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Particulate Matter emission reduction in international maritime shipping

by:

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Analysis and discussion of current status and outlook

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On behalf of the German Environment Agency

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Abstract: Analysis and discussion of particulate matter emission reduction in international maritime traffic

Ships emit significant amounts of particulate matter (PM) in addition to other air pollutants such as nitrogen oxides (NO_X) and sulfur oxides (SO_X). The introduction of a Global Sulfur cap of 0.5% (m/m) in 2020 was supposed to reduce emissions of SO_X and indirectly PM, but this has only been partially the case. For this reason, it may make sense to focus on reduction of PM mass and particle number (PN) emissions from international shipping next to the ongoing discussion in the International Maritime Organization on reducing black carbon (BC) in the Arctic. An overview of PM measurement methods and limits that have been established in PM related regulations in other transportation sectors is presented. Various ship-specific measures to reduce PM emissions are described, including the use of cleaner fuels, exhaust gas treatment systems and a combination of both. Based on the analysis of the status quo, possible measures for a regulatory framework are proposed.

Kurzbeschreibung: Analyse und Diskussion der Reduktion von Partikelemissionen des internationalen Seeverkehrs

Schiffe stoßen neben anderen Luftschadstoffen wie Stickoxide (NO_X) und Schwefeloxide (SO_X) erhebliche Mengen an Feinstaub oder partikulärem Material (PM) aus. Schiffe emittieren auch nach der Einführung der globalen Schwefelobergrenze (Sulfur Cap) in 2020, mit der die Emissionen von Schwefeloxiden und indirekt auch von PM verringert werden sollen, erhebliche Mengen an PM. Aus diesem Grund könnte es sinnvoll sein, sich neben der laufenden Diskussion in der Internationalen Seeschifffahrtsorganisation über die Verringerung von Black Carbon (BC) in der Arktis auf die Verringerung der PM-Masse und der Partikelanzahl (PN) im internationalen Schiffsverkehr zu konzentrieren. Es wird ein Überblick über PM-Messmethoden und Grenzwerte gegeben, die in PM-bezogenen Vorschriften in anderen Transportsektoren festgelegt wurden. Es werden verschiedene schiffsspezifische Maßnahmen zur Verringerung der PM-Emissionen beschrieben, darunter die Verwendung von saubereren Kraftstoffen, Abgasbehandlungssystemen und einer Kombination aus beidem. Auf der Grundlage der Analyse des Status quo werden mögliche Maßnahmen für einen Rechtsrahmen vorgeschlagen.

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Abbreviation	Explanation
BC	Black Carbon
BLG	Bulk Liquids and Gases
BtL	Biomass-to-liquid
CG	Correspondence Group
C/H	Carbon/hydrogen ratio
CIMAC	International Council of Combustion engines
CO_2	Carbon dioxide
CPC	Condensation particle counter
CR	Common Rail
CtL	Coal-to-liquid
DF	Dual fuel
DMS	Differential mobility spectrometer
DOC	Diesel oxidation catalysts
DPF	Diesel particulate filter
EC	Elemental carbon
ECA	Emission control areas
EF	Emission factor
EGCS	Exhaust gas cleaning system, also called Scrubber
ESP	Electrostatic precipitators
FAME	Fatty acid methyl ester
FSN	Filter smoke number
g	Gram
GHG	Greenhouse gas
GtL	Gas-to-liquid
H_2	Hydrogen
H/C	Hydrogen/carbon ratio (mass/mass)
HFO	Heavy fuel oil
H_2SO_3	Sulfurous acid
H_2SO_4	Sulfuric acid
ICAO	International Civil Aviation Organization

Abbreviation	Explanation
IFO	Intermediate fuel oil, marine diesel with a large share of HFO
IMO	International Maritime Organization
InP	In production turbine
IPCC	International Panel for Climate Change
ISO	International Standards Organization
kN	Kilonewton
kWh	Kilowatt hour
LII	Laser-induced incandescence
LNG	Liquefied natural gas
LPG	Liquid petrol gas
LTO	Landing and take-off
MARPOL	International Convention for the Prevention of Marine Pollution from Ships
MDO	Marine diesel oil
MEPC	Maritime Environmental Protection Committee
MGO	Marine gas oil
µm	Micrometer
NAAQS	National Ambient Air Quality Standards
NO_X	Nitrogen oxides
nm	Nanometer
NT	New turbine
NTE	Not-to-exceed (limit)
nvPM	Non-volatile particulate matter
OC	Organic carbon
OME	Oxymethylene ethers
PAS	Photoacoustic spectroscopy
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter of <2.5 µm
PM_{10}	Particulate Matter with an aerodynamic diameter of <10 µm
PMP	Particle Measurement Programme
PN	Particle Number

Abbreviation	Explanation
PN, PN>23 nm	Particle Number, Particle number with a diameter >23 nm
PPR	Pollution Prevention and Response
PtG	Power-to-gas
PtL	Power-to-liquid
S	Sulfur
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficient Management Plan
SFOC	Specific fuel oil consumption
SO_2	Sulfur dioxide
SO_X	Sulfur oxides
UFP	Ultra fine particle
UNECE	United Nations Economic Commission for Europe
ULSFO	Ultra low sulfur fuel oil
VLSFO	Very low sulfur fuel oil
WESP	Wet electrostatic precipitators
WiFE	Water in Fuel Emulsion
WHO	World Health Organization
XtL	X stands for a variable, tL for to-liquid

Summary

International shipping contributes to emissions of harmful air pollutants such as sulfur oxides (SO_X), nitrogen oxides (NO_X), particulate matter (PM) and Black Carbon (BC) from the exhaust gas of marine engines. The introduction of the Global Sulfur Cap in 2020 did not reach sufficient decrease in PM emissions, especially in the ultrafine particles (UFP) size range. After years of tough discussions on the reduction of BC emissions in/near the Arctic with only voluntary guidelines and recommendations in place and without any mandatory measure yet, it may make sense to focus on reduction of PM mass and particle number (PN) concentrations. These would also address BC emissions.

PM has a harmful effect on health because it penetrates the lung tissue and smaller particles can even reach the bloodstream and trigger various diseases in the human body. For this reason, the emission of UFP is especially relevant. For the same reason, PM is already regulated in other transportation sectors. Therefore, standardized measurement methods and experience for PM and PN reduction exist.

For an ambitious regulation for international shipping, PM and PN emission factors must be developed, which can be either fuel- or power-based. The emission factors are highly dependent on engine speed, engine type and environmental factors, which makes this task challenging.

In this report the various emission-reducing methods and technologies are presented in detail, focusing on exhaust gas aftertreatment and cleaner fuels.

Finally, regulatory measures such as the introduction of limit values, fuel standards including the introduction of emission control areas and a possible timetable for their implementation are discussed.

This report provides a starting point to the discussion and does not propose any specific limit values as this would need more scientific research.

Zusammenfassung

Die internationale Schifffahrt trägt zur Emission schädlicher Luftschadstoffe wie Schwefeloxide (SO_X), Stickstoffoxide (NO_X), Feinstaub (partikuläres Material, PM) und Black Carbon (BC) aus den Abgasen von Schiffsmotoren bei. Die Einführung der globalen Schwefelobergrenze im Jahr 2020 hat nicht zu einer ausreichenden Verringerung der PM-Emissionen geführt, insbesondere im Größenbereich der ultrafeinen Partikel (UFP). Nach jahrelangen zähen Diskussionen über die Verringerung von BC-Emissionen in/in der Nähe von der Arktis, bei denen lediglich freiwillige Leitlinien und Empfehlungen und noch keine verbindlichen Maßnahmen verabschiedet wurden, könnte es sinnvoll sein, sich auf die Verringerung der PM-Masse und der Partikelanzahl (PN) zu konzentrieren. Dies würde auch die BC-Emissionen mit einschließen.

Feinstaub hat eine gesundheitsschädigende Wirkung, da er in das Lungengewebe eindringt und kleinere Partikel sogar in den Blutkreislauf gelangen und verschiedene Krankheiten im menschlichen Körper auslösen können. Aus diesem Grund ist die Emissionsminderung der UFP besonders relevant. Aus demselben Grund ist Feinstaub in anderen Verkehrsbereichen bereits geregelt. Daher gibt es bereits standardisierte Messverfahren und Erfahrungen zur PM- und PN-Reduzierung.

Für eine Regelung in der internationalen Seeschifffahrt müssen PM- und PN-Emissionsfaktoren entwickelt werden, die entweder kraftstoff- oder leistungsabhängig sein können. Die Emissionsfaktoren sind in hohem Maße von Motordrehzahl, Motortyp und Umweltfaktoren abhängig, was diese Aufgabe zu einer Herausforderung macht.

In diesem Bericht werden die verschiedenen emissionsmindernden Methoden und Technologien im Detail vorgestellt, wobei der Schwerpunkt auf der Abgasnachbehandlung und saubereren Kraftstoffen liegt.

Schließlich werden regulatorische Maßnahmen wie die Einführung von Grenzwerten, Kraftstoffnormen einschließlich der Einführung von Emissionskontrollgebieten und ein möglicher Zeitplan für deren Umsetzung erörtert.

Dieser Bericht bietet einen Ausgangspunkt für die Diskussion und schlägt keine spezifischen Grenzwerte vor, da dies weitere wissenschaftliche Untersuchungen erfordert.

1 Introduction and Status Quo in the Transport Sector

International shipping contributes to a large extent to emissions of harmful air pollutants such as nitrogen oxides (NO_X), particulate matter (PM), and sulfur oxides (SO_X) from the exhaust gas of marine engines. But so far, only SO_X and NO_X emissions are limited by Annex VI of the International Convention for Prevention of Marine Pollution for Ships (MARPOL).

SO_X emissions are directly linked to the sulfur (S) content of fuels. Therefore, the S content of the marine fuels was limited by the International Maritime Organization (IMO): since 2015 the S content in Emission Control Areas (ECA) is limited to 0.10% (m/m). Until January 2020 the global sulfur limit was 3.50% S (m/m) globally and after that date was reduced to 0.50% S (m/m) (MARPOL Annex VI, Regulation 14). SO_X react with water to form sulfates, which constitute a major proportion of PM from the combustion of high sulfur fuels. Therefore, Regulation 14 of MARPOL annex VI also embraces PM emissions, but does not set any limits to PM. It was anticipated that the limitation of sulfur and the resulting sulfates would reduce PM emissions from shipping significantly, but from an environmental perspective this is not sufficient.

Instead of following the approach to regulate PM emissions from shipping, in 2008 discussions shifted to limit Black Carbon (BC) emissions focusing now on the climate impact. BC is emitted by ships through the incomplete combustion of diesel fuel. The global warming potential (GWP) over 100 years is 900 times higher than that of CO_2 (Olmer et al., 2017). Due to the climate forcing impact of BC, the Friends of the Earth International published a study by Green et al. (2008) as a submission to the IMO Marine Environmental Protection Committee (MEPC) (Friends of the Earth, 2008), followed by a number of submissions also from member states concerning the problem of emissions of BC by international shipping in areas that impact the climate in the Arctic. In addition to the high GWP, deposition of BC causes snow and ice melt, as it darkens light surfaces and absorbs more energy than the surroundings. This effect is threatening the Arctic regions, where maritime traffic is increasing, due to the decreasing ice coverage, which exacerbates the problem. Therefore, the discussions regarding the reduction of BC emissions were limited to the Arctic region. In 2015 the IMO itself commissioned a study on BC and its abatement measures (Lack et al., 2015).

Discussions around specification of BC and its reduction in and around the Arctic has extended for more than 15 years. Years went by with discussions about the definition of BC, its measurement methods, measurement and reporting protocol, etc. So far only voluntary guidance on control measures to reduce BC and its impact on the Arctic (Resolution MEPC.393(82)) and Guidelines on recommendatory BC emission measurement, monitoring and reporting (Resolution MEPC.394(82)) have been enacted. Further, a voluntary switch to marine distillates has been agreed in 2021 (MEPC.342(77)), which is expected to reduce BC emissions immediately when implemented by shipping companies. There are still no effective and mandatory reduction measures nor limit values for BC in place.

At MEPC 76 (2021) a HFO ban was adopted with amendments to MARPOL Annex I, which introduces a prohibition on the use and carriage for use as fuel of heavy fuel oil (HFO) by ships in Arctic waters on and after 1st July 2024. This ban covers fuel oils having a density at 15°C higher than 900 kg/m^3 or a kinematic viscosity at 50°C higher than 180 mm^2/s (MEPC. 329 (76) MEPC 2021a). Exemptions are given for ships engaged in securing the safety of ships, or in search and rescue operations, and ships dedicated to oil spill preparedness and response.

