The UUPO project – New fuels for maritime logistics as drivers of green transition and blue growth

Maritime Emissions Info Package

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SATAKUNTALIITTO
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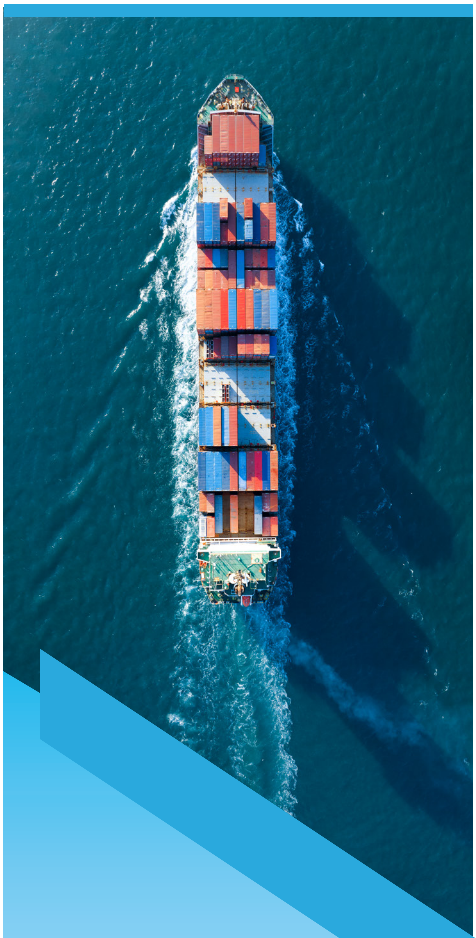
Maritime emissions



Important notes:

1. When examining greenhouse gas emissions, it is also important to consider other greenhouse gases besides carbon dioxide

2. Alternative fuels will play a crucial role in reducing greenhouse gas emissions in maritime transport

3. Maritime transport produces a significant amount of nitrogen and sulfur oxides, as well as particulate matter emissions

4. The choice of fuel has a decisive impact on the type and amount of emissions from ships

5. Exhaust gases from ship engines can be treated with various devices, thereby reducing the amount of emissions produced

A large part of global transport of goods takes place by sea, making marine logistics an essential and indispensable part of the international supply chain. Large cargo ships carry a variety of raw materials, fuels, food products, and finished goods worldwide. However, these transports do not occur without negative impacts, as maritime transport produces a significant amount of various emissions.

The fuels used in ships contribute significantly to greenhouse gas emissions, which accelerate climate change. Maritime transport also produces a large amount of nitrogen and sulfur oxides, as well as particulate matter emissions. For example, in 2018, maritime traffic accounted for 24 % of all nitrogen and sulfur oxide emissions in the EU, as well as 9 % of all particulate matter emissions smaller than 2,5 micrometers. [1] However, the amount of sulfur oxide and particulate emissions produced by maritime transport has decreased since 2018, as the International Maritime Organization's (IMO) latest sulfur emission restriction came into effect in 2020. This regulation requires ships to use fuels with lower sulfur content. Known as IMO 2020, this measure aims to reduce air quality problems caused by maritime transport and improve public health globally. [2]

Although such regulations are a step in the right direction, many challenges remain. Communities living near coasts are especially vulnerable to air pollution from maritime transport and the diseases it causes. It is estimated that maritime transport still causes around 250 000 premature deaths and over 6 million cases of childhood asthma annually worldwide. Before the IMO 2020 regulation, these figures were estimated to be around 400 000 and 14 million, respectively. [3]

In addition to the effects on climate change and human health, maritime emissions have significant impacts on both ecosystems and the atmosphere. Nitrogen and sulfur oxides contribute to increased acid rain, which can cause various serious consequences. For example, acid rain damages forest and water ecosystems, degrades soil quality, and lowers water pH levels, threatening fish stocks and other aquatic life. In the atmosphere, nitrogen oxides can also increase the amount of ground-level ozone. [4]

Since maritime transport is more challenging to electrify than road transport, energy-efficient ships and alternative fuels will play a central role in reducing these emissions. Various regulations also have their own role in guiding the maritime logistics market, as they can encourage innovation and promote sustainable development goals in maritime transport.

