THE SCIPPER PROJECT

Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations

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Executive summary

This study identifies gaps related to emission regulations for ships with a focus on enforcement. The aim is to investigate how existing regulations ensure compliance with the legislations on emissions to air. The report starts by listing the regulations and presents an overview of regulatory standards for emissions of SO_2, PM, and NO_X. In addition, expected and coming regulations are included. International shipping, in Emission Controls Areas and globally, are treated in more detail than regional and national initiatives. To some extent also emission regulations of HC, CO, and PN, which mainly apply to inland waterway vessels, are included.

A selection of mature abatement technologies that are used on ships to comply with the emission regulations is described. This aims at presenting how ships can be equipped to meet the regulatory standards, and the effects on emissions from different compliance technologies. The performance of some of the technologies is influenced by the fuel quality while others are more dependent on combustion specifics. An important example of the latter is Selective Catalytic Reduction (SCR), where the performance depends on exhaust gas temperature. SCR is a technology that can be expected to have an increased installation rate on new ships for compliance with IMO's NO_X Tier III regulations. It is common for the abatement technologies to be associated with some unregulated emissions that are potentially harmful for the environment. Examples are the methane slip from certain LNG engines, the ammonia slip from overdosage of urea in SCRs, and the discharge of scrubber wash water to the marine environment.

Enforcement practices differ significantly between the sulphur regulations and the NO_X-regulations. As emissions of sulphur oxides are directly related to the fuel sulphur content, measurement of the ratio between SO_2 and CO_2 can give an instant indication of the fuel sulphur content, and fuel samples and analysis will tell if operations comply with the regulations. Enforcement in all EU countries follow the enforcement regulations in the EU sulphur Directive 2016/802 and Implementing Decision 2015/253, relying on inspection on board and fuel sample analysis. Authorities in many countries in the SECA further use remote sensing from air-borne devices and fixed locations to have an indication of which ships that should be targeted for port state control. Enforcement of NO_X regulations will become a more urgent issue as NO_X Tier III limits starts to apply to new-built vessels. NO_X emissions are more a function of combustion characteristics than fuel when diesel engines are used, the regulations relate NO_X emissions to the work produced by the engine and not to the amount of fuel combusted. Since ships often are equipped with engines of different models which are operated by individual mode settings, the NO_X emissions cannot be related to CO_2 in the same manner as SO_2. Remote sensing is still used to some extent to have an indication of NO_X performance. In these cases, a "not to exceed" emission limit can be practical to use. Such practices are employed by the USEPA and IMO has a similar but limited approach for Tier III NO_X emission limits. No Directive on NO_X emissions from ships is in place in the EU.

Several gaps have been identified during the work with this deliverable. Some of them are regulatory gaps that, in the context of this report, typically include negative side effects of abatement technologies that could be addressed by policymakers. Many of the technologies described in this report are expected to have increased spread following coming and expected regulations issues. This increases the importance of regulations that can limit any potentially harmful emissions they may cause as by-products. Another regulatory gap that is discussed relates to the construction of engine type approval procedures which are not necessarily giving an adequate picture of the engines' operational emission performance.

Other gaps, that are of more interest in the context of the SCIPPER project, relate to the enforcement of regulations. We present the gaps and point out which could be addressed within the project scope. Important examples are the development of onboard exhaust gas sensors that can be used in an enforcement context. These include NO_X and ammonia sensors downstream an SCR, robust SO_2 and CO_2 sensors downstream a scrubber, methane sensors for LNG engine exhaust and BC sensors for potential coming regulations on soot emissions from ships. Enforcement regulations should ensure reliable performance over time, upstream and downstream of any abatement technologies. Especially important following NO_X Tier III limits is the development of onboard sensors for NO_X, for use in ship exhaust gas. This would reduce the potential to confound the test cycle. At the end of the project the aim is to provide a performance analysis of state-of-the-art sensors for marine use to policy makers.

The possibility to use remote monitoring to aid the enforcement of the sulphur regulations is used by many European countries. We identify a potential to use monitoring applications more. Among these are the potential applications at offshore locations far from the coast. This involves the use of different platforms. Regulatory approaches to the use of remote sensing technology for NO_X emissions are lacking. As far as this study has concluded it is possible,

from a legal perspective, to include these in the enforcement regulations of individual European states. This is different from the sulphur regulations for which each member state is bound by the sulphur EU Directive. Other valuable measurements from remote locations include also black carbon and methane, the same emissions as for onboard measurement. These emissions all relate to combustion characteristics or operational modes and the issue of not-to-exceed limits therefore needs to be addressed for all of them.

Another aspect that is important for all the listed sensors in the sense of enforcement practices relate to the communication of the measured results. In order to assure compliance also at remote locations a reliable system for signal transmission is needed.

For the final recommendations of the SCIPPER project it is important that aspects of the maturity and cost-efficiency of different measurement techniques are considered. A joint analysis of these findings, together with recommendations on which sensors are best use, the signal transmission technology, and the reporting structure of the measurement data, will be an output that aims at providing policymakers state of the art knowledge of the technical potential to monitor emissions from ships.

List of abbreviations

BC – Black Carbon
BDN – Bunker Delivery Note
CCNR – Central Commission for the Navigation of the Rhine
CO – carbon monoxide
CO_2 – carbon dioxide
CSI – Clean Shipping Index
DECA – Domestic Emission Control Area
EC – European Commission
ECA – Emission Control Area
EGCS – Exhaust Gas Cleaning System
EGR – Exhaust Gas Recirculation
EMSA – European Maritime Safety Agency
ESI – Environmental Shipping Index
ETM – EGCS Technical Manual
EU – European Union
FCP – Fuel Changeover Procedure
FSC – Fuel Sulphur Content
IMO – International Maritime Organization
IWW – Inland Waterways
LNG – Liquefied Natural Gas
m/m - mass/mass
MARPOL – International Convention for the Prevention of Pollution from Ships a.k.a. the Marine Pollution Act
MEPC – Marine Environmental Protection Committee
NECA – NO_X Emission Control Area
NO_X – Nitrogen Oxides
OC – Organic carbon
OMM – Onboard Monitoring Manual
PAH – Polycyclic Aromatic Hydrocarbons
PM – Particulate matter
ppm – parts per million
PSC – Port State Control
REMPEC – The Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea
SCR – Selective Catalytic Reduction
SECA – Sulphur Emission Control Area
SECC - SO_X Emission Compliance Certificate
SECP - SO_X Emission Compliance Plan
SO_2 – Sulphur dioxide
SO_X – Sulphur oxides
US EPA – United States Environmental Protection Agency
v/v - volume/volume

Contents

Figures

Tables

1 Introduction

This report aims at answering how existing regulations ensure compliance with the legislations on emissions to air from ships. It presents a brief overview of existing regulations regarding emissions of air pollutants from ship engines and their accompanying regulatory instructions and practices for monitoring. From identified gaps, loopholes and anticipated problems we give recommendations for the further research within the SCIPPER project.

Emission regulations applicable to international shipping includes quantified levels for emissions of nitrogen oxides (NO_X) and sulphur dioxide (SO_2). To some extent also carbon dioxide (CO_2) is treated in quantified terms in the internationally agreed regulations. Accompanying these standards are instructions on certificates, documentation practices and, in specific cases, measurement equipment that should be kept onboard. In addition, control procedures to be followed by port states are specified. This deliverable aims at investigating potential gaps in these regulations. Gaps include the possibility that documentation requirements fail to cover the actual emissions from an engine over time, that monitoring equipment are poorly fit for long term measurements in the conditions of the exhaust gas, or that important side effects of emission abatement technologies are excluded, to name a few.

The deliverable also covers the expected and upcoming regulations. The Nitrogen Emissions Control Areas (NECA) will be established in the Baltic and North Sea areas, requiring all ships keel laid on 1 Jan 2021 and onwards to be equipped with NOx abatement techniques which reduce these emissions below a few grams per kWh. Other expected regulations are the tighter rules for greenhouse gas emissions, as agreed by the IMO, where, as an example, one objective is to reduce the emissions of GHGs from shipping by 50% until 2050 compared to the 2008 emissions. It is also expected that particle emissions from ships will be included in future regulations in some way. Discussions in the marine environmental protection committee (MEPC) of the IMO address emission limits for black carbon in particular. Inland waterway vessels already comply with particle emission regulations in the EU.

The study lists issues related to the difficulties concerning the control measures exercised by individual states and enforcement of regulations for ships sailing the international waters or high seas. Various port states apply slightly different procedures and technologies to monitor the visiting ships. In areas where strict regulation or incentive schemes for emission reduction are applied, there are practices that could be applied in a wider scale.

One purpose of this report is to provide the SCIPPER project with input on measurement technologies that are needed from a monitoring and controlling perspective. One section of the deliverable is dedicated to the identification of gaps that could be addressed within the project.

