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EVALUATION OF APPLIED PROVISIONS AND TECHNOLOGIES ON SHIP EMISSION AND AIR QUALITY

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Abstract

Although perceived as the most environmentally friendly means of transport, ships are a significant source of pollution to the environment. The vast majority of emissions in EU sea areas are emitted from cargo ships over 500 GT. About 45% of all emissions come from EU flagged ships and approximately 20% of emissions are emitted within the 12-mile limit of territorial seas. In port cities, ship emissions are in many cases a dominant source of pollution and need to be addressed when considering compliance with legally binding air quality objectives. Moreover, emissions from ships travel over hundreds of kilometres and can thus contribute to air quality problems on land even if they are emitted at sea. This is particularly relevant for the deposition of sulphur and nitrogen compounds, which cause acidification of natural ecosystems and threaten biodiversity through excessive nitrogen inputs. Emission of toxic compounds in marine engines exhausts is limited by international legal provisions, namely MARPOL convention, which in Annex VI sets limits to SO_x and NO_x emissions and designates special areas where the limits are stringent. To comply with the provisions, marine vessels need to be equipped with installations reducing emissions to permissible levels or turn to alternative fuels. The paper presents evaluation of impact of those having been in force for the last decade limitations as well as of applied new technological solutions on improvement of air quality. The analysis was conducted for the Baltic Sea, based on available data on ship traffic in the area and emission factors.

Keywords: *transport, exhaust emission, marine engines, air pollution, modelling*

1. Introduction

Recent years show that external costs of intensive development of industry and transportation, such as life loss, health hazards and environmental pollution arise attention of scientists, policymakers and ecologists. In case of marine transportation, a lot of attention is especially paid to the environmental and human health implications of marine engines exhausts emission (in particular nitrogen oxides NO_x, sulphur oxides SO_x, carbon dioxide CO_2 and particulate matter PM). Those effects are so significant because globally, more than 70% of the emission occur within 400 km from the shore [8], while in seas, like in the North Sea, or the Baltic Sea, 90% of emissions occur within 90 km from the shore [14]. It was estimated that in parts of Northern Europe ship emissions are responsible for more than 90% of the exceeding of critical loads for eutrophication and for acidity [5]. Moreover, according to research conducted a few years ago, air pollution from international shipping is estimated to cause about 50,000 premature deaths per year in Europe alone, at an annual cost to society of more than €58 billion [3].

Whereas there can be observed a substantial decrease in land-based sources of emission of those substances since the 1990s, mainly due to technological development in the sectors of industrial production, energy production and road traffic, following more and more stringent provisions, in case of marine vessels, for a relatively long time, the problem had been perceived as negligible and left unregulated. However, for the past 15 years the significance of ship exhausts contribution to air quality has been investigated worldwide, which resulted in adoption of regulations aiming at controlling and reducing emissions from ships.

2. Impact of legal provisions on marine engines exhausts emissions

In 2002, the European Commission adopted a new strategy to reduce emission from seagoing ships and consequently the impact of those emissions on local air quality and acidification. The strategy is based on the reduction of the sulphur contents of marine fuels used in the European Union. To be more exact,

The Commission's first priority was to reduce ship emissions of sulphur dioxide (SO_2) and particulate matter (PM) from ships, which are directly related to the sulphur content of marine fuels. Marine fuel in the EU had those times an average sulphur content of 2.7%, or 27,000 ppm, which seemed significant when compared with diesel for cars and trucks, which could not exceed 350 ppm. The Commission presented a proposal for a directive to reduce the sulphur content of marine fuels [5], the main provisions of which were:

- a 1.5% sulphur limit for marine fuels used by all seagoing vessels in the North Sea, English Channel and Baltic Sea,
- the same 1.5% sulphur limit for marine fuels used by passenger vessels on regular services to or from any port within the EU, in order to improve air quality around ports and coasts, and create sufficient demand to ensure an EU-wide supply of low sulphur fuel,
- a 0.2% sulphur limit on fuel used by ships while they are at berth in ports inside the EU, to reduce local emissions of SO_2 and PM.