Further exemptions are given to parties to MARPOL with a coastline bordering Arctic waters up to 1st July 2029. According to the International Council of Clean Transportation most of the HFO being used and carried in Arctic waters will continue until 2029 as only 30% of the HFO carriage and 16% of HFO use are affected by the July 2024 ban.

Another aspect und discussion in this context is the geographical extension of the Arctic in which emission control measures shall apply. So far, in the IMO context the Arctic boundaries are only defined in the Polar Code, with a focus on safety issues; but they are not regarded as sufficient in terms of air pollutant dispersion. There is a transboundary transport of BC from areas outside the Arctic that would be neglected if the Polar Code definition was applied for any BC reduction measure.

Several IMO correspondence groups (CG) worked on the establishment of BC controlling guidelines without any success. The international discussions on BC do not seem to make any real progress and are considered deadlocked. This paper is intended to outline the initial considerations for PM emission reduction by comparison of possible options with other sectors and in relation to the existing legislation in MARPOL Annex VI. Besides its air pollution effects and health impact, PM has a climate impact and depending on its composition decides about a cooling or a warming effect.

Whereas the discussions on BC emissions are currently limited to the Arctic area, there is a global problem with PM emissions from ships, especially in the coastal regions (Viana et al., 2014). Ocean-going vessels contribute to direct emissions of PM, as well as the formation of secondary particles in the atmosphere from the emissions of nitrogen oxides (NO_X) and sulfur oxides (SO_X), which react with the PM. On a global scale, shipping emits 0.9 – 1.8 million tons PM annually and mainly affects the coastal population (Moldanová, et al., 2009; Eyring, 2005; Di Natale and Carotenuto, 2015).

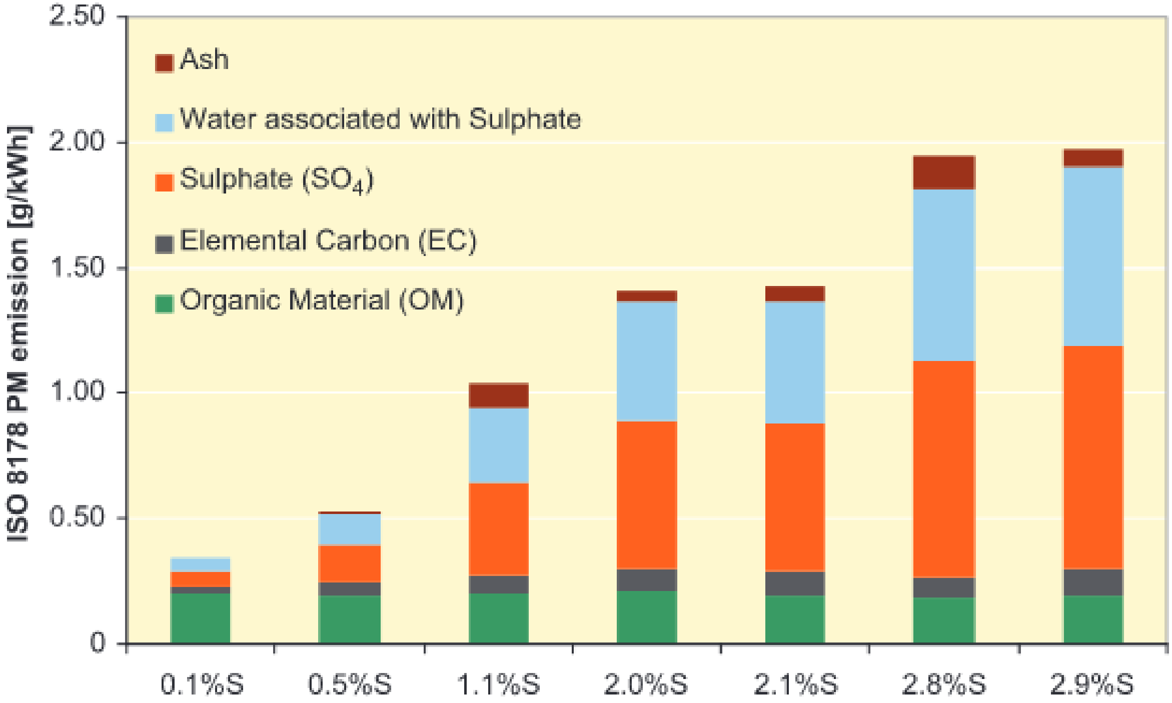
Definition

Particulate matter (PM) means the mass of all substances in the gas emitted by an engine which are deposited on a specific filter material after dilution of the gas. In order to ensure the regulation of emissions of very small particulate matter or ultrafine particles (UFP) <0.1 µm), the EU Commission introduced a particle number (PN) approach in addition to the current particle mass approach. PN means the number of solid particles emitted by an engine with a diameter of more than 23 nm. The size limit is caused by the measurement method (see chapter 1.2.2). Small particles have much higher health impacts than large particles, as they can enter the blood systems by penetrating the lung cells (see below).

PM was classified as carcinogenic of Class I by the World Health Organization (International Agency for Research on Cancer, 2013). Recent studies have linked PM emissions (PM <2.5 µm) with the development of Alzheimer disease (Li et al., 2019; Wang et al., 2020; Cheng et al., 2022). Corbett et al. (2007) have indicated that shipping-related PM emissions were responsible for ca. 60,000 cardiopulmonary and lung cancer deaths on a global scale, mainly related to an increase of $PM_{2.5}$. At that time the global sulfur limit was still 3.5% (m/m) causing much higher PM emissions with a larger health impact. Karjalainen et al. (2022) concluded from their study on PM emissions from marine engines that future research should focus on mitigating harmful particle emissions.

SO_X emissions lead to the formation of sulfurous acid (H_2SO_3) and sulfuric acid (H_2SO_4) during combustion and end up as sulfate and sulfonate (organic sulfur compounds) in the PM (Asaoka et al., 2019). Sulfate contributed to ca. 80% of PM, at the time when the S limit was 3.5% (m/m) (calculated from Lauer et al. 2024; Di Natale and Carotenuto, 2015, 2nd IMO greenhouse gas (GHG) Study, 2009). Aakko-Saksa et al. (2023), on the other hand, reported a share of hydrated sulfate in PM of only 22% – 62% for HFO and only 8.3% for marine distillate oil (MDO), both with unknown S content. Figure 1 clearly shows the increase of the sulfate and associated water share in PM with increasing sulfur content of the fuel from 0.1% up to 2.9%. Therefore, a limitation of sulfur and the resulting SO_X emissions was expected to sufficiently reduce PM.

Figure 1: The composition of PM obtained from different fuel types



Source: 2nd IMO GHG study, 2009

After the introduction of the S limit of 0.10% (m/m) sulfur since the 1st January 2015 in ECAs and 0.50% (m/m) S since the 1st January 2020 globally to reduce the SO_X emissions of shipping, a similar reduction of the associated PM was expected. While the reduction of SO_X emissions could be proven, a reduction of the PM emissions was not always encountered (Zetterdahl et al., 2016; Kuittinen et al., 2021; Wan et al., 2021; Song et al., 2022). Anderson et al. (2015) found that the use of some low sulfur fuels even leads to increased particle number (PN) concentrations at lower engine loads and a reduced particle size. Sippula et al. (2014) reported an increase of elemental carbon (EC) emissions at typical load points of the engine (50% and 75%) when switching from HFO to marine distillate fuel.

The introduction of the sulfur limits was especially not effective for the reduction of small- and nano-sized PM emissions (Winnes and Fridell, 2009; Winnes et al., 2016), which are regarded as very relevant for human health (for a review see Ohlwein et al., 2019, Schraufnagel, 2020). They occur in large numbers and pose a higher health risk than larger PM, as they can easier enter the body through the lungs and cause more pulmonary inflammation. Therefore, any limitation of PM should not be limited to PM mass, but also PN and include the problematic UFP (<0.1 µm). In the air of larger cities ultrafine primary and secondary particles mainly derive from combustion processes and the PN is mainly affected by the transport sector (tail-pipe emissions), whereas the heavier $PM_{2.5}$ particles are mainly caused by aged primary or transported secondary aerosols (De Jesus et al., 2019).

PM can be of different size and is generally defined by the aerodynamic diameter, with PM 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) being the most common size classes in the regulatory framework and relevant for human health. PM consists of solid particles and liquid droplets with a range of shapes and morphologies. Their size spans from a few nanometers to several micrometers. PM is subdivided by its average particle diameter (Di Natale and Carotenuto, 2015 and references therein):

Table 1: Categories of PM

Name	Size		
Ultrafine particles	<100 nm	Nucleation particles	<10 nm
		Nanoparticles	<50 nm
		Aitken mode particles	<100 nm
Fine particles			
(sometimes referred to <2500 nm PM 2.5)	<1000 nm	Accumulation mode	<1000 nm
Coarse mode	>1000 nm		

According to Mellqvist et al. (2022) 90% of the PM in ship plumes have a diameter of <80 nm and 50% of <40 nm and thereby belong to the UFP. The fraction <40 nm contributed to only 5% of total PM and all UFP (<100 nm) were found to contribute 50% to PM mass.

Regarding the composition of PM from ship exhaust, it can be subdivided into three main fractions (Fridell et al., 2008; Lack et al., 2009; Moldanová et al., 2009; Di Natale and Carotenuto 2015):

- minerals ashes from the fuel itself as impurities. Their sizes are in the range of 200 nm – 10 µm.
- inorganic sulfates with associated water in the range of micrometers, derived from the sulfur content of the fuel.
- Soot particles (BC), organic (OC) and elemental carbon (EC) <1 µm and <200 nm. BC is absorbing the visible light at all wavelengths of the visible spectrum, OC evaporates >350 °C, EC is the carbon, which is stable at >350 °C.

1.1 Discussions of Particulate Matter at the International Maritime Organization

MARPOL Annex VI contains Regulations for the Prevention of Air Pollution from Ships, including SO_X and PM emissions (Regulation 14), however there are no direct PM limits, so far, although MEPC and its sub-committee Bulk Liquids and Gases (BLG) nowadays Pollution Prevention and Response (PPR) discussed the issue since the mid-nineties. In 2006, a first CG was established at the 10th BLG meeting "with a view to controlling emissions of PM, study current emission levels of PM from marine engines, including their size distribution, quantity, and recommend actions to be taken for the reduction of PM from ships" (IMO, 2006).

So far, the only PM emissions limits for ocean going vessels have been proposed by the United States in their submission BLG 11/5/15 (2007), which coincide with the US EPA PM limits for inland shipping:

- [0.50] g/kWh for engines with a per-cylinder displacement of 15 liters or more,
- [0.27] g/kWh for engines with a per-cylinder displacement of 5 liters but less than 15 liters, and
- [0.20] g/kWh for engines with a per-cylinder displacement of less than 5 liters.

However, the proposed limits in square brackets were not further discussed because most delegations supported the indirect PM regulation by reducing the sulfur content in marine fuel and not by introducing specific PM emission limits in Annex VI. As sulfate-related PM emissions do not cause global warming or Arctic ice melt, the discussions at IMO shifted to the reduction of BC in order to address these climate aspects. Since then, PM limits have not been discussed for ship related emissions anymore and PN limits were not discussed at all.

1.2 Particulate Matter standards in other transport sectors

Air pollution, including PM emissions, from other transportation sectors have been reduced significantly around the world. Emission limits have been established in the European Union, Japan, the United States and other countries for passenger vehicles, commercial trucks, tractors, locomotives, in-land waterway vessels, airplanes and, in many cases, were strengthened numerous times since decades (Giechaskiel et al., 2021, Ni et al., 2020, EU, 2016)).

1.2.1 Aviation

In civil aviation the typical fuel Jet A-1 has a maximum S content of 0.30 % (m/m) (3000 mg/kg), which is a factor 300 higher than in the Euro VI EN 590 standard. Other fuels used in military aviation have S limits ranging from 0.10 % (m/m) (1000 mg/kg for JP-7) to 0.40 % (m/m) (4000 mg/kg fuel (JP-4). In March 2020 the Council of the International Civil Aviation Organization (ICAO) approved limits for non-volatile PM (nvPM) mass and number emissions for new type (NT) and in production (InP) aircraft turbine engines with a rated thrust >26.7 kN during landing and take-off (LTO-cycle). This new standard entered into force on 1st January 2023. For the constant flight conditions the PM emission limits for engines InP and NT engines are 347.5 mg/kN and 214.0 mg/kN, respectively. During take-off these limits can go up to maximum 4072.9 mg/kN for InP engines and 1066.5 mg/kN for NT engines. From 1st January 2023 the engines must comply with the LTO-cycle limitations for nvPM mass and number emissions. This standard replaced the former limit for smoke number. The nvPM contains soot (BC) and inorganic metal PM (iron, nickel, chromium, copper, tin) from additives, lubricants cat fines, etc. (Gagné et al., 2021) and is more or less comparable with a BC emission limit.