Chapter 2 of this report gives an overview of existing and expected regulations on emission limits and describes briefly their structure. Following this is a chapter on technical aspects of emission regulations. This chapter aims at presenting how ships can be equipped to meet the regulations, and the effects on emissions from different compliance technologies. In the fourth chapter enforcement regulations, guidelines and practices are presented. Differences between countries or regions are highlighted. The fifth chapter lists the gaps and chapter 6 includes recommendations on further efforts for the SCIPPER work packages.

2 Emission regulations

The emissions from ships depend on the engine speed, type, fuels used, operational practices applied and after treatment techniques installed, if any. Almost all ships use compression ignited, two- or four-stroke engines and fossil fuels. Combustion products of engines consist of carbon dioxide (CO_2) and sulphur oxides (SO_X), which are related to the chemical composition of the fuel, and carbon monoxide (CO), nitrogen oxides (NO_X) and hydrocarbons, which depend more on combustion characteristics than the fuel itself. The emission levels of particulate matter are dependent on both. The sulphur in the fuel contributes to particle mass through the formation of particulate sulphates. The relationship of increased particle mass and sulphur in fuel is particularly evident for residual fuels with >0.5% of sulphur (Buhaug et al., 2009). Also other substances, like polyaromatic hydrocarbons (PAHs) and mineral ash contribute to particle formation. Primary PM in the form of Elemental Carbon (EC), Organic Carbon (OC), ash, and metals, largely resides in the ultrafine particle (<100 nm) range (Ntziachristos et al., 2016). Using liquefied natural gas (LNG) as a fuel often involves a slip of methane (CH_4) through the engine, especially in the case of low-pressure dual fuel applications. The methane slip is reduced in high pressure gas engines operating with the diesel principle.

The emission regulations for international shipping originate from agreements in international conventions. In 1997, the IMO adopted the Annex VI of MARPOL to address air quality issues. The Annex includes the regulations for sulphur oxides and PM emissions, and emissions of nitrogen oxides. A regulation on carbon dioxide emissions is also included in the Annex VI.

2.1 Regulations on fuel sulphur content, emissions of SO_X and PM

2.1.1 International emission regulations

Fuel sulphur content and emissions of SO_X and PM are treated in regulation 14 of MARPOL Annex VI. Different limits apply in different ocean areas. The regulation requires that the fuel sulphur content (FSC) of marine fuel in a Sulphur Emission Control Areas (SECAs) does not exceed 0.10% m/m. Of the seas close to Europe, the Baltic Sea, and the North Sea and the English Channel are designated SECAs. Further, there are SECAs in the North American and US Caribbean Sea. From 1st of January 2020 a world-wide limit on maximum FSC of 0.50% will be enforced outside SECAs. This is a significant reduction from the currently allowed FSC of 3.50%. The global limits over time for sulphur content of marine fuel are illustrated in Figure 2-1. In practice, the global drop in FSC limit in 2020 will cause a large-scale shift from residual oils to distillates, typically marine diesel or gasoil, although also new types of residual and mixed products are expected on the market. Bio fuels will probably play a role in a longer time perspective.

A discussion concerning the declaration of the Mediterranean Sea as an ECA is in progress between the Barcelona convention (REMPEC) countries and the EU. Three separate cost-benefit studies (IIASA, 2018; INERIS, 2019; REMPEC, 2019 (not publicly available)) were completed to assess the viability of declaring the Mediterranean Sea an ECA. All three studies concluded that the health benefits outweigh the costs of an ECA, but it is up to the countries to find political consensus and timing for ECA application submission to the IMO.

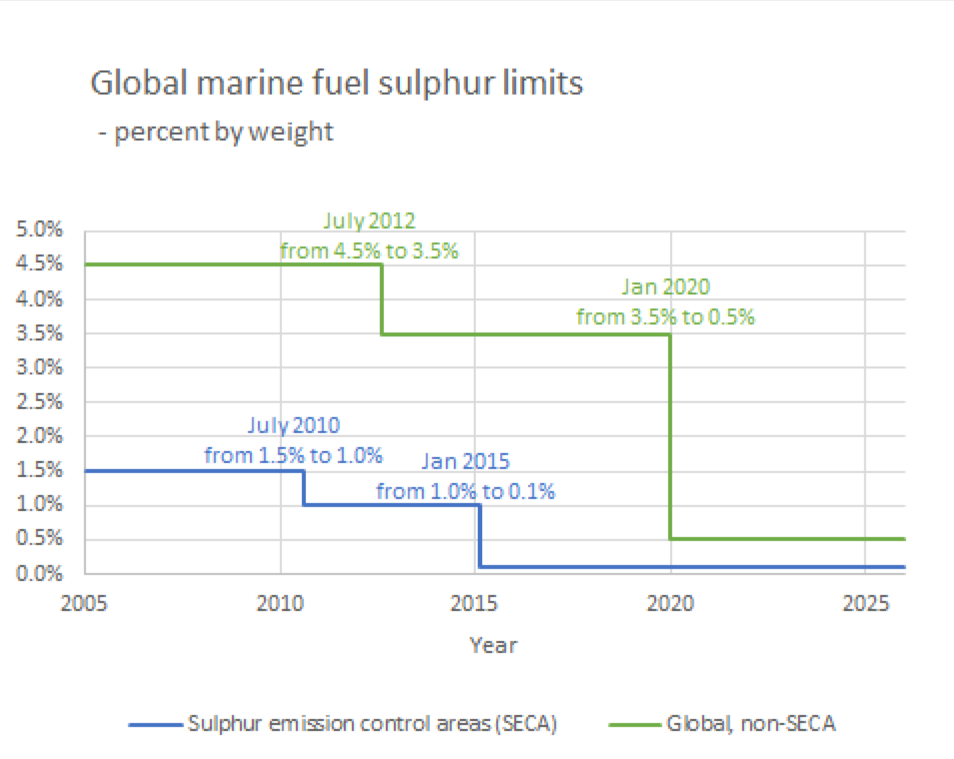

Figure 2-1. Global marine fuel sulphur regulations

An important note is that it is also allowed to use Exhaust Gas Cleaning Systems (EGCS) to reduce SO_2 in the exhaust to equivalent emission levels. Equivalent emission values for emission abatement methods are determined as a set ratio between SO_2 and CO_2 as listed in Table 2-1.

Table 2-1. Fuel oil sulphur limits recorded in regulations and corresponding emissions values (MEPC, 2015).

Marine fuel sulphur content (%), m/m	Ratio emission SO_2 (ppm)/CO_2 (%) v/v
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

Emissions of particulate matter are not regulated to specific levels but are assumed to be reduced with the fuel sulphur content. The reduction of sulphur will reduce the secondary inorganic aerosol formation, because a precursor gas emission is reduced. However, this has a minor effect on the emitted organic species, which contribute to the total particulate mass via secondary organic aerosol formation. For PM reduction, both the primary and secondary formation should be minimized. Specific components may be more relevant to regulate than total particle mass. Black carbon (BC) control is under discussion within the IMO, due to its potent impacts on climate and health (Browse et al., 2013). Investigations of appropriate control measures have been conducted, but there is to our knowledge no concrete actions planned (IMO, 2015). The IMO has made some recognition of protection of the polar regions and established the Polar Code that encourages ships not to or carry heavy fuel oil in the Arctic. No direct particle emission limits are however included and discussions on limiting mainly emissions of black carbon in the region are on-going in the Marine Environmental Protection Committee of the IMO.

EU Directive 2016/802, also known as the EU sulphur directive, converts the MARPOL-regulations to EU legislation. Additional to the MARPOL regulations, the sulphur directive includes an additional requirement for passenger ships operating in territorial seas, exclusive economic zones, and pollution control zones outside SO_X Emission Control Areas, on regular services to or from any Union port. Ships in such traffic are required not to use marine fuels with a sulphur content exceeding 1.50% by mass. This regulation applies until 1 January 2020 when the global marine fuel sulphur limit becomes 0.50%. Further, the directive states that Member States shall take all necessary measures to ensure that ships at berth in Union ports do not use marine fuels with a sulphur content exceeding 0.10% by mass. The latter does not apply when ships stay less than two hours at berth. Emission abatement methods that " […] continuously achieve reductions of sulphur dioxide emissions that are at least equivalent to the reductions that would be achieved by using marine fuels [...]" are alternatives to the use of fuels with low sulphur content (European Parliament and the Council, 2016,).

2.1.2 EU inland waterways emission regulations

Inland waterway vessels are required by regulations not to use fuel with sulphur content above 10 mg/kg (this corresponds to 0.001% m/m) from 2011 with certain flexibilities applied. The limit applies for both petrol and diesel fuels. Exceptions allow up to 20 mg/kg at final points of distribution (European parliament and council, 2009).