It was estimated that stricter limits for sulphur in marine fuels that were then proposed would reduce sulphur dioxide emissions in the EU by over 500,000 tons every year and consequently would deliver significant human health benefits reducing the incidence of asthma, bronchitis and heart failure, particularly in populated port areas. The measures will also help reduce exceedances of critical loads for acidification, which remain a serious problem in lake and forest ecosystems in northern Europe. In addition to the sulphur proposal, the strategy set out a number of other actions including a push for tougher global emissions standards at the IMO, the development of new market-based measures to reduce ship emissions beyond regulatory standards, and the creation of a new Clean Marine Award scheme to promote low-emission shipping in the EU.

Adoption of environmental regulation to prevent air pollution from ships, set by International Maritime Organisation (IMO) Annex VI to the MARPOL Convention in 2005, has been expected to have a significant impact on fuels used on-board ships and on shipping industry in general. These are the SO_x and NO_x limits (Regulation 13 and 14 of Annex VI), which recently became even more stringent and which will also hold in Emission Control Areas (ECAs) that may additionally be established in the future.

The Regulation 14, setting limits to SO_x emission, apply to all fuel oil combustion equipment and devices on-board ships. It limits the maximum sulphur content of the fuel oil used and defines two different stringency levels: one more stringent level that holds in SO_x Emission Control Areas (SO_x-ECAs, or SECAs) and another, less stringent level, outside the SO_x-ECAs, also referred to as global requirements (Tab. 1).

The sulphur requirements in and outside the SO_x-ECA are becoming more and more stringent. From the 1st January 2015 on, the maximum sulphur content of fuel oil is not allowed to exceed 0.1% m/m inside the SO_x-ECAs and, depending on the availability of the required fuel oil, either from 2020 or from 2025 on, 0.5% m/m outside the SO_x-ECA. This constitutes a significant decrease in levels of emission of SO_x, comparing to previous years and a milestone comparing to those times when it was not regulated at all.

Changes in international regulations also concern NO_x, but to a lesser extent when compared to SO_x provisions. The Regulation 13 of MARPOL Annex VI sets NO_x emission limits for installed marine diesel engines of over 130 kW output power. The requirements limit the total weighted cycle emissions in terms of [g/kWh], depend both on the date of the construction of a ship and on the engines' rated speed (Tab. 2).

Tab. 1. IMO requirements on fuel sulphur content in fuel [9, 10]

Outside SO_x-ECA (global requirement)	Inside SO_x-ECA**
4.50% m/m *prior* to 1 January 2012	1.50% m/m *prior* to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015
Note: * Depending on the outcome of a review, to be concluded in 2018, as to the availability of the required fuel oil, this date can be deferred to 1 January 2025. ** Currently, there are four SO_x-ECAs established: the Baltic Sea area, the North Sea area, the North American area, and the United States Caribbean Sea area.	

Tab. 2. IMO NO_x limits in exhausts [7]

Tier	Geographical scope	Ship construction date on or after	Total weighted cycle emission limit [g/kWh]		
			$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
I	Global	1 January 2000	17.0	$45 \times n^{-0.2}$	9.8
II	Global	1 January 2011	14.4	$44 \times n^{-0.23}$	7.7
III	NO_x-ECAs*	1 January 2016	3.4	$9 \times n^{-0.2}$	2.0
Note: n – engine's rated speed [rpm] * Currently, there are two NO_x-ECAs established: the North American area and the US Caribbean Sea area.					

Generally, the IMO Tier II NO_x limits for marine diesel engines affect all engines built since 1 January 2011, and the ships constructed after this date have to conform to Tier II NO_x requirements, which constitutes about 15% less NO_x produced when compared with Tier I engines. In contrast, the IMO Tier III requirements reduce NO_x emissions significantly – by approximately 75% in comparison to a Tier I engine. At present, no specific stringency levels hold for NO_x Emission Control Areas (NO_x-ECAs, or NECAs) in European waters, but vessels constructed on or after 1 January 2016, have for already comply with NO_x Tier III standards when operating in the North American ECA or the US Caribbean Sea ECA, which are already designated NECAs. In addition, Tier III requirements will apply to install marine diesel engines when operated in other NECAs, which might be designated in the future. However, Tier III will then apply to ships constructed on or after the date of adoption by the MEPC (Marine Environment Protection Committee, IMO) of such a NECA, or a later date that may be specified in the amendment designating the NO_x Tier III ECA.