1.2.2 Vehicles with internal combustion engines

Vehicles with internal combustion engines include cars, tractors, trucks, locomotives, but exclude seagoing shipping and aviation (EU regulation, 2016). A PN methodology was developed by the Particle Measurement Programme (PMP) of the Working Party on Pollution and Energy of the United Nations Economic Commission for Europe as UNECE Regulation 83 in 2009 (UNECE 2018) and was first established for the certification reasons of light-duty vehicles. The method determines solid particles with a size >23 nm diameter in a diluted and conditioned exhaust gas.

The choice of the size was related to technical and cost reasons (Giechaskiel, 2012). In 2011 this method was implemented in European legislation for light-duty diesel vehicles (Euro 5), for heavy-duty engine certification and was also transferred to non-road mobile machinery including inland waterway vessels. The requirement to also measure PN was first introduced in the Euro 5b in 2011 for diesel engines and in 2014 in Euro 6 for petrol engines in cars. In November 2022 the Euro 7 proposal for light and heavy-duty vehicles was proposed to the European Commission, which lowered cut-off diameter from >23 nm to >10 nm for solid PM (Giechaskiel et al., 2021) and which reached a provisional agreement in December 2023 and enters into force in 2025 (EU regulation, 2022).

The European PM and PN limits for vehicles with internal combustion engines are given as mass per distance travelled (mg/km), but also as mass per power output (mg/kWh). E.g., for a Euro 6 passenger car the PM emission limit is 4.5 mg/km and $6*10^{11}$/km for PN. In the US the current Tier 3 standard for cars, SUVs, and light-duty trucks the PM limit is 3 mg/mile (4.8 mg/km), which is slightly higher than the European limit (Environmental Protection Agency, US EPA 2024a; table 1). However, the current US EPA PM limit will be reduced to 0.5 mg/mile for cars built from 2027 onwards (Environmental Protection Agency, 2024a).

The sulfur limits for marine fuels, 0.10% (m/m) (1000 mg/kg) in ECAs and 0.50% (m/m) (5000 mg/kg) globally, are still a factor of 100 and 500 times higher, respectively, as compared to the Euro VI standard EN 590 (10 mg/kg) for road diesel.

1.2.3 Non-road internal combustion engines

The European Commission has set PM and PN emission standards for non-road mobile machinery like railroad engines and inland waterway vessels (EU Regulation, 2016) for emission stage V. The engines of the inland waterway vessels are further subdivided into engines for propulsion and auxiliary engines. However, the emission limits are identical. The PM emission limits are related to power ranges and given as mass/power output (g/kWh) of the engines with a range of 0.015 – 0.30 g/kWh for PM, with the lower emission limits for the higher power output >300 kW. The limit of 10^{12} PN/kWh only applies to engines with a power output >300 kW.

1.2.4 Current Air Quality Standards

Emission means releasing, immission means receiving. Therefore, an emission limit is limiting a pollutant at the source of emission, whereas an immission limit, also called air quality limit, is a legally permitted maximum value for pollutants such as PM in terms of environmental and health protection. Immission specifications cannot be transferred to limit values for emissions. The EU Air quality limits for PM2.5 and PM10 per volume of air (table 2) (EU 2008) are less stringent than the recommended values by the World Health Organization (WHO, 2021) and for most National Ambient Air Quality Standards (NAAQS, 1990). However, the newly introduced EU directive from 2024 (EU 2024), which will enter into force 1st January 2030, has set more stringent limit values for PM 2.5 and PM 10 emissions as shown in brackets in table 2.

Table 2: Air quality standards

	EU Air Quality Directives 2008 and 2024 in brackets			**NAAQS**	**WHO Air Quality Guidelines**
PM		Averaging period	Concentration [$\mu g/m^3$]	Concentration [$\mu g/m^3$]	Concentration [$\mu g/m^3$]
PM$_{2.5}$	Target value	24 h	(25)	35[1]	15
PM$_{2.5}$	Limit value	Annual	25 (10)	9[2] (15)[3]	5
PM$_{2.5}$	Indicative limit value	Annual	20		
PM$_{10}$	Limit value	24 h	50 (45)	150[4]	45
PM$_{10}$	Limit value	Annual	40 (20)		15

1: Primary and secondary particles 98th percentile averaged over 3 years.

2: Primary particles annual mean averaged over 3 years.

3: Secondary particles annual mean averaged over 3 years.

4: Primary and secondary particles, not to be exceeded more than once per year on average over 3 years.

2 Determination of Particulate Matter

2.1 Particulate Matter mass determination

2.1.1 Filter Smoke Number and gravimetric determination

The measurement of PM mass has many uncertainties as compared to other gaseous emissions, due to its large size ranges, variable shapes and chemical composition. The measurement of PM is very dependent on its sampling method, which is an integral part of all emission regulations. PM is normally sampled directly in the exhaust pipe. PM sampling involves isokinetic sampling of the exhaust gas, sometimes followed by a dilution step and precipitation on a filter. For ship emissions two different measurement methods were discussed by Finland (Finland, 2007) and Japan (Japan, 2006) (see below), both in use in other sectors, which differ mainly by its sampling method:

1. The dilution method defined in International Organization for Standardization (ISO) 8178-2:2021, which determines the complete solid fraction, the soluble organic fraction, sulfate particles and associated water, and
2. the undiluted dry dust method defined in ISO 9096:2017, which only determines the solid fraction.

ISO 8178-2:2021 is the internationally accepted standard for PM emissions measurement in exhaust gas from mobile sources for non-road engine applications but not for ocean vessels yet. It is used for emission certification and/or type approval testing in many countries, including the United States, European Union and Japan. ISO 8178-1:2020 specifies the measurement and evaluation methods for gaseous and particulate exhaust emission from reciprocating internal combustion engines under steady-state and transient conditions on a test bed and ISO 8178-2:2021 for field tests. The ISO 8178-4:2020 standard also includes different engine dynamometer test cycles like for NO_X compliance measurements and is carried out at <52 °C. ISO 8178-3:2019- contains the PM determination with a filter smoke meter to measure the filter smoke number (FSN), the same as suggested for BC determination. In the FSN method a given exhaust gas volume is passed through a clean filter of a defined area and the blackness condition of this filter is subsequently used to measure the filter smoke number.

ISO 9096:2017 contains a gravimetric determination of mass concentration of PM from stationary sources. The sampling is carried out with a sampling nozzle, which is inserted directly into the gas flow. Then the PM is collected on pre-weighed glass fiber filters maintained at a temperature in the range of 120 ±14 °C. The PM particulate mass, which includes any material that condenses at or above the filtration temperature, is determined gravimetrically after removal of free water.

PM determination with ISO 8178-4:2020 and ISO 9096:2017 can have a difference of up to a factor 3 (Finland, 2007), even when sampling the same exhaust gas from the combustion of conventional marine fuels. Therefore, the measurement results of the two methods are not comparable. With ISO 8178-4:2020 the exhaust gas is diluted with air prior to the filtration and includes associated water and other volatile compounds of the PM.

Finland argues in their submission to IMO (Finland, 2007) that ISO 9096:2017 is the suitable method for the determination of PM from marine engine exhaust emissions, as it can be applied with the fuel qualities used in marine engines. Further, the ISO 9096:2017 standard is used globally and on all kinds of stational industrial sources including power plants (oil fired, coal fired, etc.). The International Council of Combustion engines (CIMAC) also recommends ISO 9096:2017 for ship engines using fuels with a S content of >0.05% (m/m) (CIMAC publication 23, 2005). However, ISO recommends ISO 9096:2017 for a S content of >0.8% (m/m). On the other hand, DNV GL (2016) regard the PM measurement according to ISO 8178:2006 as suitable for ship emissions, as this method is also applied to inland waterway vessels in the EU (EU directive 2016/1628) and US (US EPA 2017).

Other PM measurement methods will be considered in the following subchapters. They cover the measurement of different properties of PM like incandescence, acoustic emissions after excitation and light scattering followed by absorption of the light.

2.1.2 Laser-induced incandescence

The measurement principle of Laser Induced Incandescence (LII) is based on the following procedure: The soot particles in the exhaust gas are heated by a short high-energy laser beam to approximately 4000 Kelvin. These activated soot particles then glow with a frequency typical for carbon. This radiation is collected and is a measure of the carbon content in the exhaust gas flow. As these processes take place very quickly, this method can be used to measure soot concentrations with high temporal and spatial resolution (Kempthorne, 2010; Michelsen et al., 2015). The measurement method is therefore frequently used in research facilities, whereby the application and measurement is always carried out by a scientist specialized in LII and is therefore not regarded as very practical as an onboard measurement method.

2.1.3 Photoacoustic spectroscopy

The photoacoustic spectroscopy (PAS) is based on the photoacoustic effect. It occurs when a pulsed light beam acts on a gas in a closed absorption cell and is absorbed by it. The absorbed radiation transforms the gas into an excited state whose excitation energy (electron or vibrational excitation) is partially or completely converted into thermal energy by collisions. In a closed system, this leads to pressure increases that occur at a frequency that corresponds to the modulation frequency of the incident light. The modulation frequency is selected so that it corresponds to frequencies in the acoustic range that can be made audible by a sensitive microphone or converted into electrical signals and recorded using a suitable pressure transducer. The intensity of the sound signal corresponds to the respective light absorption (Lack et al. 2012; Viskup, 2019).

2.1.4 Opacimeter

An opacimeter is a measuring device for measuring the turbidity of gases and liquids. The term is mainly used for devices used to measure the exhaust opacity of diesel engines. It contains an elongated chamber through which the exhaust gas flows, with a powerful light source at one end and an optical sensor at the other. The attenuation of the passing light beam by the particles contained in the exhaust gas is measured. Heaters or air curtains are used to prevent soot deposits from remaining on the optics. The concentration of the PM is calculated from light attenuation using the Beer-Lambert law of light absorption (Viskup, 2019).

FSN, LII and PAS have been recommended by IMO MEPC for the determination of BC in ships exhaust gas. Whereas FSN is used for both, BC and PM measurements, LII was developed for the determination of nvPM. PAS can be used for measurement of gaseous and solid compounds, depending on the wavelength of the laser beam. In the recent BC CG of PPR 10, there seemed to be a trend towards FSN, as this is a simple and robust method.

2.2 Particle Number determination

Particle number analyzer or counter work optically with the principle of light scattering with a strong light source – usually a laser – and a photodetector. This measurement principle is applied by most of the handheld particle counters. In scattered light particle measurement, a defined quantity of air is passed through a laser beam. The light from the laser beam is refracted by the particles or absorbed by them. Photodiodes can measure these effects and convert them into an electrical signal, which is compared to a calibration signal for a reference value (Salimifard et al. 2020).

As this standard optical particle measurement method is not suitable for smaller particles <50 nm, a condensation particle counter (CPC) must be applied. The CPC measurement method was developed by the PMP group and only considers non-volatile particles with a diameter >23 nm (see 1.2.2). The sampling line of the CPC includes a hot ejector diluter, which heats the exhaust sample to ca. 300 °C (290−330 °C) as required for the definition of non-volatile PM (Giechaskiel, 2014; Samaras, et al., 2022). In the CPC the particles are then condensed in a supersaturated vapor before they are detected by a laser scattering optical method. The particles are typically grown to a size of 10-12 µm.

More advanced technologies apply scanning electron microscopy or transmission electron microscopy, which use electron beams to create a photography of the substrate. This way also the shape of the particles can be analyzed.

