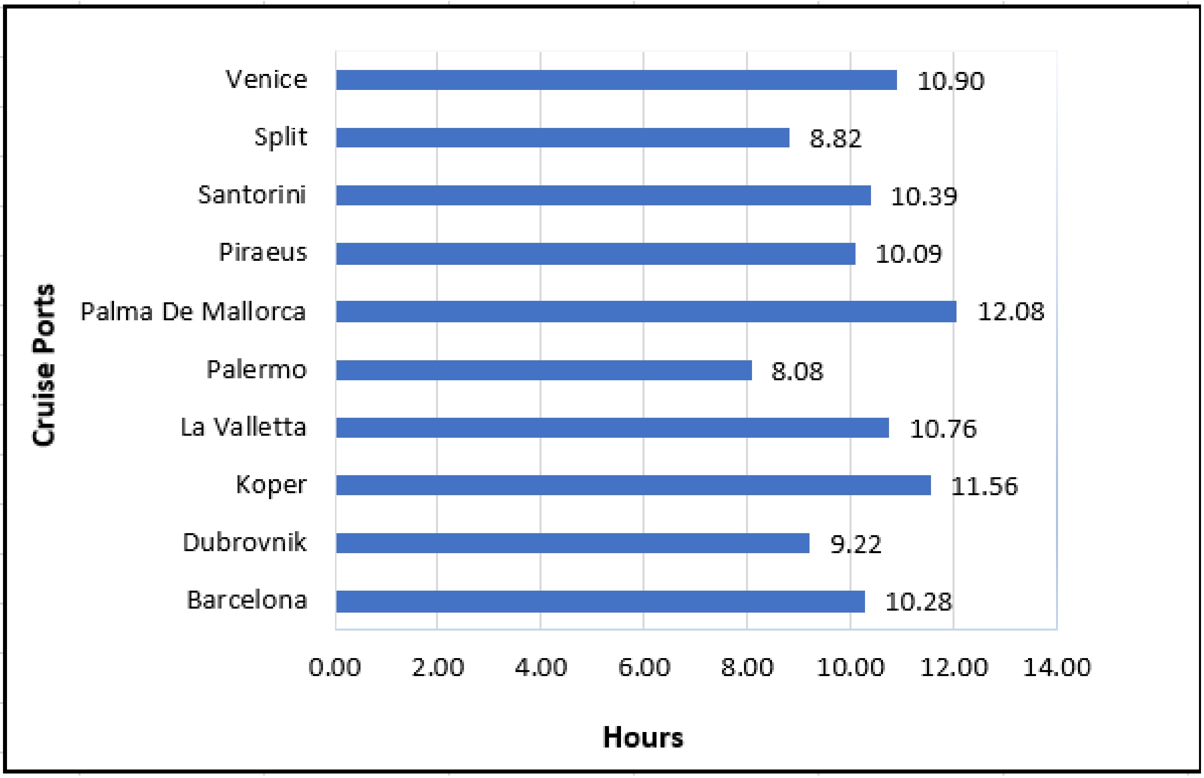


Figure 11

Figure 11 - Average Stay in port (h) per each Mediterranean Port

From above calculations it has been resulted that the average port stay in a Mediterranean port is about 10.42 hours.

5.4 Engine details

To proceed with the calculation of the emissions, it should be known the Kilowatt-hours that are produced during the port stay of an average representative cruise ship. On the basis of the vessel's name and type, online Wikipedia and the site scheepvaartwest were utilized in order to obtain data on main (ME) and auxiliary (AE) engines power for thirty randomly selected cruise ships out of 4262 vessels that are included in the research.

Utilizing the information provided on main engine’s power for all 30 different sized cruise ships, with the assumptions that have previously been made, it has been found that the average power produced from a representative cruise at port is 71797 KWh. Additionally, for better understanding of the results on later calculations on the emissions, the studied amount of cruise ships increased to 138, which are the total ships that are included at the study, with the average produced power to become 56709 KWh.