In March 2016, the Helsinki Commission (HELCOM), which consists of the nine Baltic Sea coastal countries, and the European Union, finally agreed to submit proposals to apply NO_x emission limits for international ships in the Baltic Sea. It is now expected that the impact assessments for both sea areas will be updated, and that formal submissions to the IMO will be made in July, in order for these applications to be discussed at a meeting of the IMO's Marine Environment Protection Committee in October this year. A final decision on the new NECAs is likely to follow in 2017, and the stricter Tier III NO_x standard would then apply to all newly built ships as from January 2021, i.e. with a five-year delay as compared to the North American NECA.

In the long-term perspective, it would bring effects for the environment as the IMO Tier III requirements reduce nitrogen-oxide emissions (NO_x) significantly – by approximately 75% in comparison to a Tier I engine. This requirement only applies to new vessels and engines. It poses a significant challenge to engine designers, as they need to apply NO_x-reduction measures with the help of other engine technologies.

3. Impact of technological solutions on marine engines exhausts emissions

To comply with the requirements set by MARPOL Annex VI and lessen emissions of toxic exhausts gases, shipowners need to apply different technological solutions, such as conversion to low-sulphur content fuel, modifications of the engines, installation of systems purifying the exhausts, such as SCR and scrubbers.

In principle, there are two basic ways of complying with set by MARPOL SO_x and NO_x requirements: application of primary or secondary methods. Limitation of SO_x emissions is possible simply by using fuel oil with the required sulphur content, which constitutes the primary method, or cleaning the exhaust gasses to prevent sulphur oxides emissions, which constitutes the secondary one.

Operating on low-sulphur distillate fuels (LSFO), which, depending on sulphur content limitation, could be marine diesel oil (MDO) or marine gas oil (MGO), i.e., distillates, is a relatively easy way to comply with fuel oil sulphur content limits. Other two options for compliance with strict sulphur limits are operating on heavy fuel oil (HFO) with an exhaust gas treatment system (EGTS), or operating on liquefied natural gas (LNG).

A comparison of these three main options is shown in Tab. 3, along with corresponding reductions for all types of current and expected future regulated emissions, i.e., CO_2, SO_x, NO_x, and PM.

Tab. 3. The three main options for compliance and corresponding emission reductions [12]

Compliance option	MDO/MGO	HFO	LNG
CO_2 removal	No	Abatement technologies	20-25%
SO_x removal	MDO: <2%; MGO: 0.01-1%		100%
NO_x removal	Abatement technologies		Up to 80-90%
Particulate matter (PM) removal			98-100%
Regulation in place	Yes	Yes	Developing
Infrastructure	Yes	Yes	Early stages
Cost of use	Abatement technologies required		LNG storage tank size; LNG fuel price uncertain; possible loss of cargo space
Potential to stretch the technology	End of cycle		Further CO_2 reduction
Challenges / differences	Abatement technologies Varied blends of distillates 2020		Bunker space/cryogenics/possible methane slip

Although the global 0.5% requirement can be met by mixing low and high sulphur fuel, this option is not possible for the SECA 2015 requirement of 0.1% [11]. Moreover, the low sulphur HFO (LSHFO) can only fulfil the global 0.5% and not the 0.1% sulphur requirement, as LSHFO can either be produced from very low sulphur crude oils or, alternatively, high sulphur residues are treated to produce low sulphur marine bunkers. HFO containing less than 0.5% sulphur is obtained from crude oil with sulphur content less than ~0.15%. The level of sulphur content of crude oil needed to produce HFO with 0.1% sulphur content is even lower [11]. Fuel types that fulfil global 2020/2025 (0.5%) as well as the 2015 SECA (0.1%) requirements are distillates, LNG, biofuels and other liquid or gaseous fuel options that can be used in dual fuel engines like for example LPG, Methanol, Ethanol, or Di-Methyl Ether [4]. In case of secondary compliance methods reducing SO_x emissions, scrubbers for exhaust gas cleaning can be used on-board. When a scrubber is used, the ship does not have to use a fuel other than HFO but the use of a scrubber will raise energy demand slightly.