Citations: [1], [2], [3], [4]

Greenhouse gas emissions

Greenhouse effect
Solar radiation makes life on Earth possible, but it alone is not sufficient for life to thrive. Without greenhouse gases in the atmosphere, life would be impossible. Greenhouse gases, such as carbon dioxide, methane, and water vapor, trap some of the sun's radiation and retain heat in the atmosphere. This phenomenon is known as the greenhouse effect. [5]

The amount of retained heat is strongly dependent on the concentration of greenhouse gases in the atmosphere. As the concentration of these gases increases, so does the amount of retained heat. [6]

Climate change
Human activity has increased the amount of various greenhouse gases in the atmosphere, leading to global warming. Global warming itself poses serious challenges to humanity, but it also affects the climate and environment in many different ways. For instance, it influences weather patterns, increasing the occurrence and intensity of extreme events like hurricanes, heavy rainfall, and droughts. [7]

One of the most significant impacts of global warming is the melting of glaciers and ice masses. This process raises sea levels globally, threatening low-lying areas, such as islands and coastal regions. Melting ice also affects freshwater availability, which can weaken local water supplies and ecosystems. [8]

Climate change has immense effects on animal and plant species, as many habitats are rapidly changing. Many species may not be able to adapt quickly enough to new conditions, potentially leading to population declines and even extinctions. These declines and extinctions of species may weaken different ecosystems, and in turn cause biodiversity loss. [9]

Global warming also significantly affects human health, exposing people to risks caused by heatwaves and reduced water availability. Climate change can impair food production and security as shifting weather patterns affect crop yields and livestock farming worldwide. In addition to health risks, climate change has significant social impacts that complicate people's lives. Economic downturns can increase unemployment, intensifying the effects of rising food prices. [10]

The impacts of climate change are far-reaching and severe, requiring rapid and wide-ranging action to mitigate them. International cooperation and collective efforts are essential to finding sustainable solutions and reducing greenhouse gas emissions.

Citations: [5], [6], [7], [8], [9], [10]

Greenhouse gas emissions

Different greenhouse gases
There are numerous greenhouse gases produced by human activities, but the most significant ones are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases, and black carbon. The impact of these gases on climate change depends on their individual properties. Among the greenhouse gases produced by humans, carbon dioxide has the most significant effects on climate change due to its high emission levels. However, carbon dioxide is not the strongest greenhouse gas when considering the global warming potential (GWP) of different gases per unit of mass. [11]

When comparing different greenhouse gases, they are typically evaluated using the GWP coefficient, which indicates how much more a specific greenhouse gas contributes to global warming compared to carbon dioxide. [12] Additionally, the GWP coefficient is significantly influenced by the time frame being considered since different greenhouse gases persist in the atmosphere for varying durations before breaking down. The most common time frames for reporting GWP coefficients are 20 and 100 years. [13]

The importance of considering these time frames is evident in the case of methane, as one kilogram of methane causes over 80 times more global warming over a 20-year period compared to the same amount of carbon dioxide. Over a 100-year period, the impact of methane is approximately 30 times stronger than that of carbon dioxide. [14]

GWP coefficients also allow for the estimation of the combined effect of different greenhouse gases on global warming, which can be expressed in terms of carbon dioxide equivalents (CO_2e). [15] In 2022, global greenhouse gas emissions were approximately 53,8 Gt CO_2e. Of these emissions, carbon dioxide accounted for 71,8 %, methane for 21 %, nitrous oxide for 4,8 %, and fluorinated gases for 2,6 %. [16]

Greenhouse gas emissions from maritime logistics
In 2018, EU countries produced approximately 3,8 Gt CO_2e of greenhouse gases, with transportation accounting for about 29 % of this total. Of the emissions from transportation, the largest share, specifically 69 %, came from road traffic, while both maritime and air transport accounted for roughly 14 % each. The remaining transportation emissions were generated by motorcycles, rail transport, and other modes of transport. [17]

Thus, maritime transport represented about 4 % of all EU emissions in 2018. This figure is nearly the same when considering global emissions, with maritime transport contributing approximately 3 % of all greenhouse gas emissions worldwide. [18]