6. Results

6.1 Emissions Estimation

Based on the above, knowing the amount of the Kilowatt-hours at the port, the ship exhaust emissions as well as their fuel consumption at port can be estimated. However, in order to proceed, it is further assumed that the following apply in terms of fuel and emission coefficients, according to transphorm.eu (att. At Appendices):

1. Specific Fuel Consumption (s.f.c. of auxiliary (medium speed) diesel engines = 215 g/KWh
2. SO2 emissions = 0.41 g of SO2 per KWh
3. NOX emissions = 2.26 g of NOX per KWh
4. CO2 emissions = 670 g of CO2 per KWh

Therefore, the overall fuel consumption and exhaust emissions of cruise shipping at the Euro-Med ports under consideration during the year 2019 were fund to be:

1. Fuel Consumption = 51964 tons
2. SO2 total emission = 99 tons
3. NOX total emission = 546 tons
4. CO2 total emission = 161935 tons

The perecentage distribution of overall exhaust emissions is shown in Figure 12, where the dominance of CO2 emissions is clearly evident, followed by those of NOx and SO2.

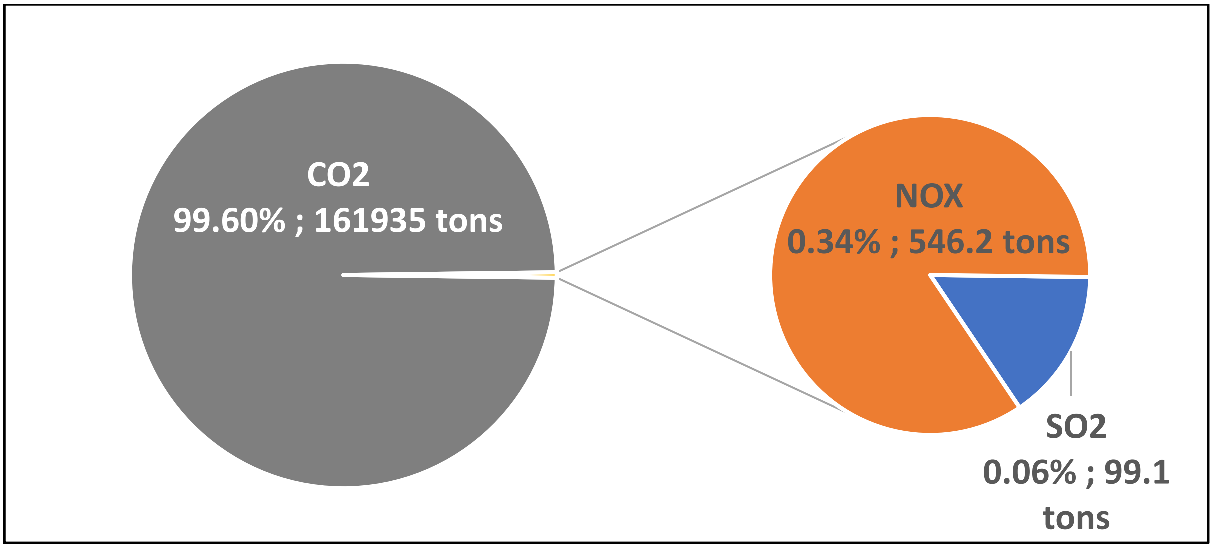


Figure 12 - Distribution of total emissions at all selected Euro-Med ports during 2019

Furthermore, Figure 13 presents the distribution of exhaust emissions at the selected Euro-Med ports for the year 2019. It is shown that SO2 and NOx exhaust emissions are lower than those of CO2 in all of the selected ports.