Regulation 2016/1628, on emissions from non-road mobile machinery, includes emission limits for engines on inland waterway vessels. The regulation introduces limits on PM measured by gravimetric methods for engines for inland waterway vessels constructed 2007 and onwards for engine category IIIA. The regulations have been gradually tightened. Current limits, the Stage V regulations, apply to vessels constructed in 2019 and 2020 and onwards. These vessels, with an installed power of 300 kW or more, will also, in addition to the regulation on particle mass, have to comply with regulations on the number concentration of particles (PN).

The limits are harmonized with the US regulations. Harmonization with US and Japan regulations is lost in Stage V since the PN standards indirectly require installation of diesel particulate filters, which US rules do not call for. European PM and PN requirements are specified inTable 2-2 andTable 2-3.

Table 2-2. Stage IIIA requirements on emissions from diesel engines on inland waterway vessels in the EU (dieselnet.com, 2019b); D = Displacement in dm^3/cylinder; P = Power in kW; PM = Diesel particulate matter measured by gravimetric methods

	Year	PM (g/kWh)
D ≤ 0.9; P > 37 kW	2007	0.40
0.9 <D≤ 1.2	2007	0.30
1.2 <D≤ 2.5	2007	0.20
2.5 <D≤ 5	2009	0.20
5 <D≤ 15	2009	0.27
15 < D ≤ 20; P ≤ 3300 kW	2009	0.50
15 < D ≤ 20; P > 3300 kW	2009	0.50
20 <D≤ 25	2009	0.50
25 <D≤ 30	2009	0.50

Table 2-3. PM and PN requirements for engines on IWW vessels in the EU in Stage V (dieselnet.com, 2019b / EU Directive 2016/1628); [a] v/c = variable/constant, number 1-4 relates to power. For variable speed engines maximum rated power, for constant speed engines rated net power; [b]particle number' or 'PN' means the number of solid particles emitted by an engine with a diameter greater than 23 nm

Category[a]	Net power (kW)	Type approval Date	Date for placing on the market	PM (g/kWh)	PN[b] (1/kWh)
v/c-1	19 ≤ P <75	1 Jan 2018	1 Jan 2019	0.30	-
v/c-2	75 ≤ P <130	1 Jan 2018	1 Jan 2019	0.14	-
v/c-3	130 ≤ P <300	1 Jan 2018	1 Jan 2019	0.10	-
v/c-4	P ≥ 300	1 Jan 2019	1 Jan 2020	0.015	$1*10^{12}$

2.1.3 The US EPA emission regulations for marine engines

The US EPA has introduced emissions standards for particles from marine engines for specified engine categories where the emission limits are gradually tightened (dieselnet.com, 2019a). Three engine categories exist, of which engine category 3 includes large marine engines (displacement per cylinder ≥ 30 dm^3). Regulations for category 3 engines are the same as the international regulations in MARPOL Annex VI. Engine categories 1 and 2, are smaller engines that are similar to those used in off-road land vehicles. For such engines stringent emission standards apply for all ships that are flagged or registered in the US.

Tier 3 has been applicable from 2009 and onwards, and Tier 4 from 2014 and onwards. Tier 4 only applies to engines of 600 kW or above. The Tier 3 standards limit PM emissions depending on power and cylinder displacement to 0.11-0.40 g/kWh and 0.24-0.34 g/kWh for category 1 engines and category 2 engines, respectively. These engines have a power below 3700 kW. PM emissions from engines of ≥ 3700 kW in categories 1 and 2 are limited to 0.06, 0.12 or 0.25 g/kWh, and smaller engines have emission limits at 0.04 g/kWh (dieselnet.com, 2019a).

2.1.4 Local requirements and incentives

Few domestic regulations are effective for shipping. An example is however the introduction of sulphur limiting regulations targeting emissions from coastal and inland shipping in Hong Kong, Taiwan and mainland China. In this "Domestic Emission Control Area" (DECA) sulphur content in fuel used in a zone outside the coast is limited to 0.50%, and in defined inland waters to 0.10% from 2019 and 2020, respectively. A revision of the emission limits is foreseen and a DECA2 initiative is currently discussed. This would further extend the Sulphur regulation to Chinese inland shipping, too.

At the European scale, the first emission limits for inland waterways were introduced by the countries bordering the Rhine River through the Central Commission for the Navigation of the Rhine (CCNR) in 2002, targeting PM amongst other emissions. The limit was lowered in 2007, and further reductions were discussed but the work was discontinued because of the similar, but wider European legislation (Pillot et al., 2016).

The issue of reducing emissions of sulphur and particles from ships connects to both economic and policy incentives. Economic schemes involve the voluntary participation by ships owners and operators who are prepared to emit less than what is prescribed by regulations. Examples of economic incentives are the credit systems based on indexes in order to give rebates on port fees. Three systems that are widely used for credits are Environmental Ship Index (ESI), Clean Shipping Index, and Green award. The ESI, which is used by several European ports, gives credit based on average sulphur content of carried fuel over periods of three months. Examples of policy incentives are local bans of the use of scrubber systems in ports. Several ports and local authorities globally ban the use of scrubbers in their waters, while others specifically state that no ban is necessary.

2.2 NO_X emission regulations

2.2.1 International NO_X emission regulations

International NO_X emission limits related to the specific emissions from marine diesel engines are constructed in a time dependent three-tier fashion specified in Regulation 13 of MARPOL Annex VI, and in the related NO_X Technical Code. The third tier is the most demanding and requires NO_X emissions reductions of approximately 90% from a non-regulated combustion[1]. Tier III regulations are only applicable in NO_X Emission Control Areas (NECA). Further, new NO_X regulations are never applied on existing vessels unless they undergo major conversion. This leads to slow introduction of Tier III vessels, because vessel lifetimes are often around 30 years. The full effect of NOx reduction can only be seen after one renewal cycle of the ship fleet. If a major conversion involves installation or a replacement of an engine, then the tier appropriate to the date of installation applies. In the North American ECA and the United States Caribbean Sea ECA the Tier III nitrogen regulations apply on vessels built after 1 January 2016. A NECA is also in place in the North Sea and the Baltic Sea to cover ships constructed on and after 1 January 2021.

The specific emission limits for marine diesel engines as specified in MARPOL Annex VI are illustrated in Figure 2-2.

[1] About 80% reduction compared to Tier I

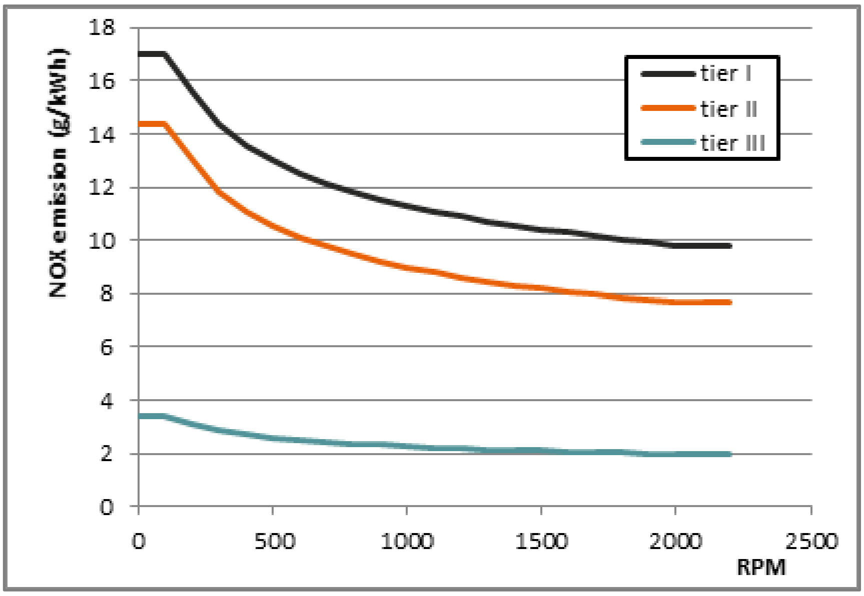

Figure 2-2. IMO regulations in emissions of NO_X from marine engines.

The limits are presented in Table 2-4

Table 2-4. IMO NO_X emission limits

Tier	Date	NOX limit		
		N < 130	130 ≤ n < 2000	n ≥ 2000
I	2000	17.0	$45*n^{-0.2}$	9.8
II	2011	14.4	$44*n^{-0.23}$	7.7
III	2016 (in NECAs)	3.4	$9*n^{-0.2}$	1.96

2.2.2 Regulations for NO_X from inland waterways vessels in the EU

The regulations on emissions from inland waterway vessels have gradually reduced the NO_X limits. Engines used for inland shipping used to be type approved under the Central Commission for the Navigation of the Rhine (CCNR) regulations. The NOx limits are functions of engine speed, similar to the IMO Tiers for maritime shipping. There are two levels: CCNR I (entry into service 2003) and CCNR II (2007), with the following limits:

- CCNR1: NO_X -limit is 45 n_{max} $^{-0,2}$ (g/kWh) for max engine power below 560 kW it is 9,2 g/kWh
- CCNR2: NO_X -limit is 45 n_{max} $^{-0,23}$ (g/kWh) for max engine power below 560 kW it is 6,0 g/kWh

Table 2-5 gives an overview of all CCNR limit values.