Regarding the provisions on NO_x emission limits, whereas the global Tier I and Tier II requirements can be met by adjustments in engine design and calibration, this is not the case for the Tier III requirements which are 80% stricter than Tier I limits. In fact, achieving NO_x Tier III limits would be possible by application the following technologies, either alone or in some combination with each other [11]: Selective Catalytic Reduction (SCR); Exhaust Gas Recirculation (EGR); the use of LNG, either dual-fuel (diesel pilot injection with gaseous LNG as main fuel) or alternative fuel arrangements; or application of other technologies: direct water injection, humid air motor, scrubbers, treated water scrubber, variable valve timing and lift, Dimethyl Ether as an alternative fuel. In the areas established as SO_x-ECAs and NO_x-ECAs (with Tier III requirements), only two main options seem to be currently viable: the use of LNG or the use of distillates together with SCR/EGR because at present it is still not clear if the combination of HFO, scrubber and SCR/EGR is technically possible (Tab. 4).

Tab. 4. Complying with MARPOL VI requirements [11]

Type of fuel	Global 0.5% m/m sulphur limit	SECA 0.1% m/m sulphur limit	NO_x-ECA Tier III NO_x limit
LSHFO	X		
Distillates	X	X	
LNG	X	X	X
HFO + Scrubber		X	
Distillates + SCR/EGR		X	X

4. Projected loads of emissions in the coming years

Projected increase of maritime transport in the coming years is followed by increasing emissions of toxic compounds in the marine engines exhausts. Observed higher and higher contribution of emissions from shipping to total global emissions results from the fact that both the world trade is growing and the land-based emission sources are becoming cleaner.

Black scenarios in studies performed for the European Commission show that, by 2020, emissions of sulphur dioxide, nitrogen oxides and primary PM2.5 from international shipping in EU seas are expected to increase from their 2000 levels by 40%, 45% and 55% to 3186, 4828 and 396 kT per annum respectively, even with effective implementation of the current IMO and EU regulatory requirements [6].

In fact, there are many factors that need to be taken into account when analysing possible future emission scenarios, such as fuel prices, legal provisions reducing permissible levels of emission, development of new environmentally-friendly technologies, and the willingness of shipowners to invest in new emission abatement technologies or to turn to more ecological alternative fuels.

The most noticable improvement in air quality, especially observed in port areas and along coastlines, is related for significantly lower emissions of SO_x in SECAs after implementation of the latest provisions in the beginning of 2015. Consequently, since then, compared with the previous year, air sulphur oxides concentration reductions of 50% and over have been reported [2].

Estimated health benefits resulting from these air quality improvements (reduction of the sulphur concentration from 1% to 0.1%) range from 4.4 to 8.0 billion euro, which is in line with other previous estimations (e.g. [1]), where it was estimated that implementing the stricter ship fuel sulphur standards will save up to 26,000 lives per year in the EU by 2020. The report [2] states that the health benefits due to lower emissions of SO_2 and PM are thus 1.9 to 3.5 times higher than the rise in fuel costs, showing that the benefits of introducing the new regulations have far outweighed the costs of that policy (the additional fuel costs for the maritime sector of using 0.1% MGO in the North Sea and Baltic Sea have been quantified at 2.3 billion euro). This statement will remain valid with future rising fuel price differences (e.g. doubling towards pre-2015 price differences).

5. Data acquisition and analysis

With the introduction of the Automatic Identification System (AIS) for ships, it became much easier to track ship movements and estimate their actual engine loads provided the necessary engine characteristics are known. In order to avoid collisions, all ships bigger than 100 gross tons (GT) are obliged to broadcast such a signal every 6 s to indicate – amongst others – their identification number, position, moving status, direction and speed over ground. On the basis of AIS data, it is possible to follow the route of a single ship and to estimate its energy demand, fuel consumption and pollutant exhaust along this route.

In this study, the area of research was the Baltic Sea as an interesting example of SECA (SO_x Emission Control Area) and possible future NECA (NO_x Emission Control Area). Research was conducted based on available data from AIS covering that region, enabling analysis of the characteristics of traffic in the area.

The Baltic Sea is the area of intensive traffic, where the most numerous group are general cargo ships – about 40% and oil/chemical tankers – about 20% (Fig. 1). Although passenger ships and Ro-Pax constitute only 5% of the total number of ships in this area, their share in overall NO_x emission is about 20%. In contrast, general cargo ships and oil/chemical tankers emit about 18% and 17% of NO_x respectively, and ro-ro ships 17%. Ships in the group 'other' these are smaller vessels, like tugs, pilots, dredgers, and their share in overall marine NO_x emission is about 10%. The age of the ships operating in the Baltic Sea is evenly distributed from new to about 40 years old, meaning there is a continuous replacement of old vessels, and it takes about ten years to replace 25% of the fleet.