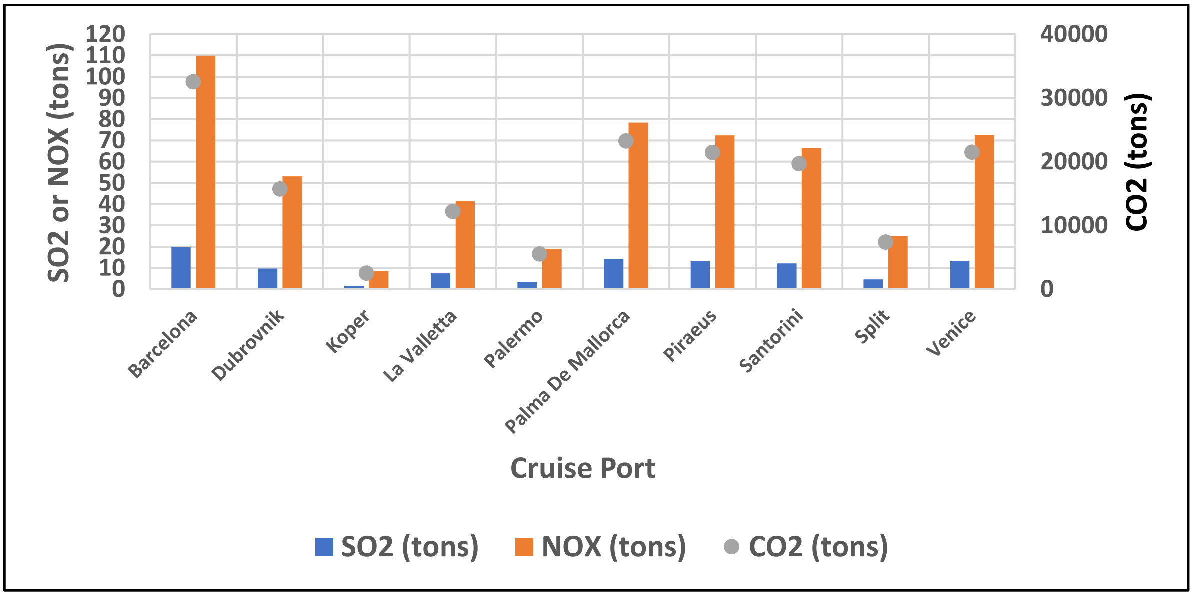


Figure 13 - Distribution of total emissions at the selected Euro-Med ports during 2019

As of the fuel consumption throughout the year of 2019, it is clear that the larger and more commercial ports, such as Barcelona, had the higher in-port fuel consumption consistent with the higher number of recorded port-calls of cruise ships.

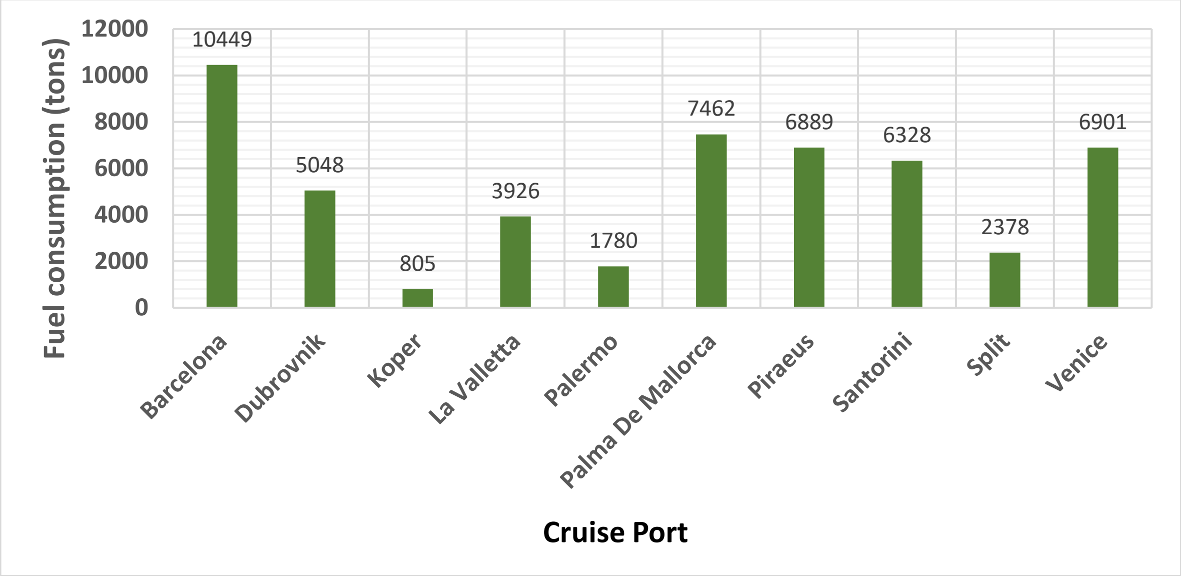


Figure 14 - Distribution of total fuel consumption at the selected Euro-Med ports during 2019