PM, PN and size distribution can also be analyzed simultaneously with a differential mobility spectrometer (DMS), which measures solid particles and liquid aerosols. The particles are positively charged in a corona chamber. The charge received by the particles is approximately proportional to their surface area. The positively charged particles reach the classification section via the air flow, where they are repelled by a positively charged electrode. Smaller particles travel faster than heavier PM. The charged particles are then separated in an electric field and are detected by electrodes. A typical size range is 5 – 2.500 nm[1]

2.3 Particle Emission factors

According to the U.S. Environmental Protection Agency (US EPA 2024b), emission factors (EFs) are defined as “a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned)”. Typically, in shipping emission factors (EF) are expressed as the mass of a pollutant per unit of energy generated (g/kWh) or unit of fuel used to generate an activity (kg/ton). Some minor studies use the unit g/km or g/nautical mile (Chu-Van et al., 2018; Grigoriadis et al. 2021). The preferred unit (g/kg fuel or g/kWh) depends on the further use of the EF. For remote monitoring of emissions, a fuel-based EF (g/kg fuel) is better suited, because

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[1] . DMS: e.g. the PM analyser Cambustion DMS500 (https://www.cambustion.com/products/engine-exhaust-emissions/dms500-particulate-analyser).

not even the specific fuel consumption data of the ship is required. Instead, a carbon mass balance is done based on the simultaneous measurement of CO_2 emissions and default fuel carbon content (e.g. 86% is used for residual and distillate fuel oils, see MEPC.340(77) - Appendix 2, MEPC 2021b). This is done for instance with the SO_2/CO_2 emissions ratio via direct monitoring to verify compliance with sulfur emissions limits. For an energy-based EF in g/kWh, the specific fuel oil consumption (SFOC) must also be known, which therefore requires additional ship information, such as engine data. Energy-based EFs are better suited for comparison between different fuels and alternative energies like electrical energy.

2.3.1 Fuel-based Particulate Matter emission factors

Typically, the PM EF are higher for HFO as compared to marine distillates. Winnes and Fridell (2009) reported PM EF in the range of 1.4 – 2.0 g/kg fuel for MDO and 2.8 – 3.7 g/kg for HFO, depending on engine load (50 – 90%). Karjalainen et al. (2022) found an PM EF of 0.327 g/kWh for a ship running on HFO, equipped with a diesel oxidation catalyst (DOC; see chapter 3.1.5) and an exhaust gas cleaning system (EGCS; see chapter 3.1.3) also known as scrubber and sailing at open sea under 65% engine load, indicating that the exhaust gas treatment in that case reduced the PM emissions to a similar range like marine gasoil (MGO).

2.3.2 Energy-based Particulate Matter emission factors

According to Winnes and Fridell (2009) energy-based EF for PM vary from 0.18 – 0.48 g/kWh for MDO and 0.56 - 2.12 g/kWh for HFO (on average 0.33 for MDO and 1.34 g/kWh for HFO with a standard deviation of 1). Van der Gon and Hulskotte (2010) found a very similar range of PM EF of 0.3 g/kWh for MDO and 1.5 g/kWh for HFO for two-stroke engines and 0.3 – 0.7 g/kWh for MGO and HFO for four-stroke engines, respectively. Grigoriadis et al. (2021) found that PM emissions rates are not so much dependent on the engine type, rather than the fuels used. For slow-, medium- and high-speed diesel engines the EF for PM were 0.624, 0.622 and 0.669 g/kWh, respectively for residual fuels and 0.196, 0.196 and 0.199 g/kWh for distillate fuels. Agrawal et al. (2008) surprisingly found that the $PM_{2.5}$ emissions did not differ very much under different engine loads in a 2-stroke engine. The EF for HFO varied between 1.091 at 27% engine load and 1.757 g/kWh at 70% engine load.

The IMO GHG study (IMO 2021) and Olmer et al. (2017) have applied the following formulas to calculate the energy-based EF for PM_{10} and $PM_{2.5}$ for HFO and MGO/MDO in g/kWh:

HFO:

$$PM_{10}\left(\frac{g}{kWh}\right) = 1.35 + SFOC\left(\frac{g}{kWh}\right) * 7 * 0.02247 * (fuel\ sulphur\ fraction - 0.0246)$$

MGO/MDO:

$$PM_{10}\left(\frac{g}{kWh}\right) = 0.23 + SFOC\left(\frac{g}{kWh}\right) * 7 * 0.02247 * (fuel\ sulphur\ fraction - 0.0024)$$

To obtain the $PM_{2.5}$ EF, it is assumed that 92% of the PM_{10} occurs as $PM_{2.5}$ (US EPA, 2019). Further, the authors of the GHG study assumed that 97.753% of the sulfur in the fuel reacts to SO_X. The rest reacts to sulfate and sulfite aerosols. The factor 7 in both equations represents the conversion of sulfur to sulfate (including associated water), and 0.02247 is supposed to reflect the proportion of the sulfur in the fuel that is converted to sulfate PM. The equations were empirically derived and are a curve fit to some test data (US EPA, 2019). The factors 1.35 and the

0.23 are the y-axis intercept when the fuel sulfur fraction is zero (pers. comm. Comer 2024). The factors on the last brackets in the formulas remain unclear to the author.

However, the calculation of PM_{10} EF with a single equation per sulfur content is questionable, as a number of factors affect them like e.g. the engine load. Also, the calculation of EF for the very low sulfur fuel oil (VLSFO) and ultra low sulfur fuel oil (ULSFO) are missing in the IMO GHG study (IMO 2021) so it is questionable if the PM emission calculations in the GHG studies are complete. This part of the IMO GHG study requires revision in future updates.

2.3.3 Fuel-based Particulate Number emission factors

Fuel-based EF for PN are very limited in the literature. Most PN determinations were carried out in ship plumes and not directly from the smokestack. However, Kuittinen e al. (2021) published some data for PN EF for the combustion of HFO in a four-stroke engine on a test bench, which varied from 5.4 - 5.8 x 10^{16} particles/kg fuel. Measurements on a ship resulted in a similar range of 2.5-4.2 x 10^{16} 1/kg fuel. Lack et al. (2009) measured an average of 1.0 x 10^{16} particles/kg from the emissions of 60 ships running on with fuels with a S-content of >0.5% S (m/m), The average of 83 sampled ships running on fuels with <0.5% S (m/m) was 7.0 x 10^{15}.

Mellqvist et al. (2022) carried out remote PM and PN analyses from a measurement site at the river Elbe in a distance of 0.5 – 1 km from the emitting smokestacks. Therefore, the measured particles include secondary particles through reaction with sulfates and nitrates, which increases their size. Mellqvist et al. (2022) found average PN EF of ships in the range of $0.8 \cdot 10^{16}$ - $1.6 \cdot 10^{16}$ particles/kg fuel for different types of seagoing ships. This is in good agreement with other reported values in the literature, which range from $0.2 \cdot 10^{16}$ to $6.2 \cdot 10^{16}$ particles/kg fuel (Sinha et al., 2003; Murphy et al., 2009; Lack et al., 2009; 2011; Jonsson et al., 2011; Juwono et al., 2013; Westerlund et al., 2015).

2.3.4 Energy-based Particle Number emission factors

Burning distillate fuels MDO (<0.10% (m/m) S) and MGO (<0.001% (m/m) S) in a four-cylinder medium-speed 4-stroke marine test bed engine resulted in PN emissions (>23 nm) ranging from ca. 1 x 10^{14} – 5 x 10^{14} particles/kWh (estimated from figure 1 in Lehtoranta et al., 2019). Modern diesel engines emit potentially less PN than older engines (Aakko-Saksa et al., 2023). In the same study, the combustion of HFO (<0.7% (m/m) S) on a cruise ship equipped with medium-speed, 4-stroke, modern engine and a hybrid scrubber resulted in PN emissions around ca. 1 x 10^{14} particles/kWh. The scrubber reduced PM, but no significant effect on PN emissions was observed as also described by Zetterdahl et al. (2016). Based on a literature study from 2015 onwards, Grigoriadis et al. (2021) found EF of 3.58 x 10^{15} ± 1.87 x 10^{15} particles/kWh for total PN and for 75% engine load, without distinguishing between residual and distillate fuels.

3 Emission Reduction of Particulate Matter

There are mainly three options to reduce PM emissions:

1. Exhaust gas aftertreatment

2. Cleaner fuels

3. Reduction of fuel consumption

In this report, the emphasis is laid on exhaust gas aftertreatment options and cleaner fuels, which are described in more detail below. Option 3 is only discussed briefly. The table in Appendix 1 offers a more detailed overview of the possible options to reduce the fuel consumption.

An important aspect that must apply to all technologies and measures is that the pollutants are not transferred from the air to the water, as is it the case with the use of EGCS, for example.

3.1 Exhaust gas aftertreatment

3.1.1 Diesel particulate filters

Diesel particulate filters (DPF) are often used to capture and remove particles from exhaust gases. These filters work by trapping the particles in a porous material so that clean air can flow through. DPF require operation with clean fuels like distillate fuels with low levels of sulfur, ash and cat fines. Corbett et al. (2010) specify that the S-content of the fuels in combination with a DPF should be <0.05% (m/m) to prevent filter clogging with large particles and soot. DPF effectively remove particles from the exhaust gas to reach levels of 36 – 82% for engine loads of 100% and 10%, respectively, with a successively decreasing efficiency with increasing engine load and using regular diesel[2] (Yang et al., 2023). Zhou et al. (2024) reported a PM removal efficiency of more than 90% with low sulfur diesel fuel (S <0.1% (m/m)).

To ensure a high efficiency of the DPF, regular maintenance and cleaning of the filters is essential for their optimum performance. Regeneration of the DPF takes place by burning the collected soot. The typical high ash content of lube oils can account for 90% of the ash in PM (Zhang et al., 2020) and is problematic as it cannot be burned from the DPF. The current fuel blends mainly used today are made by blending HFO with very low-sulfur fuel oils (VLSFO, ULSFO) to comply with the global sulfur limit of 0.50% (m/m), but these fuels cannot be combined with a DPF. So far DPF have been installed on marine engines with a power of 2-3 MW. According to an engine manufacture 4-5 MW should be possible (pers. comm. Lauer 2024).

3.1.2 Electrostatic precipitators

Electrostatic precipitators (ESP) are an important technology in removing PM from exhaust gases. They use a high-voltage electrostatic field to ionize the gases and PM, which are attracted by charged plates or electrodes. The collected particles can then be removed and disposed of properly. ESP can reduce PM, soluble organic fraction (SOF) and decreases the mean diameter of PM (Ariana et al., 2006). The advantage of these technologies is their possibility to run with fuels with more pollutants and S such as HFO, even without an exhaust gas cleaning system (EGCS). Investigations by Zukeran et al. (2014 and 2018) showed that an ESP also eliminates

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[2] The fuel is not further specified in the report from Yang et al. (2023).

polyaromatic hydrocarbons from the exhaust gas of a marine engine. A wet electrostatic precipitator (WESP) was analyzed by Järvinen et al. (2023) in combination with an EGCS. They found a reduction of 98.5% of PN and PM with HFO as a fuel. With MDO fuel, 96.5% of PN and 99% of black carbon were removed. ESP has several advantages such as high efficiency even for ultrafine particles, low pressure drop with large gas volumes, low operating costs and high reliability (Ni et al., 2020).

3.1.3 Exhaust gas cleaning systems

Exhaust gas cleaning systems (EGCS) were developed to reduce SO_X emissions from marine fuel oil combustion as an equivalent to using low-sulfur fuels. The efficiency of EGCS to remove PM is discussed controversially in the literature, as the effects are not consistent (Aakko-Saksa et al., 2023). According to Jeong et al. (2023), EGCS do not substantially reduce the number and mass concentration of respiratory PM. EGCS reduced PM and BC by 30 – 40% when burning HFO. However, they also found that scrubbers can generate new particles, as PN were increased by three times when burning MDO and PN remained relative constant before and after the scrubber when burning HFO (Järvinen et al., 2023). To further reduce emissions, the EGCS requires additional abatement systems like a wet electrostatic precipitator (WESP, see 3.4.2). The combination of an EGCS and WESP was tested by Järvinen et al. (2023) and achieved a reduction of 98.5% PM, PN and BC in comparison to the combustion of HFO.

However, the use of scrubbers is controversial because air pollutants, including toxic heavy metals and polycyclic aromatic hydrocarbons, are simply shifted from atmospheric emissions to the marine environment and contribute to ocean acidification by the release of acidic discharge water (Endres et al., 2018; Turner et al., 2017; Marin Enriquez et al., 2023).

3.1.4 Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) is primarily a NO_X abatement technology and has only a minor effect on PM reduction. It is the most effective and simplest means of NO_X reduction up to Tier III (NO_X Technical Code). NO_X emissions are reduced by adding ammonia to the exhaust gas to convert nitrogen oxide and nitrogen dioxide to elemental nitrogen and water and a small amount of CO_2. The use of ammonia on board ships leads to safety problems. For this reason, a harmless solution of urea in water is usually used, which reacts in the hot exhaust gases to form ammonia. The dosage must be well balanced to achieve a sufficient conversion on the one hand and not to release any ammonia into the environment, the so-called ammonia slip. The actual conversion takes place in a special catalytic converter. The catalyst is sensitive to sulfur deriving from the fuels, which inactivates the catalyst.