Table 2-5 CCNR emission regulations on emissions to air from engines on inland waterway vessels

Datum	Phase	Max. Power (kW)	CO (g/kWh)	HC (g/kWh)	NO_X (g/kWh)	PM (g/kWh)
2003	CCNR I	130 - 560 >560	5.0 5.0	1.3 1.3	9.2 9.2 -12.5	0.54 0.54
2007	CCNR 2	130 - 560 >560	3.5 3.5	1.0 1.0	6.0 6 – 9.5	0.2 0.2

Shortly after year 2000, a transition was started up in order to apply the same regulations in the whole EU. The CCNR regulations were replaced by European legislation. Further, the limits were synchronized with the corresponding regulations of the US EPA. This led to the Stage IIIA regulations for IWW in the EU. The applicable regulations for IWW vessels in the EU are presented in Table 2-6 and Table 2-7.

Table 2-6. Stage IIIA requirements on NO_X emissions from diesel engines on inland waterway vessels in the EU (dieselnet.com, 2019b). D = Displacement in dm^3/cylinder; P = Power in kW;

	Year	$HC+NO_X$ (g/kWh)
D ≤ 0.9; P > 37 kW	2007	7.5
0.9 <D≤ 1.2	2007	7.2
1.2 <D≤ 2.5	2007	7.2
2.5 <D≤ 5	2009	7.2
5 <D≤ 15	2009	7.8
15 < D ≤ 20; P ≤ 3300 kW	2009	8.7
15 < D ≤ 20; P > 3300 kW	2009	9.8
20 <D≤ 25	2009	9.8
25 <D≤ 30	2009	11

Table 2-7. NO_X requirements for engines on IWW vessels in the EU in Stage V (dieselnet.com, 2019b/EU Regulation 2016/1628); [a] v/c = variable/constant, number 1-4 relates to power. For variable speed engines maximum rated power, for constant speed engines rated net power; [b]6.00 g/kWh for fully or partially gaseous-fuelled engines. For sub-categories with a combined HC and NO_X limit, the combined limit value for HC and NO_X shall be reduced by 0.19 g/kWh and apply for NO_X only; [c]$HC+NO_X$

Category[a]	Net power (kW)	Type approval Date	Date for placing on the market	HC[b] (g/kWh)	NO_X (g/kWh)
v/c-1	19 ≤ P <75	1 Jan 2018	1 Jan 2019	4.70[c]	
v/c-2	75 ≤ P <130	1 Jan 2018	1 Jan 2019	5.40[c]	
v/c-3	130 ≤ P <300	1 Jan 2018	1 Jan 2019	1.00	2.10
v/c-4	P ≥ 300	1 Jan 2019	1 Jan 2020	0.19	1.80

The emission limits do not apply to the engines of sea-going vessels. (European parliament and council, 2016b).

2.2.3 The US EPA regulations for NO_X emissions from marine engines

The US EPA regulations on marine engines include NO_X limits that go beyond those set in the MARPOL Annex VI for engine categories 1 and 2. As described briefly in section 2.1.3, these US EPA engine categories are mainly small engines, and the regulations apply for ships registered or flagged in the US. Regulations for category 3 engines are the same as the international regulations in MARPOL Annex VI (dieselnet.com, 2019a).

Tier 3, applicable from 2009-2014, limit NO_X emissions from category 1 engines to 4.7 – 7.5 g/kWh depending on power and cylinder displacement. NO_X emissions from category 2 engines are subject to limits that also restrict HC emissions. These are set between 6.2 – 11 g/kWh depending on power and cylinder displacement. The Tier 3 regulations apply for new engines onwards for all ships with power below 600 kW. Tier 4 applies to engines of 600 kW or above from 2014 and onwards and the limit is set to 1.8 g/kWh. Tier 3 and Tier 4 is only applicable for category 1 and category 2 engines (dieselnet.com, 2019a).

A delayed introduction of the Tier 4 regulations for high power marine diesel engine has recently been proposed by the US EPA.

2.2.4 Local requirements and incentives

Regional and local requirements and voluntary commitments are to some extent similar to those described for sulphur and particulate matter on page 4. As such, the Rhine Commission introduced emission levels for NO_X from engines on inland waterway vessels on the Rhine by 2002, strengthened in 2007. Another example is the incentives in ports that use credit systems based on indexes in order to give rebates on fees. The environmental ship index (ESI), and the clean shipping index (CSI), both reward a good performance of NO_X. Other incentives that stimulate low-NO_X technologies are the Norwegian NO_X-tax and NO_X-fund that apply to shipping in the Norwegian territorial waters. No limits are quantified but economic refunds have stimulated extensive investment in LNG-engines, exhaust gas recirculation technologies (EGR), and selective catalytic reduction systems (SCR).

2.3 Other regulated emissions to air

Regulations on emissions from marine and inland waterway vessels other than those of primary importance in the SCIPPER project include regulations on CO_2-emissions, and pollutants CO and HC.

2.3.1 Regulations on greenhouse gas emissions

The existing regulations on emissions of CO_2 in the MARPOL-convention include mainly two measures. One is the Energy Efficiency Design Index (EEDI) that prescribes step wise reductions of CO_2-emissions in relation to ship size and transported goods. The regulation refers only to ship designs and does not cover actual emissions from ship operations although a consequence of an energy efficient design is a good prerequisite for energy efficient operations. Another part of the regulation is the Ship Energy Efficiency Management Plan (SEEMP) which does not dictate any compliance levels but rather suggests how ship energy consumption and emissions can be managed.

In April 2018, the IMO agreed on quantified targets for the reduction of GHG emissions from shipping. The goal consists of three main parts:

- to strengthen existing rules for more energy-efficient ship designs
- to reduce CO_2 emissions in relation to transport work by 40% or more until 2030 and striving to reach 70% by 2050, compared to the 2008 level.
- to reduce shipping's total emissions of greenhouse gases as soon as possible and to release half as much GHG in 2050 as in 2008 (International Maritime Organization, 2018).

Specific measures to reach the goals are to be worked out. The timetable is not yet set, but references are made to the Paris Convention's temperature target (International Maritime Organization, 2018).

2.3.2 Regulations on air pollutants other than SO_2, PM and NO_X

For inland waterway vessels, existing air pollutant regulations include engine related requirements for CO and HC, in addition to the regulations on particles and NO_X, and on the fuels used in these vessels, see Table 2-8.

Table 2-8. Requirements on emissions of CO and HC for engines on IWW vessels in the EU in Stage V (EU Regulation 2016/1628); [a]v/c variable/constant, number 1-4 relates to power. For variable speed engines maximum rated power, for constant speed engines rated net power; [b]6.00 g/kWh for fully or partially gaseous-fuelled engines. For sub-categories with a combined HC and NOx limit, the combined limit value for HC and NOx shall be reduced by 0.19 g/kWh and apply for NOx only; [c]HC+NOx

<table>
<tr><th>Category[a]</th><th>Net power (kW)</th><th>Type approval Date</th><th>Date for placing on the market</th><th>CO (g/kWh)</th><th>HC[b] (g/kWh)</th><th>NOx (g/kWh)</th></tr>
<tr><td>v/c-1</td><td>19 ≤ P <75</td><td>1 Jan 2018</td><td>1 Jan 2019</td><td>5.00</td><td colspan="2">4.70[c]</td></tr>
<tr><td>v/c-2</td><td>75 ≤ P <130</td><td>1 Jan 2018</td><td>1 Jan 2019</td><td>5.00</td><td colspan="2">5.40[c]</td></tr>
<tr><td>v/c-3</td><td>130 ≤ P <300</td><td>1 Jan 2018</td><td>1 Jan 2019</td><td>3.50</td><td>1.00</td><td>2.10</td></tr>
<tr><td>v/c-4</td><td>P ≥ 300</td><td>1 Jan 2019</td><td>1 Jan 2020</td><td>3.50</td><td>0.19</td><td>1.80</td></tr>
</table>

New marine engines on vessels flagged or registered in the USA has, in addition to the NOx limits in the MARPOL Annex VI, adopted a HC emission standard of 2.0 g/kWh and a CO standard of 5.0 g/kWh from Category 3 engines. Category 3 engines are very large marine diesel engines used for propulsion power on ocean-going vessels. The Tier 2 limit of maximum 5.0 g/kWh also applies for the engine categories 1 and 2, the smaller marine engines, while limit on emission of HC is significantly lowered to 0.19 g/kWh for these categories in Tier 4 (dieselnet.com, 2019a).