With regard to the seasonal distribution of the overall emissions, Figure 15 clearly shows that the third quarter (Q3) is the highest, consistent with the peaking of the cruise traffic activity during this period.

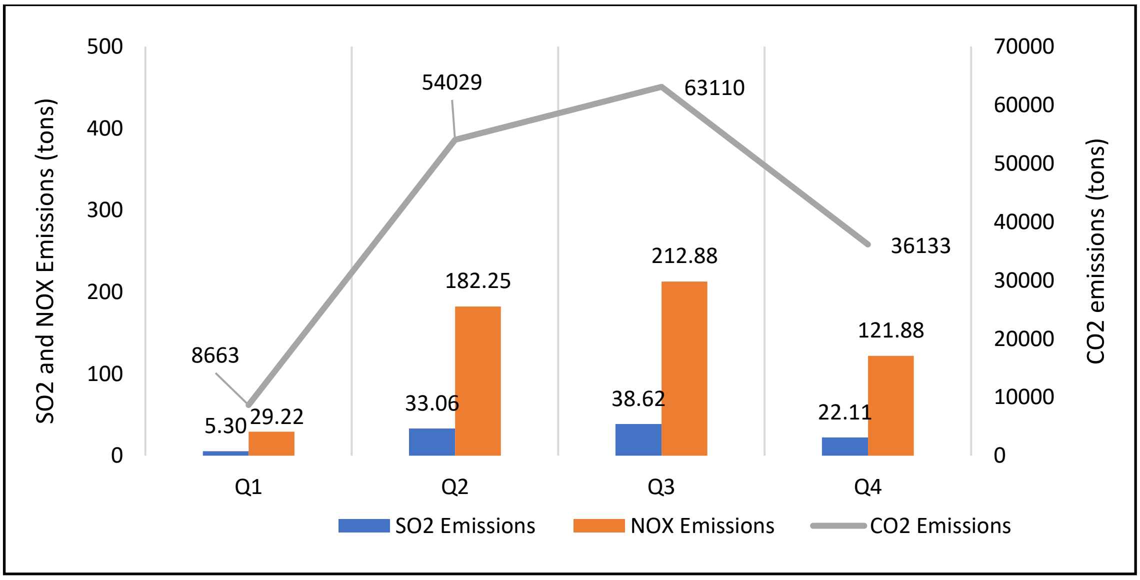


Figure 15 - Seasonal distribution of overall emissions at all selected Euro-Med ports during 2019

6.1.1 MRV Data vs Cruise Shipping Emissions (Case Study's Data)

Figure 16 presents the comparison of MRV data with the results of the current case study, with regard to the quantities of the in-port fuel consumption and exhaust emissions from shipping.