The influence of the SCR on PM emissions is currently not clear, as there are contradictory statements. On the one hand, there is a reduction potential of up to 35% BC and PM (Lack et al., 2015; Jayaram et al., 2009). On the other hand, an increase of BC emissions of about 15% can be found in the literature (Canada and Denmark, 2018). These contradicting statements may result from varying sulfur contents of the fuels, as a reduction of PM is caused by the oxidation of the organic fraction (Karjalainen et al., 2022), whereas an increase in sulfur causes increased sulfate formation in the catalyst, which constitutes to PM (Jayaram et al., 2009).

3.1.5 Diesel Oxidation Catalysts

The primary function of Diesel Oxidation Catalysts (DOC) is to reduce carbon monoxide and unburned hydrocarbon emissions. In this way, some of the volatile components of the exhaust gas are oxidized and there is less secondary particle formation in the accumulation mode, which reduces PM emissions. The residual oxygen in the exhaust gas reacts within the catalytic converter with the hydrocarbons and carbon monoxide to form CO_2 and water (Leinonen, 2016). The technology has been widely used in diesel cars for a long time and is therefore well known.

DOCs are purely passive systems and therefore require very little maintenance. They consist of ceramic or metallic material, which is usually installed in a honeycomb shape in a housing. The internal surfaces are catalytically coated and provide a large area for the reaction due to the long channels (Leinonen, 2016). The PM reduction potential is reported as 20 – 40% (Lack et al., 2015) and up to 50% (Lehtoranta et al., 2019).

3.2 Cleaner fuels

The use of cleaner fuels can avoid the production of air pollutant emissions, such as SO_X, PM, BC due to their lower content of pollutants, such as sulfur, metals and ash. Depending on the definition of “cleaner fuels” marine diesel fuels already count as cleaner fuels as compared to HFO. In the authors view the term should be used for advanced clean fuels such as liquefied natural gas (LNG), methanol or synthetic fuels. One way of determining the level of PM/BC emissions from the fuel composition is the hydrogen to carbon (H/C) weight ratio (see 3.2.1). Nevertheless, the fuels should also have an advantage in terms of their climate impact and thus be produced with renewable energy in the medium- to long-term.

3.2.1 Fuels with high hydrogen/carbon weight ratio

All fuels with C-based structure – so all except hydrogen (H_2) and Ammonia in this chapter – can also be defined by its hydrogen/carbon weight (H/C) ratio and additionally, it can be related to their molecular weight (weight ratio). Hydrocarbon fuels are always composed of three main classes of compounds, paraffins, naphthenes and aromatics (Riazi, 2005). Each of these compound classes have their own range of H/C weight ratios. The properties of all fuels depend on the proportions of the three compound classes.

$$\frac{H}{C} weight\ ratio = \frac{\dfrac{Mass\ share\ H\ [\%]}{Atomic\ mass\ H\ [\frac{g}{Mol}\ (1.008)]}}{\dfrac{Mass\ share\ C\ [\%]}{Atomic\ mass\ C\ \left[\frac{g}{Mol}\right]\ (12.011)}}$$

The H/C weight ratio for e.g. methane (CH_4) is 0.3356 and for benzene (C_6H_6) is 0.0839. Low H/C weight ratios indicate a highly aromatic fuel, which causes high soot and PM emissions. Hydrogenation of the fuel in the refinery increases the H/C weight ratio and therefore reduces the sooting tendency of the fuel. In a measurement campaign the highest H/C weight ratio of 0,179 was determined for GtL with nearly zero aromatic content and the lowest H/C weight ratio of 0,113 for a VLSFO with 97% aromatic content (Finland and Germany, 2020). A high H/C weight ratio makes these fuels preferable to other types of fuels. Alternatively, the reciprocal value, the C/H ratio, either on a weight or on a molecular basis, can be used to determine the degree of aromaticity of a fuel.

As the H/C weight ratio is not a mandatory parameter in ISO 8217:2024 marine fuel standard, there is limited information in the literature about the H/C weight ratio of different fuels or fuel blends.

In the following sections cleaner fuels, currently available on the market such as Marine Distillates or LNG as well as future fuels, are described in more detail.

3.2.2 Marine Distillates

A switch from HFO to marine distillate fuels (MDO/MGO) or higher quality low sulfur fuels would be very effective regarding the reduction of exhaust gas emissions. A reduction of 90% PM emissions has been reported by Petzold et al. (2011) at 75% engine load when switching from intermediate fuel oil (IFO, a marine diesel with a large share of HFO) with 2.1% (m/m) S to a marine distillate fuel (<0.10% (m/m) S). Elemental carbon and organic matter contents were lowered by about 50%. According to RINA (RINA, 2023) a 65% reduction of BC emissions as part of PM would be achieved by a switch from HFO to marine distillates.

3.2.3 Liquefied Natural Gas

Fossil natural gas (NG) consists primarily of methane, but also contains other components like ethane, propane, butane, hexane and nitrogen. The exact composition of NG depends on the gas source. NG is produced from onshore and offshore natural gas and oil wells as well as from coal beds. NG has a boiling point of -161.5 °C. Below this temperature and at atmospheric pressure NG is in a liquid state and is then called liquefied natural gas (LNG). Liquefaction of NG reduces its volume significantly by a factor of ca. 600 (UBA, 2019) and is an energy-intensive process. The energy demand for the liquefaction of NG is assessed to be equivalent to up to 10% of the total energy supplied NG (Pospíšil et al., 2019).

The combustion of NG generates considerably less PM emissions than traditional fuels (Gilbert et al., 2018; Korakianitis et al., 2011). The reason is its low number of carbon atoms per molecule and its high H/C ratio. Lehtoranta e al. (2023) reported a reduction of 72 – 75% PM with LNG as compared to MDO as fuel in a dual fuel (DF) engine and PM emission levels of 0.02 and 0.03 g/kWh, which compares well with Gilbert et al. (2018). Aakko-Saksa et al. (2023) reported PM emissions of 0.003 g/kWh from a marine DF engine >1 MW and at >40% engine load. This is 10 times lower and would fulfill for example the European limits of inland waterway vessels (0.015 g/kWh.) A 98.14% reduction of PM was determined by Livaniou et al. (2022) when comparing LNG combustion with MGO. In terms of PN, the particles emitted by an LNG DF engine were <23 nm and therefore not detectable by the standard measurement methods (Corbin et al., 2020).

As LNG reduces PM and PN emissions significantly, it seems a good alternative fuel option, but there is a negative side effect of the methane slip from the engines and methane emissions during extraction, production and transport, which can lead to a negative GHG balance. Methane has a global warming potential of 82.5 on a 20-year scale, meaning that its climate impact is 82.5 times higher than CO_2.

3.2.4 Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) consists of one or more easily liquefiable hydrocarbon compounds with three or four carbon atoms. Propane and butane are mostly used, but LPG can also include propylene, butylene, isopropylene and isobutylene (EC, 2008). LPG is transported and stored under modest pressure in liquid form. At room temperature, the gas already begins to liquefy at a pressure of around 8 bar, whereby the volume of the liquefied material is reduced to around 1/260. Gaseous LPG is highly flammable and forms explosive mixtures with air. Depending on the hydrocarbon mixture, the explosion limits are between 1.5 and 11% by volume in air. eLNG and eLPG can be produced by using carbon, H_2 and electricity generated from renewable sources.

As compared to LNG, LPG does not contain methane, a severe GHG. Propane and butane are not listed as GHG by the International Panel for Climate Change (IPCC, 2021). LPG is an attractive fuel for LPG carriers, but also retrofits to other ship types as dual fuel engines are possible. Engine technology has been developed and there is sufficient infrastructure for distribution of LPG in place. The only barrier seems to be the price gap to conventional fuels (Kjartansson, 2011). The same author reported PM emission reductions of 37% as compared to HFO, whereas others claim a 90% reduction (Brinks and Chryssakis, 2017).

3.2.5 Methanol

Methanol consists of one carbon, four hydrogen and one oxygen atom. The major advantage, compared to LNG and H_2, is that it is liquid at ambient temperatures with a boiling point of 64.7 °C. Currently methanol is produced almost exclusively from fossil natural gas, but it can also be produced from carbon-neutral methane, by direct hydrogenation of CO_2 (e-methanol) or from biomass. Methanol is toxic when swallowed, inhaled or by skin contact (Wissner et al., 2023) and the methanol flame is invisible, due to its low PM forming potential. On the other hand, methanol readily dissolves in water in case of a spill and is easily degraded and has only a low toxicity to marine life. A disadvantage is its lower energy content per volume of 20 MJ/L, which requires larger tanks. For example, compared to HFO, methanol needs 2.5 times larger tanks and 1.3 times larger than for LNG for the same energy output (DNV, 2022a).

Methanol cannot be used in conventional HFO optimized engines, but with some engine modifications it is possible (Ming and Chen 2021). However, methanol can be used in dual fuel engines in combination with conventional fossil fuels like HFO or MGO. Methanol has poor autoignition properties (DNV 2022a) and therefore requires a pilot fuel of 5% diesel.

Like methane, methanol has no carbon-to-carbon bonds, and its potential to form soot is therefore extremely low. Methanol reduces PM emissions ca. by 90% (Ellis and Svanberg, 2018; DNV 2022a; Wissner et al., 2023). The remaining PM emissions are caused by the pilot fuel and by the lubrication oil (Aakko-Saksa et al., 2023).

3.2.6 Oxymethylene ethers

Oxymethylene ethers (OMEs) belong to the synthetic fuels with a chain length of 3–5 carbon atoms, are liquid and have properties like marine diesel (Hackbarth et. al., 2018). Therefore, OME can be used as drop-in fuel but can also be applied as pure fuel with reasonable modifications of the engine. Due to the higher oxygen content of OME compared to conventional marine diesel, it has less soot and NO_X emissions. The reduced soot emissions are again the result of missing carbon-carbon bonds. OMEs can be produced in an environmentally friendly way from carbon dioxide (CO_2) via methanol.

3.2.7 Hydrotreated vegetable oils and fats

Hydrotreated vegetable oils (HVO) are paraffinic diesel fuels that are obtained by hydrogenating fats and oils. HVO can be used as a single fuel or as a drop-in fuel. In addition to vegetable oils, waste oils and fats, such as used cooking oil, can also be used. The vegetable oils are converted into hydrocarbons through a catalytic reaction with H_2 (hydrogenation). Hydrogenation leads to a splitting of the fats and oils, during which all oxygen atoms and unsaturated bonds are removed. Long-chain paraffins are formed from fatty acids. Due to the paraffinic nature of HVO the PM emissions are generally reduced when compared to MGO (Murtonen et al., 2010). Ushakov and Lefebvre (2019) reported a reduction of 30% PM compared to MGO when HVO was used as fuel in a marine engine, but an increase in PN in the size range of 14 – 750 nm. The reduction of PM was related to the elevated H/C ratio and the absence of aromatic compounds.

3.2.8 Fatty acid methyl ester or biodiesel

Oxygenated biodiesel or fatty acid methyl ester (FAME) is made by transesterification of vegetable oils and animal fats. The fatty acids of the triglycerides react over a catalyst with e.g. methanol to form methyl esters (DNV 2020). ISO 8217:2017 has specified the maximum of 7% FAME content in distillate marine fuels as a blend. Other standards and specifications for FAME used for blending are EN 14214 or ASTM D6751. Due to the oxygen content of FAME, the combustion temperature is higher, and the ignition is delayed compared to conventional diesel fuels. This leads to an increased formation of NO_X of typically up to 25% (Aakko-Saksa et al., 2023).

In terms of PM emissions, FAME fuels have less emissions as compared to conventional road and non-road diesel fuels (Aakko-Saksa et al., 2016). This is explained with the better oxygenation of PM during the combustion. Another advantage is that FAME fuels do not contain polycyclic aromatic hydrocarbons or other aromatic compounds or cyclic hydrocarbons, which are precursors of soot formation. Typical PM emission reductions of 25 - 75% have been reported with FAME as fuel blends when switching from residual to distillate fuels (Aakko-Saksa et al., 2023).

3.2.9 E-fuels or Synthetic fuels

E-fuels, also known as synfuels or electricity-based synthetic fuels are synthetic fuels that are produced from water and carbon dioxide (CO_2) (Ragwitz et al., 2023). The e-fuels can be used as drop-in fuels. To produce a climate-neutral fuel, the energy must come from renewable sources, such as wind power or photovoltaics. This process is known as power-to-fuel. Water is split into H_2 and oxygen by electrolysis. The H_2 is then converted in a further process step with CO_2 into carbon-containing compounds such as methane or liquid fuels.