3 Emission abatement technologies

This listing of emission abatement technologies aims at pointing out the most mature technologies for marine applications and address issues relating to their function and principles for emission abatement and potential side effects.

3.1 Low sulphur marine fuels

Marine distillate fuel oils and blends with residual streams from the refineries are common fuels for ships. Regulations are merely specifying the fuel sulphur content of the fuel and the variety on fuel qualities can therefore be large, although the ISO 8217 standard on marine fuels include also physical properties of the fuels. After the emission limits for SECAs became effective in 2015 a number of new fuels with varying quality was seen on the market. The emission characteristics of these have not been extensively studied although they do fulfil the sulphur regulations. It can be expected that mixed fuels with a sulphur content below 0.5% will be placed on the market in 2020.

The emissions of sulphur oxides are proportional to the fuel sulphur content (FSC). It is, naturally, more difficult to describe the emissions of particulate matter based on the FSC of the fuel oil used. For high fuel sulphur content there is an increase of exhaust gas particle mass concentration with fuel sulphur content. This effect is uncertain at FSC below 0.5%. Further, engines are often adjusted to operate on one fuel. At changes to fuels of significantly different combustion characteristics, depending on such as cetane number, viscosity, and density, products of incomplete combustion can increase. Further, conversion of fuel Sulphur to particulate sulphate is load dependent, which makes PM emission factor development challenging (Zhou et al., 2019).

Other low sulphur fuels are Liquefied Natural Gas (LNG), Methanol, Liquefied Bio-Gas (LBG), and other biofuels. LNG is the most widely spread of these and described separately below.

3.2 Scrubber technologies

An exhaust gas cleaning system, a so-called SO_2 scrubber, referred to as exhaust gas cleaning systems in the regulatory texts, can be installed in the exhaust channel of a ship as an alternative to the use of low sulphur fuels. Approximately 3500-4000 ships are equipped with scrubbers or have scrubber installations ordered (DNVGL, 2019). Most installed scrubbers are open loop scrubbers in which the exhaust gases are washed with sea water, which is released back to the sea. Other systems are closed, which means that a strongly alkaline solution is used for the scrubbing, and the fluid is recirculated over the exhaust gas flow. High sulphur heavy fuel oil can be used since exhaust gas SO_2 and SO_3 react with the water and are neutralized by the alkalinity of the fluid.

Negative aspects of the scrubber exhaust gas treatment relate to the substances discharged to the marine environment. The volumes of discharge are significantly smaller from closed loop systems than those from an open system. Further, the closed loop systems allow for treatment of the water before the discharge to the marine environment. Scrubber effluents have been shown to have detrimental effects on zooplankton in eco-toxicity tests (Magnusson et al., 2018). Treated effluents from a closed loop scrubber were however in one test proven to cause significant environmental risk. Even though the volume of discharge is smaller, the concentrations of harmful substances were more concentrated. This occurs as the systems are operated in compliance with regulations.

The scrubbers are effective at reducing the emissions of sulphur oxides but if levels of emissions of particulate matter reach those resulting in the use of low-sulphur fuels remain uncertain. In general terms, measurements have indicated that the low-sulphur fuel is preferable to scrubber treatment in the sense that particle emissions are lower (Winnes et al., 2019a). However, particulate matter is reduced compared to combustion of high sulphur heavy fuel oils. This should be considered with the knowledge that particle measurements in the wet and cold exhaust gases downstream a scrubber are not standardized and that these conditions influence particle formation. Also for black carbon there are doubts if scrubbers are effective (ICCT, 2016; Winnes et al. 2019b).

There are also dry scrubbers in which the exhaust gas passes through a granulate of lime.

3.3 Liquefied natural gas (LNG)

Liquefied Natural Gas (LNG), is an alternative fuel that has been used in LNG tankers traditionally, but that has had increased used in other segments of shipping during the last decade. LNG can be used as single fuel or in dual fuel engines that can operate on either gas or oil and that use a small amount of oil as ignition fuel. Marine LNG engines are often applying the Otto-cycle or a combination of the Otto-cycle and Diesel-cycle, which keeps temperatures and pressure relatively low during combustion. NO_X emission are kept at low levels without additional abatement technologies. These LNG-engines comply with both sulphur regulations in SECAs, and Tier III NO_X-regulations. A side effect is that engines that fully or partly utilize the Otto-cycle have a slip of the greenhouse gas methane. This slip has been reported to be between 2-4% of the fuel over a test cycle in modern engines and is higher at low engine loads (Ushakov et al., 2019). LNG engines that utilize the Diesel combustion cycle do not have a significant methane slip. A down-side with these engines are however that they do not comply with the Tier III NO_X -regulations unless aftertreatment is used.

3.4 Methanol

Methanol is used in a few ships in dual-fuel engines or spark-ignition engines. The emissions of PM and SO_X are low while abatement measures for NO_X are still needed to meet Tier III requirements.

3.5 Selective catalytic reduction (SCR)

Selective Catalytic Reduction (SCR), which is a mature after-treatment technology tested on over 500 ships, accomplishes efficient NO_X reduction at reasonably high exhaust gas temperatures. Using an SCR implies the use of urea or ammonia for the NO_X reduction over a catalyst. If the urea is not properly dosed in relation to the temperature, NO_X content, and exhaust flow, a slip of ammonia may occur. SCRs are not always well functioning at low engine loads as exhaust gas temperatures are possibly too low for the catalytical reaction to be fast enough. Further, the catalysts, although very durable, may be deactivated through poisoning or thermal degradation. It is also possible that manufacturers strongly reduce the urea dosing below 25% load, since this load is not a part of the E3/E2 test cycle for emission, for economic reason. For most vessels, reductions for Tier III compliance will largely be achieved by using Selective Catalytic Reduction (SCR) devices. Combining an SCR with a scrubber could present issues, after a scrubber the exhaust temperature will be too low for operation of an SCR. If the SCR is placed upstream the scrubber the high content of SO2 in the exhaust will decrease the activity; however, SCR systems can operate with high sulphur fuel if the exhaust temperatures is kept high.

3.6 Exhaust gas recirculation (EGR)

With exhaust gas recirculation (EGR), a fraction of the exhaust gas is cooled and recirculated into the engine. This lowers the formation of NO through changes in oxygen concentration and heat capacity. According to engine manufacturers, EGR can be used to reach Tier III levels for all marine engine types. However, EGR is currently only offered on a few engine brands and engine series. Possibly, EGR is more attractive for engines which sail the majority of the time outside the NECA zones since the ratio of investment costs over operational costs are lower for EGR than for SCR.

The exhaust that is recirculated must sometimes be purified from particles and sulphur oxides in order to protect the engine from soot deposits and corrosion. This can be achieved by filters if low-sulphur fuel is used or with scrubbers which can absorb both SO_2 and particulate matter. In cases when a scrubber is used a small fraction of the scrubber liquid is discharged to the sea as bleed off. This water is contaminated from the exhaust gas and the effects on the marine environment from these discharges remain to be quantified.

3.7 Wet technologies

Adding water to the combustion is another method to decrease the combustion temperature and thus the formation rate for NO. Water can be added in three different ways: either by direct injection into the engine, through saturation with water vapour of the scavenging air or through a fuel-water emulsion. These methods have been used for several years and can reduce the emissions of NO_X significantly, however not down to Tier III levels. The methods may be used in combination with e.g. EGR to reach Tier III.

3.8 Diesel particle filters

Diesel Particle filters (DPFs) are very efficient in reducing PM emissions from road diesel engines. However, they are today not widely applied for large ship engines. There can be problems with the fuel quality, back pressure over the DPFs and also with the costs. Even when DPFs function well, the maintenance costs are substantial. This is also due to ash accumulation, which needs to be physically removed from the DPF periodically.

4 Regulatory enforcement practices

Using the emission abatement technologies (Chapter 3) to comply with emission regulations leads to increased ship operational costs. This creates an incentive for non-compliance, and regular controls are therefore important. So far, legal compliance monitoring can be carried out only by the responsible authorities when sending trained inspectors onboard a vessel. Onboard inspections, so called MARPOL inspections, are usually carried out when ships are at berth.