The global warming potential (GWP) of different greenhouse gases

Greenhouse gas	Chemical formula	Lifetime in the atmosphere (a)	Global warming potential (GWP)		
			20 years	100 years	500 years
Carbon dioxide	CO2		1	1	1
Methane	CH4	11,8	83	30	10
Nitrous oxide	N2O	109,0	273	273	130
HFC-32	CH2F2	5,4	2693	771	220
HFC-134a	CF3CH2F	14,0	4144	1526	436
CFC-11	CCl3F	52,0	8321	6226	2093
PFC-14	CF4	50 000,0	5301	7380	10587
Black carbon			3200	910	280

Citations: [11], [12], [13], [14], [15], [16], [17], [18], [Table 1]

Greenhouse gas emissions

Reduction targets for greenhouse gas emissions from Maritime Logistics in the EU
Various communities and organizations have established numerous targets and strategies to mitigate emissions generated by maritime logistics.

At the beginning of 2024, maritime transport was included in the EU Emissions Trading System (ETS). As a result of this change, vessel owners and operators will need to purchase emission allowances to offset their carbon dioxide emissions, encouraging them to reduce their emissions and invest in cleaner technologies. However, the implementation of the emissions trading system will be gradual, with full compliance required from maritime vessels starting in 2027. This phased approach allows stakeholders time to adapt to the new regulations and make necessary investments to reduce their emissions. [19]

The EU also aims to reduce emissions from member states by 55 % by 2030 as part of the Fit for 55 package. This package takes into account emissions from shipping, which are intended to be mitigated through the FuelEU Maritime regulation. The goal of this regulation is to gradually reduce greenhouse gas emissions from vessel fuels from 2 % in 2025 to as much as 80 % by 2050, for instance, by adopting alternative fuels. [20]

Like the EU, the International Maritime Organization (IMO) has set several emissions reduction targets. According to its latest strategy, member states have committed to achieving a net-zero status by 2050. Additionally, there are plans to reduce total emissions by 20 % by 2030, aiming for a 30 % reduction, and a 70 % reduction by 2040, with a target of up to 80 % reduction from 2008 levels. [21]

Methods for reducing greenhouse gas emissions from maritime logistics
Greenhouse gas emissions resulting from shipping can be reduced in several ways. One of the key methods is to transition to using more energy-efficient vessels and equipment. Additionally, optimizing fuel usage and adopting alternative fuels, as well as battery technologies, are crucial steps toward a more sustainable future for maritime transport. [22]

Enhancing logistical processes is also critical when considering the overall picture of greenhouse gas emissions in maritime logistics. More efficient route planning, improved cargo handling, and optimization of transport flows can reduce unnecessary emissions and enhance resource utilization. Digital technologies play a key role in streamlining logistical processes, as they improve collaboration and information sharing among various stakeholders. [23]

In the future, capturing carbon dioxide and other greenhouse gases from exhaust emissions may also become a standard practice and could play a significant role in achieving climate goals. [24]

Nitrogen oxides emissions

Formation of nitrogen oxides (NOx)

Nitrogen oxides are formed during combustion processes, such as in internal combustion engines, when nitrogen and oxygen in the air react under high temperatures. Additionally, some fuels, such as ammonia, contain nitrogen, which can increase the amount of nitrogen oxides in exhaust gases. Generally, combustion processes primarily produce nitrogen monoxide (NO), but small amounts of nitrogen dioxide (NO_2) can also be generated. In the atmosphere, nitrogen monoxide reacts with ozone (O_2) to form the more harmful nitrogen dioxide. This reaction can also proceed in the opposite direction under the influence of UV radiation, breaking nitrogen dioxide back down into nitrogen monoxide and free oxygen atoms. The released oxygen atom can then react with oxygen in the air (O_2) to produce ozone. Therefore, NOx emissions can both deplete and produce ozone depending on environmental conditions, such as the amount of light present. [25]

NOx emissions have numerous detrimental effects on the environment, animals, and human health. Like other emissions, nitrogen oxides degrade air quality, leading to various symptoms and illnesses in humans. NOx emissions also contribute to the formation of acid rain, which directly impacts the balance of aquatic and terrestrial ecosystems. Furthermore, NOx emissions can increase the amount of ground-level ozone, which itself has many harmful effects. [26]