XtL fuels (also known as Fischer-Tropsch fuels) include various synthetic fuels in which a solid or gaseous energy source is converted into a carbon-containing fuel that is liquid at room temperature and atmospheric pressure. Depending on the origin of the synthesis gas, electricity-based (power-to-liquid, PtL & power-to-gas, PtG), biogenic (biomass-to-liquid, BtL) or fossil (gas-to-liquid, GtL and coal-to-liquid, CtL) synthetic fuels are produced. Well-known synthesis processes are Fischer-Tropsch and methanol synthesis, as well as methanization. In the GtL process (gas-to-liquids), natural gas is converted into synthesis gas by adding oxygen and water vapor and this is then converted into liquid hydrocarbons. A high-quality fuel for diesel and gasoline engines can be obtained from this by fractionation. This colorless and odorless liquid is completely sulfur-free and contains no aromatic compounds.

In comparison to distillate fuels, paraffinic sulfur-free fuels (GtL, XtL) reduce PM emissions, as these fuels also have a high H/C ratio and low aromatic and sulfur content (Ushakov et al., 2013; Aakko-Saksa et al., 2023). Ushakov et al. (2013) compared GtL versus MGO emissions and found a decrease of PM by 16% at medium and high engine loads and an increase of PM by 12 – 15% under low loads. In the same study an increase of PN by 21% was reported. In another measurement campaign with different fuels GtL had the lowest PM emissions with 0.049 g/kWh as compared to DMA with 0.087 g/kWh. HFO, as expected, had the highest PM emissions with 0.858 g/kWh (Finland and Germany, 2020). Why there are different trends in emissions (increase/decrease) in the comparison of GtL to MGO in the above studies cannot be clarified here.

3.2.10 Hydrogen

H_2 has the highest energy content of all fuels with 120.2 MJ/kg, but not per volume. Liquefied H_2 requires two to four times more space as compared to LNG and MGO (ABS, 2021). Depending on its production pathway, H_2 can be subdivided into green, blue, grey and red H_2.

Green H_2 production is based on renewable energies. In most scenarios it is produced using electricity from wind energy and photovoltaic systems via electrolysis. During electrolysis, water is split into H_2 and oxygen, which requires a lot of electrical energy.

Blue H_2 is produced from steam reforming of natural gas. In the process, the gas is split into H_2 and CO_2. During the production of blue H_2, the resulting carbon dioxide is stored using carbon capture and storage technology (CCS) and stored underground. This technology means that no CO_2 emissions are produced during H_2 production.

Grey H_2 is produced from natural gas using steam reforming. In contrast to blue H_2, the resulting CO_2 is not captured and stored underground but released to the atmosphere. Today, most H_2 is produced by using this process.

For red H_2 electricity from nuclear power is used. From an environmental point of view, this production path is not sustainable.

Storage of H_2 is very challenging in liquid form at temperatures <-252°C, which requires a lot of energy, special tanks and pipes. The great disadvantage of H_2 is that it is extremely explosive and therefore requires special fire hazard standards. Further, the availability of H_2 is still very limited and very expensive (ABS, 2021). Another challenge is the lack of infrastructure.

The combustion of H_2 in all energy converter options is nearly emission-free.

3.2.11 Ammonia

Ammonia is produced by the Haber-Bosch process, in which the synthesis gas is produced from nitrogen and H_2. The ammonia fuel therefore contains no carbon and does not release any CO_2 during combustion. Ammonia is a gas, which evaporates at -33°C. The ammonia molecule consists of the combination of one nitrogen with three hydrogen atoms (NH_3) (Inal et al., 2022). Ammonia has a pungent smell and is toxic. In a gas concentration of >0.5% ammonia is lethal (DNV, 2022b). In case of a spill, ammonia would also cause harm to aquatic organisms (Ayvalı et al., 2021)

Nevertheless, it is one of the most produced chemicals in the world. The chemical industry uses it as a starting material for the synthesis of many compounds, with most of the ammonia being processed into fertilizer. 90% of today's ammonia is produced from fossil fuels and the production is very energy consuming (Bongrand and Allemand, 2020). Green ammonia is produced by synthesizing CO_2-neutral H_2 and nitrogen. The required nitrogen occurs as 78% in air and can be extracted from it, the H_2 can be produced by electrolysis of water with electrical power from wind or solar energy. Ammonia is also discussed as a H_2 carrier, as its storage is easier at -33°C as compared to -252°C.

Ammonia as a fuel for shipping requires a few hurdles to overcome such as the supply infrastructure, future costs of green ammonia, availability of engine technology and the necessary safety considerations (DNV, 2022b). As with other future fuels, the challenge is to produce significantly larger quantities and at the same time reduce production costs in order to make the fuel profitable for shipping.

Ammonia can be combusted, but it could also be used in a fuel cell. The combustion of ammonia is more difficult than for diesel, as it burns more slowly and it requires a much higher ignition temperature of 630°C, whereas diesel burns at 210°C. This means that sustaining combustion once it gets started is also more difficult with ammonia than with other fuels. Another shortcoming are the increased NO_X emissions and the emission of laughing gas (N_2O), which is a 283 times stronger greenhouse gas than CO_2 over a time horizon of 100 years (IPCC, 2021). However, there are exhaust aftertreatment technologies like the SCR to reduce NO_X and N_2O (Westlye et al., 2013).

As ammonia requires diesel type pilot fuel for ignition (5%) it has some PM emissions, but 95% less than those of MDO (Zincir, 2022). The PM emission is therefore dependent on the quantity of pilot fuel (Cames et al., 2021). Ammonia is also a precursor of aerosol formation and therefore contributes to secondary particle formation (Myhre et al., 2013).

3.3 Reduction of fuel consumption

Any volume of fuel that is not burnt reduces emissions on board. In the international debate, energy efficiency measures are mainly discussed or regulated with the focus on GHG reduction, however, they also achieve air pollutant emission reductions, so they are also mentioned here. On regulatory pathway is the "Ship Energy Efficient Management Plan, SEEMP" procedures (International Maritime Organization, 2012). The SEEMP includes improvement of voyage planning, weather routing, just in time delivery, speed optimization in relation to the just in time delivery, optimization of shaft power, trim and ballast optimization, use of autopilots to optimize rudder handling, hull maintenance, engine maintenance, improved antifouling systems, air lubrication and propeller design (list is not exhaustive) and therefore addressing fuel consumption reduction. Also, the use of alternative power sources like shore power in harbours, fuel cells, batteries, wind and solar power reduce the fuel consumption. Reviews of the fuel reducing technologies have been published by Di Natale and Carotenuto (2015) and Aakko-Saksa et al. (2023).

Slow steaming can reduce most air emissions by burning less fuel, however it is advised to de-rate the engine, as engines are optimized for a specified engine load and speed. The impact of slow steaming on PM emissions is discussed controversially: some report a reduction of PM emissions by 18 - 69% by burning less fuel (Di Natale and Carotenuto, 2015; Bongrand and Allemand, 2020). On the other hand, there is the possibility that BC emissions can increase at low engine loads (Finland and Germany, 2020). The reduction of PM or BC by engine tuning normally leads to an increase of NO_X emission (NO_X trade-off), which can be reduced by SCR (see chapter 3.1.4).

Further technology options to reduce energy consumption in conjunction with a decrease of air pollution are regular maintenance, modifications of injectors, common rail technology or slide valves. Especially, engine maintenance, which includes regular inspections, replacement of worn-out parts, optimal lubrication and cleaning of engine parts is an important instrument for clean combustion.

Common rail technology provides accurate electronic control of high-pressure injection. The injection process is controlled in terms of duration, timing or even several stages. The combustion is optimized, leading to decreased fuel oil consumption, compared to a normal diesel engine, especially at part loads. The engine can be optimized by engine de-rating for slow steaming, etc. A control system monitors all engine parameters and adjusts the fuel flow accordingly. A modern common rail system also allows switching between different grades of fuel.

Slide valves are common techniques, already implemented on some newbuild engines and often retrofitted on old engines (Comer et al., 2017; Lack et al., 2015). Slide valves improve fuel atomization by changing the spray pattern, which results in more even and therefore better combustion. The reduction of PM emissions is between 10 – 50% (Corbett et al., 2010).

Water in Fuel Emulsion (WiFE) is an attempt to reduce NO_X and PM emissions by adding water to the fuel. The method has been analyzed for a long time but is not widely applied yet in maritime shipping or other areas. As water and fuel do not mix, the two substances are emulsified before being injected into the combustion chamber. According to Lack et al. (2015) WiFE reduces PM emissions by 42 – 63%, Corbett et al. (2010) reports a reduction of 20 – 50%.

Other implemented climate instruments such as the European Emission Trading System (Regulation (EU) 2023/957) or the FuelEU Maritime (Regulation (EU) 2023/1805) or a currently discussed global fuel standard on IMO level will hopefully also contribute to the reduction of air pollution.

3.4 Summary of Particulate Matter reduction options

As outlined above there are many different options to reduce the PM/PN emissions from ships. Some of them are already in use or will be introduced to reduce the climate impact of shipping, by reducing fuel consumption and/or improving fuel efficiency or switching to alternative clean fuels. The other option is reducing emissions with exhaust gas aftertreatment technologies. In some cases, their focus is the reduction of PM, in other cases, the PM reduction is just a side effect.

All options differ in their reduction potential. Some technologies can be introduced only on newbuilds, some can be retrofitted on existing ships, some of them work best in combination with clean fuels like a DPF. The table in Appendix I (Appendix 1) contains an evaluative overview of different options which were discussed as BC reduction options during PPR (United States, 2023).

4 Discussion of reduction options and Outlook

The compiled information shows the need for action to reduce PM and PN emissions of maritime transport. The existing sulfur regulations and the so far unsuccessful discussions on BC reduction in the Arctic are not sufficient to adequately protect the marine environment and human health from PM and, as part of it, BC emissions. As detailed above, regulations already exist in all other transport sectors, at least in large parts of the world. PM and PN measurement technologies and standards have already been introduced there. Chapter 3 also shows that there are technical and operational options to reduce PM emissions from maritime transport. Regarding the mitigation measures and abatement technologies, mostly the same measures as identified for BC reduction in ships exhaust gas apply in a similar way to PM reduction, so they are already on the table and discussed at IMO in depth. The argument that technological solutions do not exist or are not ready for the market must be questioned. These technical systems, e.g. SCR or methanol engines, are often only developed when there is a pressure generated by environmental legislation. In order to initiate the development of necessary reduction technologies in good time, the target and limit values must be set as early as possible.

Concerning **short-term measures,** a switch to marine distillates or other clean fuels would reduce the PM, PN, BC and SO_X emissions immediately. Building on the basis of cleaner fuels, measures to further reduce PM/PN emissions must be implemented in **the medium term.**

The following aspects must be considered when drafting such a regulation:

- In general, a **regionally and temporally differentiated approach** seems to be reasonable for a PM/PN regulation, with an earlier introduction of more ambitious limits in sensitive areas such as the larger Arctic and densely populated coastal areas.
- Differentiating the targets for **new and existing ships** could help to ensure that some measures are introduced earlier for newbuilt ships than for the existing fleet.
- Differentiating the targets for **different types of ships or engines** can also help to ensure that an ambitious limit value is prescribed in each case.
- Differentiating the targets associated with various **load points of the engine** can also be a way of achieving ambitious reductions.
- Differentiating emission limits values related to the **particle sizes**, and inclusion of **PN limits** to cover small particles are also required.

All aspects must be discussed in detail regarding their advantages and disadvantages, as greater differentiation according to ship size, engine type and load condition, for example, could lead to a very complex and difficult to control design of a regulation. A balance must be found between ambitious limit values and regulations that can be implemented and monitored in practice. Some of the aspects are described in more detail in the following chapters, but many questions remain unanswered (see section 4.4).

A **regional differentiation** is already implemented in other IMO regulations. MARPOL Annex VI contains the concept of ECA for SO_X and NO_X emissions and could be expanded to include PM/PN limits. Regulation 14 already formally includes PM, but without setting any PM limits. The existing ECAs could be extended to include PM and PN with enforcement dates as proposed in the following chapters 4.1 and 4.2. A legal review is necessary to determine whether the ECA requirements may be changed retrospectively - without new application for the existing ECAs.