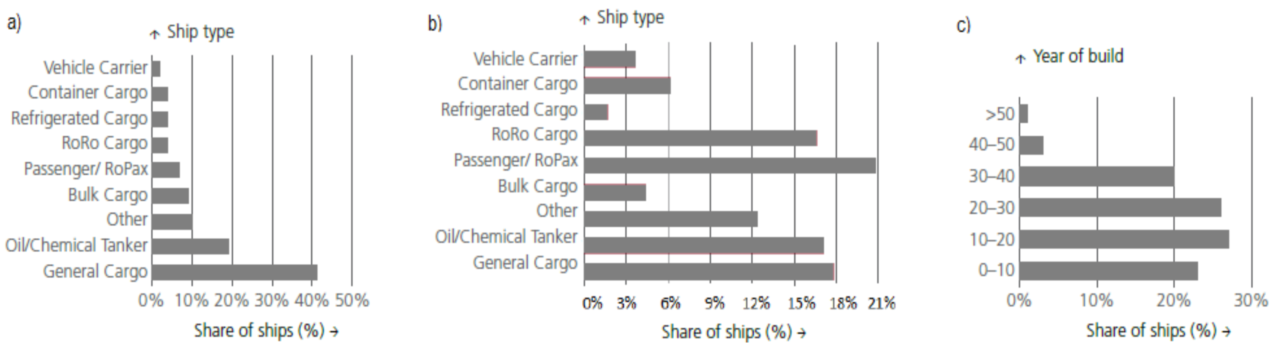

Fig. 1. Distribution of ship types (a), ship emission (b) and ship age (c) in the traffic in the Baltic Sea region

During the research, to compare obtained results, some reports containing estimation and characteristics of the traffic were analysed. The analysis also covered the share of different types of ships in the overall traffic in the research area and their emission factors, as well as the legislation, technology and projected trends. All that enabled to estimate the load of emission of main components in marine engines exhausts in the past, at present and to project emission in the future.

The baseline for the analysis was the year 2010, when emission permissible levels for NO_x was Tier I and permissible sulphur content in fuel was 1.5% for the first half of the year and 1.0% since then. Then, regarding nowadays legislative provisions – sulphur content in fuel 0.1% since 2015, Tier II for ships constructed on and after 2011 and projected future ones – Tier III for ships constructed in the future, probably as stated above on or after 2021, it was possible to perform a simulation of total emissions of different exhaust gases. Visualisation of the obtained results is given in Fig. 2.