Effects of nitrogen oxides on human health

The most significant health impacts of NOx emissions are observed in the respiratory system. They are particularly associated with the increased prevalence of various respiratory diseases, such as chronic obstructive pulmonary disease (COPD). Additionally, impaired air quality can worsen asthma and trigger its symptoms. NOx emissions also affect heart and vascular function, and they may increase the risk of diabetes and cancer. [27] The increase in ground-level ozone due to NOx emissions further exacerbates respiratory diseases and asthma symptoms. Moreover, ozone can irritate the eyes and increase the incidence of inflammation. [28]

Effects of nitrogen oxides on human health on the environment and animals

Nitrogen oxide molecules react with water in the atmosphere to form nitric acid (HNO_3). [29] This nitric acid reaches the ground in the form of acid rain, which causes numerous effects on soil, water bodies, animals, and plants. Acid rain can damage the leaves of plants and trees, impairing their photosynthesis. [30] Additionally, increased ground-level ozone can further hinder plant photosynthesis. [31] Acid rain can also leach harmful chemicals, such as aluminium, from the soil, increasing their prevalence and adverse effects. Some essential nutrients for plants may also leach deeper into the soil, making them unavailable to plants. Other impacts of acid rain include the acidification of soil and water bodies. These pH changes and acid rain generally affect various organisms in numerous ways. For example, in aquatic environments, acidification can impair fish reproduction or the ability of fry to hatch from eggs. In the soil, altered pH can affect the activity of microorganisms. Nitrogen-rich acid rain can also increase the eutrophication of water bodies. [32]

Other Effects of Nitrogen Oxides

The increased amount of ozone in the lower atmosphere contributes to the formation of smog. [33] Smog has various health effects and reduces visibility in the environment. The damage to materials caused by NOx emissions is also a significant consideration. Acid rain and nitrogen oxides can react with other air pollutants, negatively affecting the durability and condition of buildings and other materials. Over time, this can lead to structural damage and additional maintenance costs. [34]

Citations: [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]

Nitrogen oxides emissions

Legislation on NOx Emissions in maritime logistics

Numerous laws have been established due to the harmful effects of nitrogen oxides. The International Maritime Organization (IMO) has set various emission standards for NOx emissions in accordance with Regulation 13 of Annex VI of the MARPOL convention. These standards apply only to diesel engines with a power output exceeding 130 kW. The emission standards are divided into three different tiers based on the ship's construction date or whether significant modifications have been made to the engine, such as replacement or modification. The emission tier classification also depends on whether the vessel operates in designated NOx Emission Control Areas (NECAs).

There are six NOx emission control areas: the Baltic Sea, the North Sea, the eastern and western coasts of North America, the Hawaii area, and the waters surrounding Puerto Rico and the U.S. Virgin Islands. [35]

NOx Emission Limits According to IMO MARPOL Annex VI

The NOx emission limits (g/kWh) for different emission tiers are defined based on the engine's rated speed (n) and also depend on the construction date of the vessels. Typically, NOx emissions are highest at lower engine speeds. [36]

NOx emission tiers:

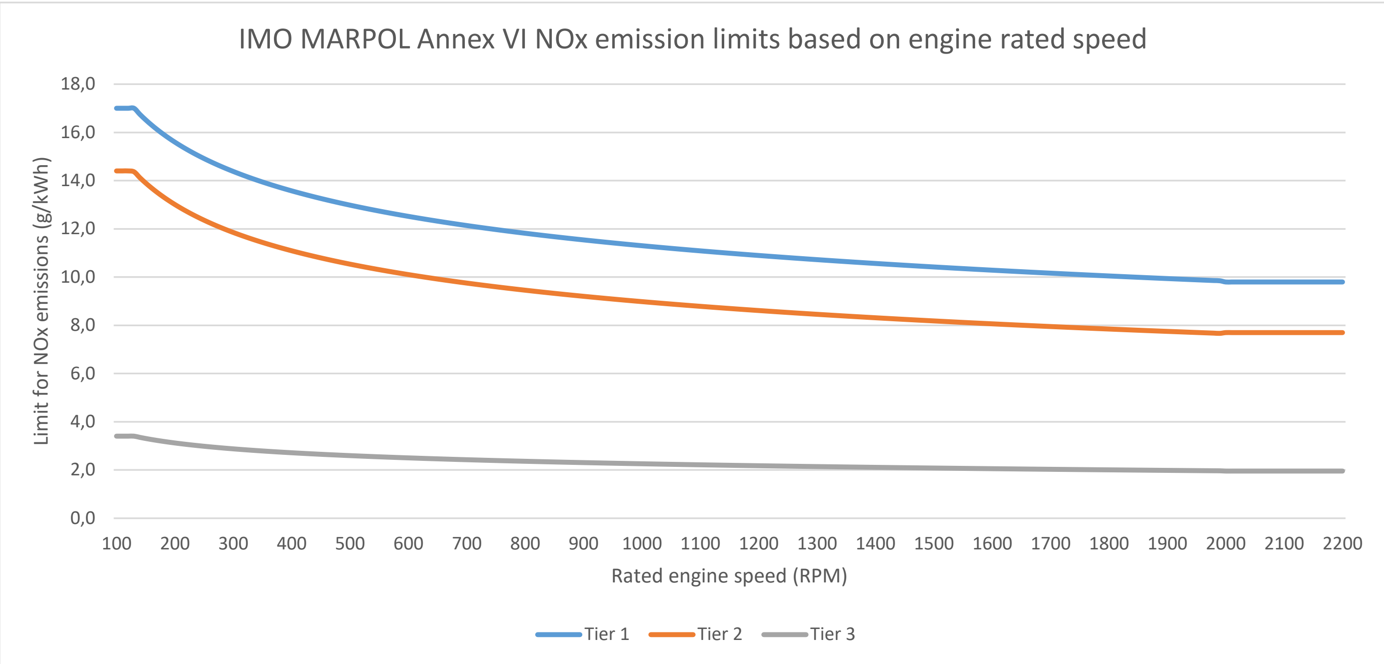
Tier 1 Emission requirements apply to vessels constructed from the year 2000 onwards.

Tier 2 Emission requirements apply to vessels constructed from the year 2011 onwards.

Tier 3 Emission requirements apply to vessels constructed from the year 2016 onwards that operate in designated emission control areas. If a vessel operates outside these areas, Tier 2 requirements apply. [37]

NOx emission limits according to IMO MARPOL annex VI

Tier	Date	NOx emission limits based on rotational speed		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier 1	2000	17,0	45 * (n^-0,2)	9,8
Tier 2	2011	14,4	44 * (n^-0,23)	7,7
Tier 3	2016	3,4	9 * (n^-0,2)	1,96



Citations: [35], [36], [37], [Graph 1], [Table 2]

Nitrogen oxides emissions

Management of NOx Emissions
The amount of nitrogen oxide emissions can be influenced in various ways even before they are formed. NOx emissions are closely linked to the type of fuel used; for instance, methanol produces significantly fewer NOx emissions compared to heavy fuel oil or FAME biodiesel. [38]

The operating parameters of ship engines significantly influence the formation of nitrogen oxides. For example, adjusting the timing of fuel injection and using cooled intake air can lower combustion pressure, resulting in lower temperatures in the combustion chamber during the reaction. While lower temperatures lead to reduced NOx emissions, they may cause an increase in other types of emissions. A lower combustion temperature can also be achieved through exhaust gas recirculation (EGR), where part of the exhaust gas is redirected back into the intake air. However, EGR systems may increase the amount of particulate matter emissions. [39]

NOx emissions generated in combustion chambers can be prevented from entering the atmosphere using selective catalytic reduction (SCR) systems. In an SCR system, ammonia is injected into the nitrogen oxide-containing exhaust gas before it enters the SCR chamber. Inside the chamber, ammonia reacts with the nitrogen oxides from the exhaust gas in the presence of a catalyst, forming nitrogen gas and water. The cleaned exhaust gases are then released from the system into the atmosphere. [40]

According to studies, SCR systems on ships have been able to reduce NOx emissions by more than 90% in some cases. [41]