The MARPOL inspections are labor intensive, time consuming and therefore costly. Consequently, only a small amount of ships calling a port are inspected. According to the Commission Implementing Decision (EU) 2015/253 the rate of onboard ship inspections must be 10% of the total number of individual ships calling in the relevant Member State per year (European Commission, 2015). This rate can be reduced to a minimum of 5%, when risk-based targeting mechanisms or innovative compliance verification technologies like remote sensing technologies or quick scan analyzing methods are used. Usually ships are selected for onboard inspections according to different criteria like port of departure, flag state, result of previous inspections and elapsed time since last inspection. Several remote measurement techniques have been developed within research projects like MeSMarT (www.mesmart.de), SIRENAS-R, IGPS+, SNOOP, BSR InnoShip and CompMon (www.compmon.eu) in the last years. The aim of the remote measurements is to identify potential violations according to MARPOL annex VI by measuring the ships exhaust gas composition during cruise. Based on the availability of remote measurements results in near real time, measured ships can be selected for onboard inspection (targeting method), if the values indicate a suspected violation. This reduces the number and increases the efficiency of legal onboard inspections.

The following paragraphs will introduce different approaches to enforce emission regulations. The air pollutant emissions are split in two groups: emissions of species that are mainly fuel dependent (SO_2 and PM), and those whose formation mainly depend on engine type and combustion characteristics (NO_X, HC, CO, and BC). Particle fractions can be found in any of the two groups.

4.1 Enforcement of regulations of fuel dependent pollutant emissions

Enforcement of the existing emission regulations is to a large extent dependent on the fuel sampling procedures during port state controls. The following paragraphs describes those procedures and the support to this process gained from remote monitoring of exhaust gases.

4.1.1 Onboard inspection of fuel related pollution

The amount of SO_X and PM emission depends on the Fuel Sulphur content (FSC). Therefore, the content of sulphur in the currently burned fuel oil is limited as described in Chapter 2. If a ship enters a designated ECA, it must use compliant fuel or must clean the exhaust gas with an Exhaust Gas Cleaning System (EGCS). Existing international regulations prescribe compliance through documentation on the bunkered oil, the use of oil, and monitors for SO_2 and CO_2 in the case of scrubber installations. If a ship carries and is operated on fuels of different sulphur content, any fuel shift according to the fuel changeover procedure (FCP) must be well documented in the oil record book. The FCP is a ship specific document, describing how the changeover must be carried out. Ships that are equipped with EGCS need to carry onboard relevant documentation on the scrubber systems. A SO_X Emission Compliance Plan (SECP) and certificate (SECC), an EGCS Onboard Monitoring Manual (OMM), and an EGCS Technical Manual (ETM) should be kept onboard. Further there need to be an Exhaust Gas Cleaning Record Book or Electronic Logging System (MEPC, 2015). The regulations provide two alternative schemes: Scheme A and Scheme B, where “A” relies on parameter and emission checks and “B” includes continuous monitoring of SO_X emissions.

The FSC of the fuel bunkered by the ship must be stated by the supplier on the bunker delivery note (BDN) that is always kept onboard. In addition to the BDN, which specifies at least the date of bunkering, bunkered volume, viscosity, density and the FSC, a fuel sample from the bunkering should be available onboard for inspection and laboratory analysis. This sample is often referred to as the MARPOL sample and should be stored onboard for one year. MARPOL annex VI regulation 14 (SO_X) states that the verification of the sulphur content in the used fuel can only be done by documentary inspections, onboard sampling and fuel analysis according to MARPOL Annex VI appendix VI (regulation 18.8.2) and MEPC.182(59). This is further endorsed by the EU implementing act 2015/253 article 5 and 6.

Onboard inspections are often carried out by the Port State Control (PSC) at the port of call. A common THETIS system for port state control was built to facilitate information transfer of inspections. THETIS is used by the EU

Community, Canada, Iceland, Norway and the Russian Federation which constitute the Paris MoU members. In the THETIS system it is indicated which ships have priority for inspection. Results of inspections can also be recorded and visible to the authorized users of the system (emsa.europa.eu, 2019).

A typical inspection, based on an example from BSH in Germany, could look like this: The selection of the ships that are subjected to inspection is determined by the national targeting mechanism related to the risk, as well as by the alerts that are included in the THETIS-EU system. During an onboard inspection, usually the BDN, the oil record book, and the corresponding FCP are checked first. If the ship is operated in a designated SECA, often a visual check of the fuel (temperature, color and viscosity) is done. According to vessel risk profile (suspicious activity, earlier cases of non-compliance, high result in remote measurement), fuel samples are taken at several representative locations (e.g. fuel filters, main engine, auxiliary engine). Inspectors are also allowed to take the MARPOL sample. The fuel samples are sealed and brought to a certified laboratory to determine the FSC. In case the ship is sailing before the exact result from the fuel sample analysis is available, the responsible authorities can take a safety deposit which will be refund in case the suspicion is not confirmed.

Another possibility is to use a handheld device for XRF Spectrometry. The XRF tool gives immediate indication if the bunker fuel exceeds the allowed limits. In case an exceedance is indicated, a bunker sample will be sent to laboratory. The XRF tool is used in Sweden, the Netherlands and Finland. The XRF tool is perceived as a robust tool for measurements but has the disadvantage of being quite heavy for the inspectors to carry.

4.1.2 Onboard monitoring

One possibility to monitor the compliance of vessel air emissions is the use of onboard exhaust gas measurement systems. However, currently only ships equipped with SO_X Scrubbers Scheme B must be equipped with SO_2 and CO_2 monitors. Logs from the monitoring equipment are required to be stored onboard for a specified amount of time to prove MARPOL-VI compliance when the ship is inspected (IMO resolution MEPC.184(59) 2009).

4.1.3 Remote sensing

As a complement to the onboard control procedures required by the regulations, remote sensing techniques are increasingly used to assess compliance with the sulphur regulations. In these methods the sulphur content of the burned fuel is derived from the measurement of the SO_2 to CO_2. The remote measurement results cannot be used as grounds for prosecution, this information is instead used by local authorities to select ships for legal onboard inspections (risk-based targeting). According to the Commission Implementing Decision (EU) 2015/253 the number of onboard inspections can be lowered by up to 50% when remote sensing techniques are carried out in the member state (European Commission, 2015).

As part of several national and EU projects (i.e. BSR Innoship, CompMon, Envisum) relevant instrumentation for remote sulphur-compliance monitoring of ships has been developed and demonstrated over the last 10 years. These systems have been deployed in ports, shipping lanes and the open sea. Currently, remote sensing is carried out with fast and highly sensitive in-situ trace gas monitors (exposed to diluted plume), with low cost electrochemical sensors (exposed to high concentrated plume), or with optical remote sensors (Differential Optical Absorption Spectroscopy; DOAS).

In the EU, measurements take place in UK, Belgium, Netherlands, Sweden, Denmark, Germany and Finland using fixed ground based and airborne carrier platforms, see Table 4-1. Moreover, the European Maritime Safety Agency (EMSA) offers their member states campaign based airborne measurements. Suspected non-compliant ships can be reported to the local authorities at the port of call. An alert is created in the THETIS-EU data base that all authorities have access to. More detailed information on current available remote systems for ship emission measurements will be provided in SCIPPER Deliverable 2.1.

Table 4-1. Summary of current EU MARPOL-VI remote sensing compliance measurements.

Location	Operated by	Platform	Method
BEL, North Sea/ English Channel	MUMM	Airborne (fixed wing aircraft)	In-situ (Sniffer)
North- and Baltic Sea	Chalmers	Airborne (fixed wing aircraft)	In-situ (Sniffer) + DOAS
North- and Baltic Sea	EXPLICIT	Airborne (Helicopter + UAV)	Low cost Sniffer
North- and Baltic Sea	AEROMON	Airborne (UAV)	Low cost Sniffer
Europe	EXPLICIT/ AEROMON (on behalf of EMSA)	Airborne (UAV)	Low cost Sniffer
UK, Plymouth	PML	Ground based (fixed site)	In-situ (Sniffer)
NL, Rotterdam	TNO	Ground based (fixed site)	In-situ (Sniffer)
NL, North Sea/ English Channel	MUMM	Airborne (fixed wing aircraft)	In-situ (Sniffer)
DK, Great Belt	Chalmers	Ground based (fixed site)	In-situ (Sniffer)
DK, Oresund	Chalmers	Ground based (fixed site)	In-situ (Sniffer)
SE, Gothenburg	Chalmers	Ground based (fixed site)	In-situ (Sniffer)
GER, Bremerhaven	BSH	Ground based (fixed site)	In-situ (Sniffer)
GER, Hamburg	BSH	Ground based (fixed site)	In-situ (Sniffer)
GER, Kiel	BSH	Ground based (fixed site)	In-situ (Sniffer)
FI, -1, Hamina/Kotka	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -2, Porvoo	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -3, Helsinki	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -4, Hanko	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -5, Turku	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -6, Vaasa	Kine Robot	Ground based (fixed site)	In-situ (Sniffer)
FI, -7	Kine Robot	Mobile (Boat)	In-situ (Sniffer)

The current monitoring programs as well as temporary measurement campaigns suggest that in coastal areas at the entrance to harbors the compliance rate is well above 95%. However, in certain areas at open sea within the ECA, up to 13% may be violating sulphur related limits. This indicates that the prescribed compliance documentation does not suffice. No permanent monitoring methods exist in important shipping regions such as the Mediterranean and Black Seas. In the EU, sanctions for violating the Sulphur directive are very variable because they are not harmonized. (Ringbom et al., 2017).