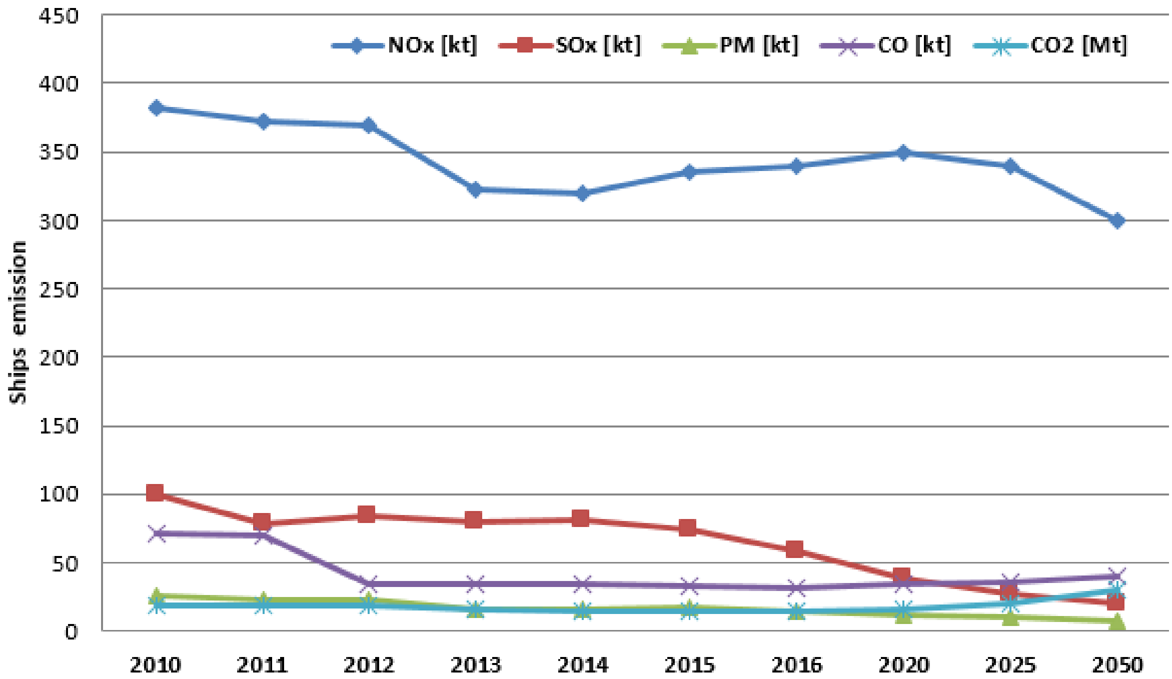

Fig. 2. Estimated and projected emissions in marine engines in the Baltic Sea region

Based on the results and with regard to existing trends of shipping emissions, there can be concluded that maritime CO_2 emissions are projected to increase significantly in the coming decades, and depending on future economic and energy developments, according to some studies, e.g. [12], an increase by 50% to 250% in the period to 2050 is probable. Increasing emission of this greenhouse gas has been already an issue of a big concern. According to the IPCC if these emissions continue at the present level the temperature is likely to rise by more than 4 degrees by 2100, and an additional effect of emissions of carbon dioxide is that they act as the primary source of ocean acidification, because one-third of the carbon dioxide emitted is absorbed by the world's oceans. In the oceans, it reacts with calcium and water to produce carbonic acid, which leads to the pH lowering [13]. Even in a long-term scenario, assuming turning to alternative fuels, such as LNG, which is one of the most prospective, significant decreases in emission of CO_2 seem unlikely.

Most other emissions increase in parallel with CO_2 emissions and fuel consumption, with some notable exceptions. Emissions of NO_x increase at a lower rate than CO_2 emissions as a result of the replacement of old engines by Tier II and Tier III engines entering the fleet and the increasing share of LNG in the fuel mix. In addition, the engines of new ships in NO_x-ECAs will meet Tier III requirements, so some studies that assume an increase in the share of fuel used in ECAs show a slower increase in NO_x emissions or even a decrease. We should also take into account a steady increase of the number of ships equipped with NO_x abatement installations (such as SCR). However, if Tier III was not going to be applied for the Baltic Sea in the future, then it is very likely that NO_x emissions will continue the rising trend. Emissions of particulate matter (PM) show a decrease in the longer perspective, and SO_x continue to decline through 2050, which is mainly driven by MARPOL Annex VI requirements on the sulphur content of fuels (which also impact PM emissions). In addition, EU sulphur directive requirements, which limit the fuel sulphur to 0.1% during harbour stays, contributed to this result. In scenarios that assume an increase in the share of fuel used in SO_x-ECAs (maximum 0.1% S), the impact of these regulations is stronger.

Methane emissions are projected to increase rapidly (although from a low base) as the share of LNG in the fuel mix will be increasing, which can be principally observed in ECAs. Another remark is pertrained to HFC emissions, which result from leakage of refrigerants and coolants and are a function of the number of ships rather than of the amount of fuel used.

6. Conclusions

Even though generally considered as the most carbon efficient mode of transport, shipping is a significant source of air pollution. Emissions of sulphur oxides, nitrogen oxides and particulate matter, including black carbon, should be of particular concern. These emissions are mainly due to the poor quality of fuel used in maritime transport and due to still weak emission standards applicable to ship engines. As a result of the fact that these emissions have been left unregulated for so long, the contribution of shipping in total emissions is growing while the pollution from other sectors is decreasing. And unless the trend is reversed, as soon as by 2025 emissions from marine engines of ships operating around Europe are likely to exceed all emissions from all EU land-based sources [11].

As shipping emissions often occur in coastal areas as well as in large city ports, they impact greatly on human health and our environment. With the exception of SO_x, emissions from international shipping are still poorly regulated in Europe and the EU heavily relies on the standards adopted at international level under the MARPOL Convention on the prevention of air pollution from ships.

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