Another option would be to develop independent PM ECA criteria, for which the regions would then have to submit new applications. From an environmental perspective an ambitious PM limit regulation, first in ECAs, followed by a global limit would be the appropriate way forward.

As it is much easier to comply with ambitious PM limit values for **new ships** than for the **existing ships**, which can only be met by technical measures such as exhaust gas aftertreatment systems or special engines for alternative fuels, it makes sense to include different introduction dates for the limit values. More ambitious requirements can be demanded earlier for newbuilds, as the retrofit installation of e.g. exhaust gas aftertreatment technologies on existing ships can be challenging. Nevertheless, the emissions of the existing fleet must be addressed as well and could be easily reduced by switching to cleaner fuels as a first step.

In order to achieve the highest possible reduction in emissions, it makes sense to address emissions very specific for the **ship size, engine type and load points**. However, it should be kept in mind that a highly differentiated regulation requires an intensive investigation before limits can be set. The PM emissions of different engine types like 2-stroke, 4-stroke and high-speed engines differ significantly. Further, PM emissions are very load dependent. Therefore ISO 8178-4:2020 requires PM measurements under defined test cycles. So, one option could be to introduce a “not-to-exceed” (NTE)-limit as a single target (e. g. over all load points of a specific engine group) or on top of a more detailed emission limit values as specified in ISO 8178-4:2020.

From an environmental perspective, the PM regulation shall apply to “all ships sizes”, including especially small ships, which are often excluded from IMO regulations. Smaller vessels are mainly sailing near the coast, close to vulnerable ecosystems and densely populated areas, so their inclusion in a regulatory framework is very important from an environmental view but this might increase the administrative burden.

In general, in addition to PM emission reduction, **PN reduction** is necessary, as smaller particles constitute a special threat for human health. But only limited information regarding the PN emissions of marine ship engines is available, especially in conjunction with different fuel types. Therefore, it is not possible to discuss a PN limit value, yet. However, a decrease of PM emissions from a switch to cleaner fuels can be associated with an increase in PN emissions in the exhaust gas. Therefore, an additional measure on top of a fuel switch is important from an environmental and especially from a human health perspective. Hence, an additional PN limit value must be introduced. This corresponds to the experience with Euro standards for road traffic[3]. However, the PN limit value could be introduced in a future review phase of the regulation to not delay the start of the enforcement process. When specifying PN limit values, the particle size range for which this limit value then applies should also be defined.

The ongoing process of reducing GHG emissions from maritime shipping can also help to reduce PM/PN emissions, as it is expected that most of the low-carbon or even zero-carbon fuels will also imply significantly reduced emissions of air pollutants and can also be easily combined with exhaust gas aftertreatment systems. Furthermore, negative climate effects of “alternative” fuels such as methane slip during LNG combustion or throughout the production chain shall be considered. The use of modern marine engines and good maintenance of the engine and the exhaust gas aftertreatment systems will also help to reduce PM/PN emissions.

From the authors' point of view, there are still many open questions (see 4.4) that need to be clarified before PM/PN limit values are introduced in the maritime shipping sector, but two

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[3] PN limits were introduced with Euro 5b for diesel cars (2009), Euro 6b for petrol cars (2014) and Euro VI for trucks (2011).

basic options for the way forward for the establishment of a Particle Emission Regulation are considered that differ in their basic approach.

Option I requires specific PM/PN limit values for exhaust emissions (4.1); option 2 (4.2) includes the reduction of PM/PN via the introduction of clean fuels. Both options present a very optimistic scenario in terms of political ambitions and the timeline of introduction.

4.1 Particle Emission Regulation – Option I: Emission Limits

One possibility is the implementation of gradually and regionally differentiated PM and PN exhaust gas emission limits. This approach assumes that limit values for PM/PN emissions are determined – presumably differentiated according to engine type, ship size and load points, which implies a considerable amount of research to set an appropriate maximum emission limit.

Further, it must be decided whether the limit values apply to an engine on the test bed or on board a ship in service or possibly a combination is possible. Both options lead to a different test procedure and monitoring regime.

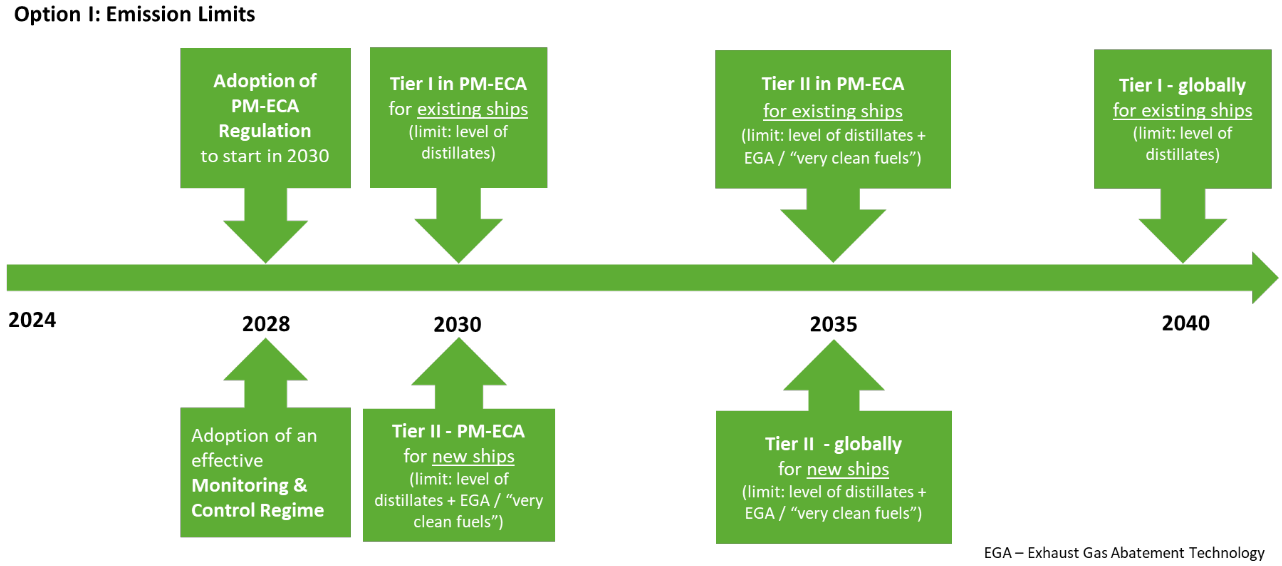
This approach means that PM/PN regulations can only be introduced comparatively late, as the limit values have to be determined beforehand through research and development. But on the other hand, as these limit values are technology-neutral, each ship owner and each ship can individually select their own measures to reduce PM/PN emissions. In addition, a PM/PN-parameter is independent of the fuel selection, so that there might be little need for a future revision when introducing new fuel types or new fuel blends.

As there are no emission limit values developed yet, the following terms are used in this report. They do not differentiate further between ship/engine types yet:

- **Tier I** “level equivalent to a reduction with clean fuel”. Here a reduction of PM by 90%, similar to a switch from HFO to MGO, methane etc., is required (see 3.2.1).
- **Tier II** “level equivalent to a reduction with clean fuels plus exhaust gas aftertreatment technology” or “very clean fuels”. Here a reduction of PM by >95% compared to HFO is required. This can be achieved by the use of e.g. DPF, ESP or WESP (see 3.1.1 and 3.1.2) or by the use of near zero-emission fuels such as hydrogen (see 3.2.9). This would also reduce the PN emissions.

The option also includes a regional and temporally differentiated approach using the existing ECA concept of MARPOL Annex VI. For existing ships, the author suggests a PM limit on the reduction level of marine distillate fuels as a first step in the PM-ECA. For newbuild ships more ambitious PM limits on the level of “very clean fuels” and/or the installation of exhaust gas aftertreatment technologies could be introduced earlier, so they are suggested as a first step. Figure 2 shows a corresponding scenario which includes the different dates of introduction for newbuild ships and for the existing fleet, and the regional differentiation with PM-ECA emission limits and global limit values. It is assumed that the IMO resolutions on greenhouse gas neutrality close to 2050 will make a Tier 2 limit for all ships superfluous.

Figure 2: Suggested timeline for Option I: Emission Limits



Source: own illustration, Brigitte Behrends

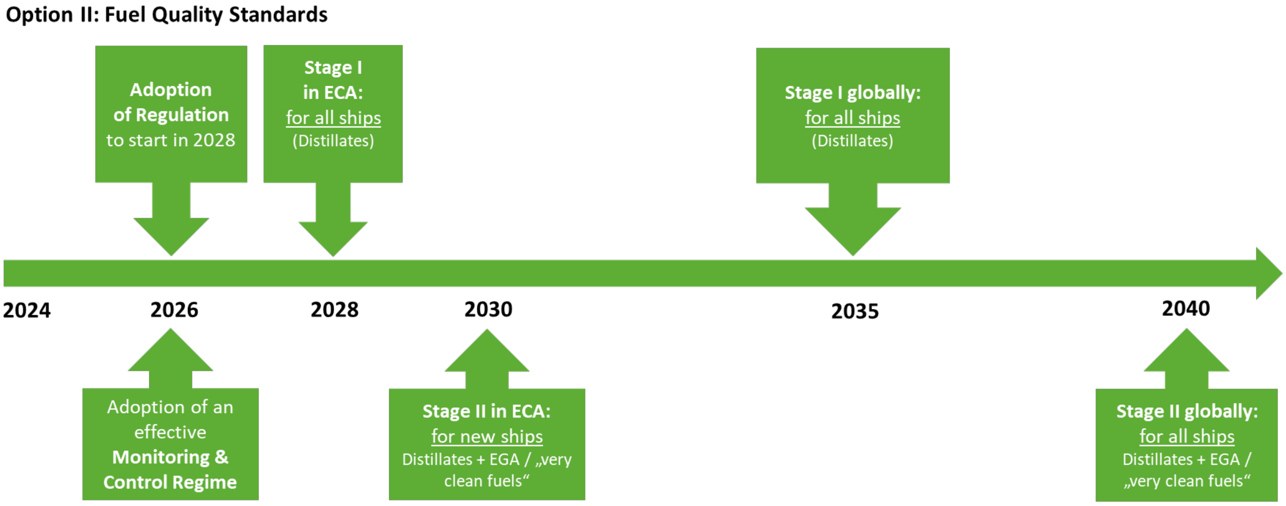
4.2 Particle Emission Regulation – Option II: Fuel Quality

An alternative approach would be to limit PM/PN emissions mainly via fuel quality requirements. The aromatic content of a fuel and thus the parameter H/C weight ratio or C/H ratio (see 3.2.1) plays a major role in BC and PM formation and emission. Consequently, the H/C weight ratio could be an adequate parameter for the fuel quality. But as there is only limited data available for this parameter for different fuels and their associated emission levels, it would take some time to develop an adequate fuel limit value based on the H/C weight ratio. Additionally, neither the aromatic content nor the H/C weight ratio are currently recorded and documented e.g. in the ISO standards or the Bunker Delivery Note, so it cannot be expected that the missing information will be available in the near future.

Alternatively, and as a **short-term measure**, the existing fuel categories could be used either for a requirement (e.g. "distillates only") or a prohibition ("HFO ban") for ECAs and/or globally. This "**stage I**" does not need any emission limit research in advance and could be implemented very quickly at least in ECAs. The global switch depends on the availability of clean fuels. More research is needed to analyze when they will be available in sufficient quantities. The scenario in Figure 3 proposes the global introduction of clean fuels for 2035 as a realistic option from the author's view. According to DNV's scenarios for future fuels (DNV, 2024), relevant quantities of HFO and VLSFO will still be used in 2035, so additional efforts are needed.

But since a fuel switch alone cannot achieve a sufficiently ambitious reduction of PM emissions in the **medium-term**, especially with regard to PN, further reduction is necessary. Therefore, the use of "very clean fuels" and/or exhaust gas aftertreatment must also be included in this option. Therefore, we suggest introducing them in a **second step** (**"Stage II**" in Figure 3), with different introduction dates for existing ships and newbuilds.

Figure 3: Suggested timeline for Option II: Fuel Quality Standards



EGA – Exhaust Gas Abatement Technology

Source: own illustration, Brigitte Behrends

However, as the IMO regulations are intended to be technology-neutral, further consideration must be given to how to include exhaust gas aftertreatment technologies in a fuel quality approach without setting emission limits. One option would be to allow exhaust gas aftertreatment technologies as an “equivalent technology”, as it is already set out in MARPOL Annex VI Regulation 4. In that case, particular attention must be paid to ensuring that no negative side effects occur - as is the case with EGCS discharge water.