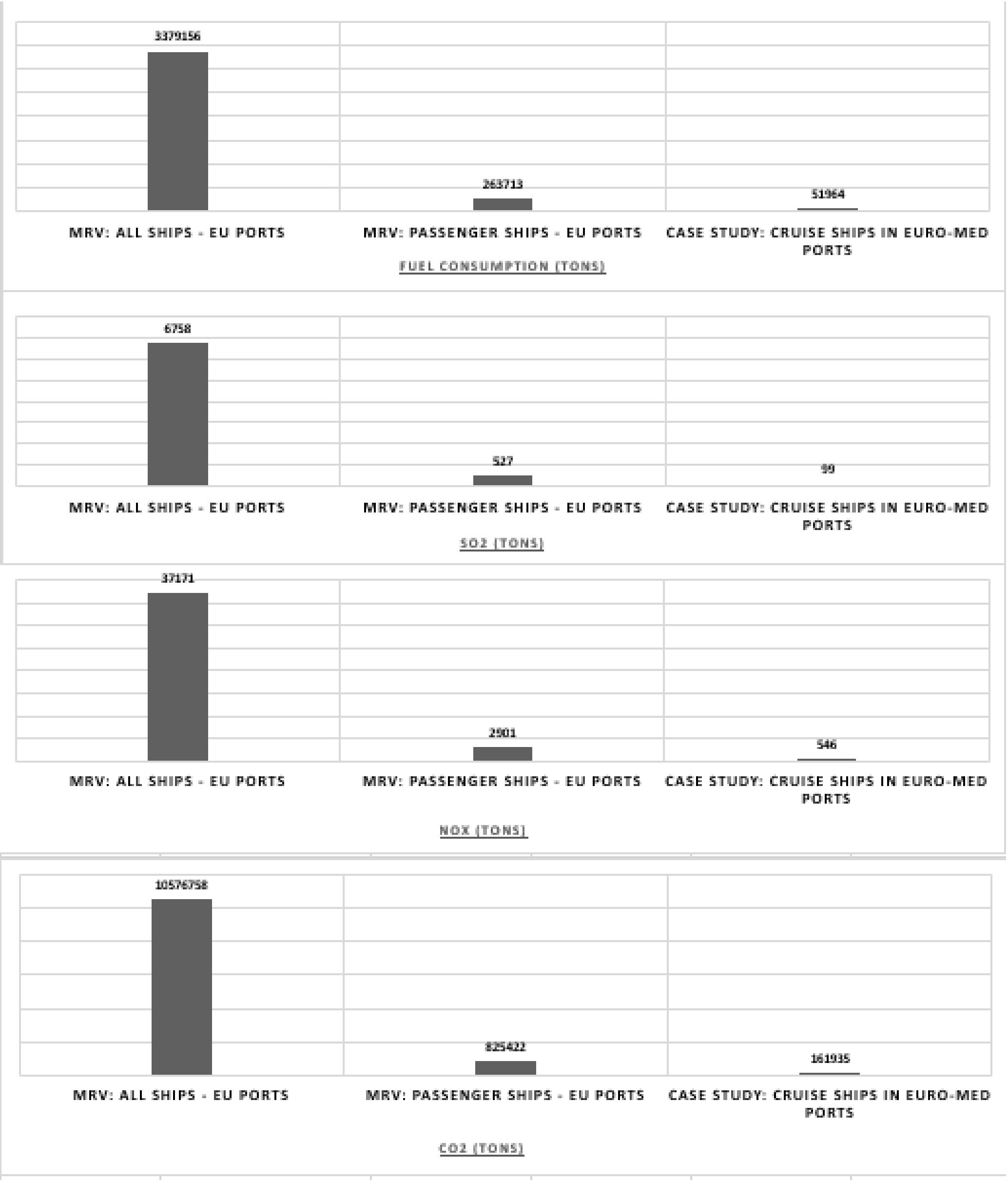


Figure 16 - Comparison of MRV data (for all ships & cruise ships only) in all EU ports with cruise shipping at the selected Euro-Med ports during 2019

Based on the aforementioned MRV data and case study results, Figure 17 shows that the contribution of cruise shipping within the selected Euro-Med ports in terms of fuel consumption and emissions during 2019 is approximately equal to 1.5% of the fuel consumption and emissions in all EU ports by all types of ships. However, the share of cruise shipping within the selected Euro-Med ports rises to almost 20% when reference is made to the cruise (passenger) ships only.