Current remote techniques exhibit limited sensitivity to detect slight exceedances, i.e. when FSC is in the range 0.10% to 0.20%. Onboard fuel sampling demonstrates that most non-complying ships operate on fuel within this FSC range. This can be the result of contamination from prior operation on high FSC in non-SECA regions. Identifying this type of incompliance requires more sensitive techniques than those currently available. Finally, techniques that allow open-seas monitoring are required to enforce the global cap of 0.50% FSC in 2020. New techniques, such as satellite monitoring, may be required in cases that terrestrial techniques become infeasible.

4.1.4 Differences in enforcement between European states

Similarities in the port state control procedures exist between all EU member states. The same Commission Implementing Decision (EU) 2015/253 lay down the rules concerning the sampling and reporting under the sulphur directive (EU) 2016/802 and establishes the frequency of sampling obligations for Member States of marine fuels used onboard ships (European Commission, 2015; European Commission, 2019; European Parliament and the Council, 2016a,). The European Commission issues inspection obligations for each EU country depending on the total number of individual vessels calling each country per year, aiming at obligatory inspections on 10% of these vessels. In total, the EU states have reported 49 541 fuel related inspection occasions to the THETIS database from 2015 until September 2019. Total non-compliance was found for 2 196 ships (4.4%), a number that include non-compliant ships logbooks, fuel change over procedures and records, emission abatement methods, MARPOL sample, Bunker Delivery Notes and, or, the use of high sulphur fuel (portal.emsa.europa.eu, 2019).

Differences between the PSC of Europe's different regions can relate to the different requirements on FSC but may also be influenced by other issues. The short sea shipping, i.e. maritime transport of goods between EU ports, is important for all EU sea areas. The Mediterranean Sea is the area with the largest share of freight shipping (29% of the total short-shipping tonnage), followed by North Sea (26%) and Baltic Sea (21%) for the year 2017 (Eurostat, 2019). The Mediterranean Sea further is a busy sea area surrounded by three Continents (Europe, Africa, Asia) and constitutes a crossing point between the Red Sea and the Atlantic. It serves both short-distance and intercontinental transport of goods, as well as ferry and the world's busiest cruise ship transport of passengers. Monitoring and enforcement in the Mediterranean Sea is prone to challenges, compared to the SECAs. Since the requirements of operations on low sulphur fuel are limited there is little experience of the Mediterranean state authorities of environmental regulations for compliance. Further, there are many ferries with short scheduled berth times that makes traditional compliance checking, including fuel sampling, difficult. Yet another important issue relates to the intense cruise ship activity with vested interests of cities and regions to accommodate those ships in their ports. Such interests go against efforts to mandate frequent fuel sampling in such ships. In the same line, the neighboring of several countries not covered by EU regulations creates a very versatile and environmentally uncompetitive situation. Overall, shipping is one of the strongest industries in the area serving both tourism and commerce and constitute a very sensitive area in any policy decisions. Such a background creates the complex environment on which emission enforcement in the Mediterranean Sea will have to be materialized. Similar situations may, however, to varying extents exist in other parts of the EU as well.

Information on fuel sampling procedures in Belgium, Denmark, Germany, the Netherlands, Norway, and Sweden, indicate similar procedures in these SECA countries. All countries use, or have used, remote sensing techniques, to varying extents, for indications of which ships to inspect and collect samples from. Differences instead mainly relate to the implementation of fines or other consequences of non-compliance. Most countries apply fines. The fines depend on the severity of the offence. To give a few examples the fines are based on durability of using higher than allowed FSC in Germany, engine power or engine type in Germany and Sweden, and in Denmark the fine is set considering similar environmental crime fines. Examples of ranges applied are: 100 € for minor mistakes in the documentation to 44 000 € for burning HFO for 12 hours inside a SECA without exhaust gas cleaning in Germany; between approximately 10 000 € and 61 000 € in Norway; and 470 € to 47 000 € in Sweden. Denmark is the only of the investigated countries where severe cases of non-compliance can result in a prison penalty of maximum two years. Penalties are given to the responsible person onboard the ship (ship owner, captain or chief engineer).

Another difference between countries relate to the share of visiting ships from which fuel samples should be analyzed. In Greece 20% of the inspected ships sampling and/or analysis should followed. From the 1st January of 2020, as the new sulphur regulations are effective, this percentage is increased to 30%.

Table 4-2 presents an overview of aspects related to the enforcement of the sulphur directive and for a few European countries. The number of ships that are fined for non-compliance are few. The severity of the offence is not included in the analyses. However, exceedances of the few cases in Sweden have been in a range between 0.10 and 0.12% FSC.

Table 4-2. Aspects related to the enforcement of the sulphur directive and for a few European countries ([a]European Commission, 2019)

Country	Obliged number of checks [a]	Nr of fuel checks required[a]	Remote sensing applied/Type	Actions based upon remote sensing results	No. of non-compliant ships /yr(s)	Penalty	Responsible authority
BE	552	220	YES / Aircraft sniffer applied across SECA area (Belgium, Netherlands, United Kingdom	Ships scoring above 0.15% will be visited for fuel sampling	<1%	No information available	FPS Mobility and Transport https://mobilit.belgium.be/en
DE	537	214	YES / Fixed site sniffers	Multiple fuel samples at suspected non-compliance.	No information available	Fine: 100€ - 44 000 € based on duration of violation and type of engine	The Federal Maritime and Hydrographic Agency (BSH) inspections by the Waterway police https://www.bsh.de/EN/Home/
DK	286	114	YES / Helicopters, fixed site and UAV	Inspection onboard in DK or information passed to country of destination via THETIS	No information available	Fine or up to 2 years in prison	Danish Maritime Authority https://www.dma.dk
FR	594	178	no	Not applicable	3 / 2016	No information available	Ministère de la Transition Écologique et Solidaire; Sous-direction de la sécurité maritime https://lannuaire.service-public.fr/gouvernement/administration-centrale-ou-ministere_169904
GR	490	98	YES / EMSA's UAV has been used for limited amount of hours	No information available	No information available	No information available	Ministry of Maritime Affairs and Insular Policy/Hellenic Coast Guard (HCG)
NL	803	321	YES / fixed sniffer at port entrance and MUMM	Prototype on line results of sensing. Based on results PST targets vessels for fuel sampling	No information available	No information available	Ministry of Infrastructure and water management https://english.ilent.nl/
NO	367	110	YES / drones	No information available	17 / 2015-2019	100 000 NOK – 600 000 NOK	Norwegian Maritime Authority (sdir.no, 2019)
SE	275	110	YES/fixed site sniffer	Inspection onboard in SE or information passed to country of destination via THETIS.	5 / 1 year	5 000 SEK – 500 000 SEK, based on level of exceedance and installed engine power	Swedish Transport Agency
FI	??	??	YES/Fixed site sniffer, one boat installation	??	??	??	Finnish Transport and Communications Agency

4.2 Enforcement of regulations on combustion dependent pollutant emissions

The MARPOL regulations in this category address only emissions of NO_X. The introduction of the Nitrogen Emission Control Area (NECA) in the Baltic Sea and the North Sea, aims at significant reductions of NO_X emissions from shipping. The new regulations apply to all new built ships from 2021, and onwards, in traffic in the areas. Facilitating the enforcement of this regulation, via e.g. sensor technique onboard or from remote locations, could help ensure compliance from vessels in operation.

MARPOL Annex VI regulation 13 does not provide an exclusive methodology on enforcement of NOx-compliance by PSC similar to that for SO_X. Moreover, there is no EU directive on the matter which gives more freedom to implement national enforcement methods, as e.g. potential to apply penalties for NO_X violations based on air emission monitoring.

The USEPA regulations for marine engines include also HC and CO, and so does the inland waterway regulations in EU. The new EU IWW regulations, Stage V, also includes a limit value on particle mass (PM) and particle number concentration (PN). This is described in more detail in Chapter 2.

4.2.1 Type approval documentation

Type approval is applied for both engines for marine service and inland waterway service to measure NO_X. the same cycles apply also for determining emissions of CO, HC, PM and PN from IWW engines.