Sulfur oxides emissions

Formation of sulfur oxides (SOx)

Sulfur oxides are formed when the sulfur bound in fuel reacts with oxygen during combustion. This means that the amount of sulfur oxides in exhaust gases is directly proportional to the sulfur content in the fuel. The majority of the generated SOx emissions are sulfur dioxide (SO_2), although small amounts of sulfur trioxide (SO_3) and sulfate (SO_4) can also form during combustion reactions. [42] In the atmosphere, sulfur dioxide oxidizes to form sulfur trioxide. [43]

SOx emissions have numerous adverse effects on the environment, wildlife, and human health. Like other emissions, sulfur oxides degrade air quality, leading to various symptoms and illnesses in humans. Additionally, SOx emissions contribute to the formation of acid rain, which directly impacts the balance of aquatic and terrestrial ecosystems. Furthermore, SOx can react with other compounds in the atmosphere to create fine particulate matter, which poses several health risks to humans. [44]

Effects of sulfure oxides on human health

The most significant effects of SOx emissions on human health occur in the respiratory system. SOx emissions have been linked to the prevalence of various respiratory diseases, such as chronic obstructive pulmonary disease (COPD). Deteriorating air quality can also exacerbate or trigger asthma symptoms. In addition to respiratory effects, SOx emissions may increase the prevalence of allergies, vascular diseases, cancers, and strokes. Some studies have also indicated that sulfur oxides can impact reproductive organs and fetal development. [45] Furthermore, the increased particulate matter resulting from SOx emissions poses numerous health risks to the respiratory system and raises the number of cardiovascular diseases. [46]

Effects of sulfur oxides on the environment and animals

In the atmosphere, sulfur trioxide reacts with water to form sulfuric acid (H_2SO_4). This sulfuric acid eventually falls to the ground as acid rain, causing numerous effects on soil, water bodies, animals, and plants. Acid rain can damage the leaves of plants and trees, impairing their ability to photosynthesize. Additionally, acid rain can leach harmful chemicals, such as aluminium, from the soil, increasing their prevalence and detrimental effects. Essential nutrients for plants may also leach deeper into the soil, preventing plants from utilizing them. Other effects of acid rain include the acidification of soil and water bodies. These pH changes and acid rain generally affect various organisms in numerous ways. For instance, in aquatic environments, acidification can hinder fish reproduction or the ability of fry to hatch from eggs. In the soil, altered pH can affect the functioning of microorganisms. [47]

Other effects of sulfure oxides

Sulfur oxides contribute to the formation of atmospheric fine particles, which promote the development of haze, or aersol, reducing overall visibility in the environment. [48] Another important consideration is the damage to materials caused by SOx emissions. Acid rain and sulfur oxides can react with other air pollutants, negatively affecting the durability and condition of buildings and other materials. Over time, this can lead to structural damage and increased maintenance costs. [49]

Citations: [42], [43], [44], [45], [46], [47], [48], [49]

Sulfur oxides emissions

Legislation on SOx emissions in marine logistics
Several laws have been enacted due to the numerous adverse effects of sulfur oxides. The International Maritime Organization has established various requirements for fuel sulfur content under the MARPOL Annex VI, specifically regulation 14, to address marine pollution. This regulation aims to prevent the emissions of SOx and the associated particulate matter. The sulfur content limit of the fuel also significantly depends on whether the vessel is operating in a designated SOx Emissions Control Area (SECA). There are six recognized SOx control areas: the Baltic Sea, the North Sea, the eastern and western coasts of North America, the Hawaiian area, and the waters surrounding Puerto Rico and the U.S. Virgin Islands. [50] Additionally, the Mediterranean Sea will also become a SOx control area starting from May 2025. [51]

Sulfur content Limits for Fuels under IMO MARPOL Annex VI
In SOx emission control areas, the sulfur content of fuels must not exceed 0,1 % by mass, while the corresponding limit in other maritime areas is 0,5 %. [52]