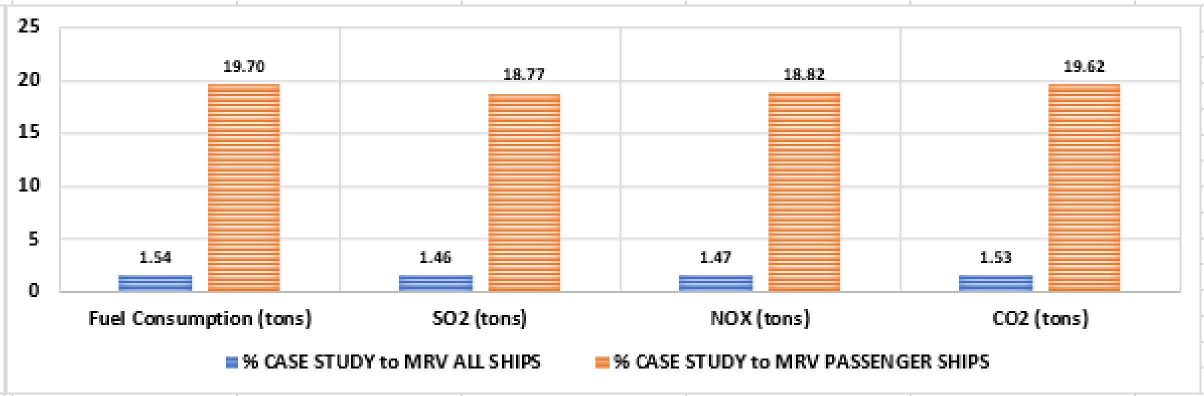


Figure 17 - Percentange contribution of cruise shipping in selected Euro-Med ports in relation to MRV data (all ships & cruise ships only) in all EU ports during 2019

7. Conclusions

Ten Euro-Med cruise ports were selected to perform a cruise ship emission inventory, as they combine adequate emitter and receptor characteristics, deriving mainly by the generated port traffic and the urbanized character of the port, respectively.

It was found that, during 2019, the in-port CO2 emissions from cruise shipping were almost three times higher than the combined NOX and SO2 emissions. The larger Euro-Med ports appear to suffer the most from the cruise shipping activity, due to the increased navigational traffic (higher number of ship port calss). CO2 emissions were found to be dominant throughout the year, followed by those of NOX and thirdly SO2 emissions.

The seasonal distribution of in-port ship emissions is also related to the cruise traffic. As expected, summer emissions were almost double than the equally placed autumn and spring emissions, whereas winter emissions were found to be trailing by almost 50% of those of summer. This seasonal variation of emissions is very significant as it affects the air quality of ports along with the cities near them. The results indicate that the seasonal distributin of in-port emissions varies for each port, depending mainly on the duration of ship port calls.

With respect to the reliability of the port-call data inventory, emission inventory and power estimation, it should be mentioned that in-port ship activity, engine use (power) and emission factors are based on numerous assumptions made through other researchers, as well as by the current author. They are bound to have considerable uncertainty and therefore they can influence the reliability of the calculated emissions. The case study has been approached in an approximate way and the purpose is to have an overview of the average cruise ship emissions that are produced in Mediterranean ports. Furthermore, although the applied assumptions are widely used in many research studies, it is acknowledged that there is adequate margin for improvement through the broadening of the range of calculations and more accurate evaluation.

Finally, the comparison of the case study results with those from MRV EU for all ship types in all EU ports reveals that the emissions of cruise shipping within the selected Euro-Med ports are low. On the contrary, the emissions within the selected Euro-Med ports from cruise shipping were found to constitute around 1/5 of the overall cruise ship emissions in all EU ports, which indicates that the Mediterranean cruise industry carries a significant share of in-port emissions in relation to corresponding European.

Taking into account that the case study refers to an important but in any case, limited sample of cruise ports, it has been revealed that the need to accelerate the implementation of the emission control measures in the energy demanding and emission prevelant sector of cruise shipping is imperative in order to meet the relevant IMO and EU policy objectives and ultimately safeguard the air quality of the Mediterranean Sea and its environmentally sensitive port-cities.

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9. Appendices

- Cruise shipping and emissions in Mediterranean ports – excel file
- Emissions Factors – pdf file
- EU MRV Publication of information - Comparison with Cruise Shipping Study – excel file
- Ship Efficiency – pp file