Figure 2 and 3 draft a challenging timeline for the implementation of options I and II. This presupposes that the necessary decisions are made at IMO as soon as possible and regulations are implemented promptly. Being aware of the slow IMO processes and that the current focus of its work is on climate protection legislation, the timeline is more of an exemplary nature. The Figures show that even when the implementation dates are ambitious, it will take a while for improvements to become noticeable for humans and the environment. This shows how important it is to continue working in this field and to introduce PM/PN limit values.

In the author’s view, and as shown in the timeline, in Option II, the route via Fuel Quality Standards as the first steps can be implemented faster, so that emission reductions can be achieved earlier. As this option also requires exhaust gas aftertreatment technologies in stage II, further consideration regarding a realistic introduction and a practical implementation timeframe is also required here. Further, there is the possibility of a combination of both options. In a first step the introduction of a Fuel Quality Standard, followed in a second step by the introduction of Emission Limits.

4.3 Enforcement & Control / Measurement Options

For both options an effective documentation, control and monitoring regime must be introduced. **Option I** requires direct emission measurements in the exhaust gas. It can be carried out with test bed and/or onboard measurements. Measurements on a test bed allow PM/PN measurements under stringent laboratory conditions at exactly controlled load points of the engine. Test bed PM/PN emission limits can be differentiated regarding engine types (2- or 4-stroke or high speed) and different representative engine load points. ISO 8178-4:2020 includes a corresponding concept, but as it does not include measurements at lower load points, it has to be further developed. At least an emission limit at 10% load should be included. PM/PN measurements on a test bed are only possible for new engines and therefore only for newbuilds.

In comparison, onboard measurements cannot be so ambitious, as the measurement at sea is affected by many environmental factors like temperature, humidity, vibration, etc., which all lead to a measurement inaccuracy. But, as engines wear out over time and particulate emissions can increase, a permanent control regime is very important.

Here, the concept of a NTE limit value covering the whole load range (10% - 100%) seems to be a suitable option. Onboard measurement equipment must extract the exhaust gas directly from the exhaust gas pipe for the measurements of PM/PN to ensure continuous compliance with these emission limits.

This is also a feasible option for existing ships. As a measurement method the existing ISO 8178-2:2021 standard for measurement of PM emissions under field conditions can be applied. The ISO 8178-3:2019 standard includes the FSN as measurement method, which is widely accepted, and which was agreed at IMO as one out of three BC measurement methods. PN should be measured with a condensation particle counter (CPC).

Continuous monitoring data should be recorded and checked by Port State Controls or even better, the data could be transmitted automatically in electronic form to the authorities.

In addition to online monitoring, remote measurement systems could help to detect presumed exceedances of PM and PN limits or the use of incompliant fuel. This could help to detect conspicuous ships and to focus on onboard inspections on these ships, like current SO_X control.

For this purpose, Option I should contain fuel-based EF in g/kg fuel as this would be a better value for remote control systems. Real time fuel consumption can be determined remotely via CO_2 emissions in the exhaust gas, as long as the fuel type is known and no CO_2 reduction technologies like carbon capture and storage are applied or other fuels like ammonia are used. In contrast an energy-based EF (g/kWh) does require more specific data like fuel type, fuel consumption and engine load at the time of remote measurement and especially operational real time information such as the load point is difficult to obtain.

Furthermore, maintenance - and calibration intervals as well as other relevant parameters must be specified in the regulation for the measurement instruments used on board to ensure the proper functioning of the technology and to measure reliable and trustworthy values.

In principle, the introduction of a regular exhaust emissions test, similar to the requirements in road traffic, e.g. in connection with the regular inspection by classification societies that takes place anyway, would be a sensible measure to monitor the durability of the technologies and compliance with the limit values.

Option II – at least the first phase – has the major advantage to regulate emissions purely via fuel qualities, which only requires a control regime via Bunker Delivery Notes, Engine Record Book and as surveillance fuel sample controls by Port State Control. This would simplify the control process and reduce lengthy discussions about specific PM/PN limits associated with engine types and load points before introducing the regulation.

The H/C weight ratio or the C/H ratio would be a very precise factor to classify the BC emission potential of the fuels. But, as there is not enough data regarding the H/C weight ratio, this parameter is not a possible value for a regulation yet. Therefore, the acceptable fuels under such a regulation have to be classified by other fuel specifications, which are already included in the ISO 8217:2024 standard. This would have to be worked out in detail.

Option II requires a further reduction of PM emissions by the combination of clean fuels with exhaust gas abatement technologies or very clean fuels for new ships in stage II. These abatement technologies could be DPF, ESP or WESP as outlined in chapter 3.1.

The negotiations on BC regulations for the Arctic in the IMO show how difficult and lengthy the introduction of emission standards can be. For this reason, the author assumes that a pragmatic, easy-to-introduce and easy-to-implement approach must be chosen for a new PM/PN regulation. This can then be handled in parallel with the important IMO-work to decarbonize the shipping sector. In the medium- to long-term, both paths will probably join as GHG-neutral fuels reduce or completely eliminate PM emissions.

4.4 Open Questions

The following research topics should therefore be addressed to start the development of a PM/PN Regulation as soon as possible:

- General outline of a new PM/PN emission regulation framework and its ambition level.
- Determination of the PM/PN emissions for conventional and alternative fuels as well as for combination with abatement technologies as a basis for emission reduction limits.
- Evaluation of an adequate PM/PN limit for ECAs and globally. The level of ambition should be set primarily by environmental protection requirements and not e.g. by costs for abatement technology or costs for cleaner fuels.
- Develop specific limit values depending on engine types and for different load points and/or in combination with a NTE limit approach.
- In case of newly defined PM/PN ECAs: Definition of the extent of the ECAs, coupled e.g. with modelling of the transboundary transport of emissions to the coastlines or the Arctic area.
- Availability of cleaner fuels (distillates and new fuels) at the time of possible introduction dates.
- Cost-benefit analysis of different regulation options.
- Generate and analyze data for H/C or C/H weight ratios of the different fuels in case the fuel quality pathway is taken.
- Development of a monitoring and control regime for a fuel standard or an emission limit, together with fuel data and measurement methods.
- Definition of PM and PN measurement equipment calibration and maintenance intervals for on board use.

4.5 Conclusions

In summary, the development of a new regulation approach for PM/PN emissions from international shipping is very challenging as a lot of aspects and parameters must be included. But the environmental and health benefits from reduced air emissions are worth it. We suggest starting more research and discussion as soon as possible to tackle this major task.

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A Appendix 1

Technology options, measures, applicability and other considerations for BC control policies. [4]

The table is taken from the BC discussions at PPR, first presented by Canada (2020), republished by the United States (2023), with some amendments and additions by the author (*in italics*).

Possibility to apply:

✓ possible (✓) possible with constraints and associated with high costs/efforts X virtually impossible

Effectiveness:

+++ to +: very high to good; 0: neutral - to - - -: poor and very poor n/a: not applicable

Measure	Detailed technology	BC reduction potential in relation to HFO	Possibility to apply the technology to ships			Effectiveness of detailed technology if required as mandatory policy option ATTENTION: effectiveness related to its BC reduction potential			Comments / constraints
			new	re-fit	existing	new	re-fit	existing	"re-fit" means that a measure can be applied to an "existing" ship after modifications; "existing" means a ship as it is, with no (technical) changes.
engine internal measures	common rail (CR, adaptive injection timing)	about 15%	✓	X	X	+	n/a	n/a	"Miller timing" und "2-stage turbocharging" are additional engine internal measures often combined with CR; in this case BC red. potential maybe up-to about 50%
	variable camshaft	about 10%	✓	X	X	+	n/a	n/a	

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[4] Annotation: All measures and their BC reduction potential depend also on engine load, engine type and working principle (2- or 4-stroke, mean engine speed)

Measure	Detailed technology	BC reduction potential in relation to HFO	Possibility to apply the technology to ships			Effectiveness of detailed technology if required as mandatory policy option ATTENTION: effectiveness related to its BC reduction potential			Comments / constraints
exhaust aftertreatment	DPF (Diesel Particulate Filter)	80 – 99%	✓	(✓)	X	+++	+++	n/a	only in combination with extreme low sulfur / ash fuels, like in the automotive sector. Marine ULSF is still not suitable due to too high ash content; however, availability is a concern. DPF technology is not yet available for very large engines >2 MW and marine fuels. Further upscaling is required in future. Update by the author: DPF have been installed on marine engines with a power of 2-3 MW.
	ESP (Electrostatic Precipitator)	70% (estimate)	✓	(✓)	X	++	+	n/a	Safety aspects yet unsolved may hinder the application of ESP onboard ships Annotation: other PPR CG-rounds conceived 15 - 90% BC red. potential
	wet EGCS (Exhaust Gas Cleaning System, “scrubber”)	0 - 25% (high uncertainty)	✓	(✓)	X	0	0	n/a	Annotation: other PPR CG-rounds conceived 25 - 70% BC red. potential ATTENTION to unwanted side-effects: The use of EGCS implies negative impacts on the marine environment, like discharge water polluted with polycyclic aromatic hydrocarbons and heavy metals released into the sea.
cleaner fuels	Distillates	30 - 65%	✓	✓	✓	+	+	+	30% with a low aromatic content (high H/C ratio). A lower H/C ratio means an increase in unsaturated hydrocarbons which indicates an increase in aromatic content which results in higher BC emissions. (earlier PPR CG on BC reported up to 45%) Regarding PM reduction: up to 90% PM and up to 65% reduction of BC emissions by a switch from HFO to marine distillates have been reported.
	LNG	>85%	✓	(✓)	X	+++	++	n/a	ATTENTION to unwanted side-effects:

Measure	Detailed technology	BC reduction potential in relation to HFO	Possibility to apply the technology to ships			Effectiveness of detailed technology if required as mandatory policy option ATTENTION: effectiveness related to its BC reduction potential			Comments / constraints
cleaner fuels	(Liquified Natural Gas)								Depending on engine technology, some methane slip occurs during operation as well as production
	LPG (Liquified Petroleum Gas)	>85%	✓	(✓)	X	+++	++	n/a	Reduction potential is probably like LNG, but without methane slip
	Methanol	>85%	✓	(✓)	X	+++	++	n/a	Reduction potential is probably like LNG, but without methane slip
	OME (Oxymethylene ethers)	>85%	✓	(✓)	(✓) (up to 15% mixing ratio)	+++	+++	+	OMEs contain oxygen and their combustion is clean, probably like LNG. However, it is not commercially available, yet. Can be used as drop-in fuel. BC red. potential relates to mixing ratio. side effect: they can be produced in an environmentally friendly way from carbon dioxide (CO_2).
	Biofuels	-15 – 95 (PM)	✓	✓	✓	+	+	+	PM emission red. potential largely varies and depends on the fuel production pathway, its property and quality. The negative value is probably caused by impingement of the fuel (GtL) on the cylinder walls under low engine loads (Ushakov et al., 2013). The PM reduction of biofuels in blends reduce PM proportionally to their mixing ratio. This way 25 – 75% reduction of PM is possible. ATTENTION to unwanted side-effects: Biofuels are expected to be limited in availability and require sustainability criteria.
	sustainable synthetic fuels, PtX (Power to Gas or Liquid)	20 – 80%	✓	✓	✓	++	++	++	Since these are sulfur and ash free fuels, they would provide the necessary basis for DPF application. Annotation: Synthetic fuels are yet not produced / available in larger quantities.

Measure	Detailed technology	BC reduction potential in relation to HFO	Possibility to apply the technology to ships			Effectiveness of detailed technology if required as mandatory policy option ATTENTION: effectiveness related to its BC reduction potential			Comments / constraints
									Ammonia reduces PM emissions by 95% compared to MDO, 5% remaining due to the necessary pilot fuel. H_2 is nearly emission-free.
	Fuels with high H/C ratio	10 – 60%	✓	✓	✓	+	+	+	The H/C ratio provides information on the aromaticity of a fuel, decreased ratio means higher aromatic content (H/C ratio is not provided in ISO 8217)
other	Onshore Power Supply	100%	✓	(✓)	X	at sea: 0 in port: +++	at sea: 0 in port: +++	n/a	Effective only if non-oil / non-coal sources are used to produce electricity grid power. Would only be effective during port time.
	fuel cells / batteries	100%	✓	(✓)	X	+++	+++	n/a	In case of a hybrid solution (ICE engine & battery), the BC reduction is limited and dependent on the load capping, shaping, and shifting strategy. However, might be highly effective during transients. Not applicable for long distances and presumably not applicable in polar waters (energy demand and reserve not predictable).