IMO MARPOL annex VI fuel sulfur content limits	
SOx ECA	Global
0,10 %	0,50 %

Management of SOx emissions
It is important to note that although the IMO regulations set limits on the sulfur content of fuels, shipping companies can still use fuels that exceed these limits if the vessels are equipped with exhaust gas scrubbers or other devices for reducing SOx emissions. This possibility is also acknowledged in Regulation 4 of MARPOL Annex VI. [53]

Typically, the operation of exhaust gas scrubbers is divided into either dry or wet systems. However, in practice, all scrubbers function similarly; they inject various substances into the exhaust gases that react with the sulfur oxides, capturing them so they can be removed from the exhaust stream. [54] The use of an exhaust gas scrubber for example enables the utilization of heavy fuel oil (HFO), which typically has a sulfur content of 3,5 %. [55]

A simpler method for managing SOx emissions is to choose fuels with sulfur content within the limits set by IMO regulations. For example, marine diesel oil (MDO) and marine gas oil (MGO) contain significantly less sulfur than heavy fuel oil. [56] Additionally, LNG and methanol contain extremely low amounts of sulfur, making the SOx emissions from these fuels practically negligible. [57]

Citations: [50], [51], [52], [53], [54], [55], [56], [57], [Table 3]

Other emissions

Ships and maritime logistics, in general, produce not only greenhouse gases and nitrogen and sulfur oxides but also other harmful emissions.

Particulate matter emissions
Particulate matter (PM) emissions consist of very small particles, typically classified into different categories based on their size. The particle size affects both the distance particles can travel in the atmosphere and their potential health impacts. [58] Particulate matter is generally divided into the following categories:

PM 10: Particles with a diameter of less than 10 micrometers. These can penetrate the lungs and cause various health issues, such as asthma attacks and chronic obstructive pulmonary disease, especially when exposed to long-term or high concentrations. [59]

PM 2,5: Particles with a diameter of less than 2.5 micrometers. Due to their small size, these particles can infiltrate the alveoli, causing severe illnesses. [60] These include various chronic cardiovascular and respiratory diseases. [61]

In the atmosphere, SOx emissions can react with other compounds to form particulate matter. [62] This means that the sulfur content limits imposed by Regulation 14 of MARPOL Annex VI also reduce particulate matter emissions.

VOC emissions
Volatile organic compound (VOC) emissions include many different gaseous organic compounds. These emissions occur during the combustion processes of fuels, but they also arise during the transportation and distribution of fuels when some of the fuel evaporates and is released into the atmosphere. This evaporation can occur, for example, in tankers and distribution infrastructure, such as tank trucks and storage facilities. [63] [64]

Additionally, chemicals used in the maintenance and repair of ships, such as solvents and paints, often contain volatile organic compounds that can be released into the environment. [65] Building materials, such as insulation, sealants, and floor coatings, can also be sources of VOC emissions, particularly in new or recently renovated vessels, when materials release compounds during drying and curing. [66] [67]

Because VOC emissions include so many different compounds, their effects are extremely diverse and variable. For humans, VOC emissions can cause respiratory diseases, cancers, and central nervous system disorders. In the atmosphere, VOC emissions may contribute to the formation of ground-level ozone. [68]

Regulation 15 of MARPOL Annex VI has established various conditions for tankers aimed at preventing VOC emissions from these vessels. [69]

Black carbon
Black carbon, or soot, is produced during the incomplete combustion of carbon-based fuels. Black carbon falls into the PM 2,5 category of particulate matter, meaning it can have very harmful health effects on humans. [70] It is also a potent greenhouse gas, as one kilogram of black carbon causes over 3 000 times more global warming than one kilogram of carbon dioxide over a 20-year period. [71] Black carbon is particularly significant as a greenhouse gas in shipping. Between 2013 and 2015, black carbon accounted for about one-fifth of the climate-warming impact of greenhouse gas emissions from international shipping. [72]

Black carbon does not remain in the atmosphere for more than 4–12 days before it settles back to the Earth's surface. On the surface, it can have severe impacts, such as contributing to glacier melting. When black carbon settles on glaciers and snow-covered areas, it reduces their reflectivity, or albedo. This means that solar radiation is not reflected back into space but is instead absorbed by the darker surface, resulting in increased temperatures in the area and faster melting of glaciers. [73]

Citations: [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73]

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