MARPOL's NO_X regulations are described in the 'NO_X Technical Code 2008' (NTC). The NTC describes the surveys required including:

- a pre-certification survey to confirm compliance and if compliance is confirmed the assigned administrations can issue an 'Engine International Air Pollution Prevention' (EIAPP) certificate;
- An initial certification survey upon installation on the ship in order to account for that no major modifications are made since the pre-certification.
- Renewal, annual and intermediate surveys to ensure continuous compliance
- Surveys onboard after major conversions

The NTC further requires that a 'Technical file' accompany all marine engines onboard throughout the life-time of the engine. The 'Technical File' should be at the disposal of the appointed control administration.

4.2.2 Engine emission measurements and monitoring

Ships fitted with NO_X-reducing devices could verify compliance by onboard direct measurements according to the procedures stipulated by the Code. However, depending on the technical possibilities of the used device, other relevant parameters could be monitored. The approval testing can cover individual engines, or parent engines representing engine groups or series produced engines, so-called engine families. The NTC further requires monitoring on consumption of additional substances used for NO_X compliance, e.g. urea used in SCR treatment. This is in order to provide evidence that the consumption of such substances is consistent with achieving compliance with the applicable NO_X limit. Another option for exhaust gas after treatment, is to keep an emission certificate that covers the equipment together with the engine.

The NTC stipulates three means of onboard verification for NOx emission compliance. The simplest is an engine parameter check method that verifies that an engine's component, setting and operating values have not deviated from the specifications in the engine's technical file. The other verification methods include measurements of which one specifies the method of direct NO_X-measurements onboard the vessel.

For every individual engine, parent engine of an engine family or engine group, approval requires that emissions are measured according to specified and standardized methods and test cycles. Test cycles include tests on several engine loads, and the weighted average should not exceed the MARPOL limit value. Separate test cycles exist for main and auxiliary engines, constant or variable speed engines, and whether the propeller is operated with controllable pitch or not. The test cycles applied in NTC contain four test points for main engines: 100%, 75% 50% and 25% power, weighted 0.2, 0.5, 0.15, and 0.15, respectively. Test cycles for auxiliary engines includes more test points and the weighting is more evenly distributed over the engine loads than test cycles for propulsion engines. The NTC also requires that the specific emission at each individual mode point in the test cycle shall not exceed the applicable NO_X

emission limit value by more than 50% for a certification of a Tier III engine. Exceptions are made for low load points and idling for auxiliary engine test cycles.

The NTC also specifies how specific emissions are calculated from a measured concentration in the exhaust gas including e.g. corrections for humidity and temperature of inlet air.

Minimum requirements on contents of the 'Technical File', carried onboard together with the engine, NTC, 2008:

1. identification of those components, settings and operating values of the engine that influences its NO_X emissions including any NO_X reducing device or system;
2. identification of the full range of allowable adjustments or alternatives for the components of the engine;
3. full record of the relevant engine's performance, including the engine's rated speed and rated power;
4. a system of onboard NO_X verification procedures to verify compliance with the NO_X emission limits during onboard verification surveys in accordance with chapter 6 [of the NTC];
5. a copy of the relevant parent engine test data, as given in section 2 of appendix V of this Code;
6. if applicable, the designation and restrictions for an engine that is an engine within an engine family or engine group;
7. specifications of those spare parts/components that, when used in the engine, according to those specifications, will result in continued compliance of the engine with the applicable NO_X emission limit; and
8. the EIAPP Certificate, as applicable

The onboard monitoring for NO_X is possible but not required by international regulations. Limited experience exists for continuous monitoring of NOx emissions. In SCR-equipped vessels, either NOx sensors are used to adjust the urea injection quantity[2] or open-loop systems without NOx feedback are implemented.

Enforcement through emission measurements and monitoring from engines on inland waterway vessels have different approaches and the practices in the EU differ from those in the USA. As a part of the type approval process the EU Regulation 2016/1628 requires emission tests on engines for inland waterway vessels taking into account 10 000 hours in operation - the emission durability period. The emission levels measured after this period are used to determine a deterioration factor, which indicates emission changes over time. This procedure aims to prove that emissions will remain within the prescribed limits over the lifetime of an engine. The Regulation further specifies obligations by involved parties. Member States shall provide for penalties for infringement of this Regulation, and of the delegated or implementing acts adopted pursuant to this Regulation, by economic operators or OEMs. The penalties provided for shall be effective, proportionate and dissuasive (EU, 2016). The approach in the US is instead to use so called not "not-to-exceed" (NTE) emission limits in the monitoring. All engines of category 1 and 2 can be monitored by an emission factor that shall never be exceeded. The factor is 1.2-1.5 in Tier 1 and 2, and 1.2-1.9 in Tier 3 and 4, and is multiplied with the weighted test results of emissions over the test cycle used for certification. Category 3 engines are not subject to not-to exceed limits. All the regulated pollutants NOx, THC, CO, and PM have the same factor. The regulations are stated in the following rules: 1999 Marine Engine Rule [40 CFR Parts 89, 92][64 FR 64 73300-73373, 29 Dec 1999], 2003 Category 3 engine rule [40 CFR Part 9 and 94][68 FR 9745-9789, 28 Feb 2003]; 2008 category 1 and 2 engine rule [73 FR 88 25098-25352, 6 May 2008]; and additionally 2009 Category 3 Engine Rule for alignment with the amendments to MARPOL in 2008. This aims to assure that emissions at any engine operating conditions below an NTE limit are acceptably close to the average level of control. The difference compared to the NTC is that the NTE emission limit of the US EPA is applicable for all engine loads while the NTC limit applies only to individual mode points in the test cycle.

[2] Most probably the NOx sensor is used to correct (adapt) an open-loop (map based) control strategy.

Article 19 IWW Monitoring of emissions of in-service engines

1. The gaseous pollutant emissions from engines belonging to engine types or engine families of emission Stage V that have been type-approved in accordance with this Regulation shall be monitored by testing in-service engines installed in non-road mobile machinery and operated over their normal operating duty cycles. Such testing shall be conducted, under the responsibility of the manufacturer and in compliance with the requirements of the approval authority, on engines that have been correctly maintained, in compliance with the provisions on the selection of engines, test procedures and reporting of results for the different engine categories.

   The Commission shall conduct pilot programmes with a view to developing appropriate test procedures for those engine categories and sub-categories in respect of which such test procedures are not in place.

   The Commission shall conduct monitoring programmes for each engine category to determine to what extent the emissions measured from the test cycle correspond to the emissions measured in actual operation. Those programmes and their results shall, on a yearly basis, be the subject of a presentation to the Member States and, subsequently, of a communication to the public.

2. The Commission is empowered to adopt delegated acts in accordance with Article 55 for the purpose of supplementing this Regulation with detailed arrangements with regard to the selection of engines, test procedures and reporting of results referred to in paragraph 1 of this Article. Those delegated acts shall be adopted by 31 December 2016

Local incentive systems in Sweden and Norway on NOx reduction measures both require regular onboard emission measurements of NOx emissions. In Norway measurements is required every five years on one of the engines on a ship in the incentive program. The measurements should be done at all the load points in the applicable test cycle and weighted accordingly. For the Swedish system with rebate on the fairway due for low NO_X ships measurements were required every three years at 75% load for main engines and 50% on auxiliary engines for all engines on the ship. The emissions for the ship was then obtained by weighting the results according to engine maximum power. Measurements at SCR installations have in the Swedish system also covered ammonia slip according to specified guidelines on allowed levels (maximum 20 ppm). Also records of urea consumption are required to be kept onboard.

4.2.3 Remote sensing

Most of the fixed remote sensing stations listed in Table 4-1 are equipped with NO_X sensors as well. There are also examples of NO_X sensors placed in helicopters and UAVs for remote sensing. From the measured NO_X to CO_2 ratio in the ship's plume a NO_X emission factor in the unit of gram per kg burned fuel can be estimated. The challenge to monitor NO_X compliance from remote is to know the NO_X emission limit of an individual ship, which strongly depends on the type of engine and its current load. As an example, the NO_X emission reduction may at instances legally be reduced or switched off, even without a technical reason, e.g. below 25% load.

Also, satellites have the potential to monitor the NOX-concentration in ship lanes.

4.2.4 Examples from different countries

As far as studies have reached in the preparations of this report, it appears no schemes or sanctions are yet in place in relation to the upcoming needs for procedures and sanctions for the nitrogen oxide levels for new vessels.

The North America, which have had a NECA since 2016, reportedly mainly examine consistency of engines with EIAPP Certificate and its Supplement, the Technical File and, if applicable, the Engine Record Book. The inspection also controls that no unapproved modifications, which may affect on NO_X emission, have been made to the diesel engines and the any diesel engine which has been subject to a major conversion, as defined in regulation VI/13, has been approved. Finally, an inspection includes a verification that the ship's emergency diesel engine(s) is use only for emergencies. This is done during regular port inspections.

5 Gaps in the enforcement procedures

The following paragraphs aims at pointing out gaps in the regulatory enforcement. It separates between fuel dependent pollutant emissions and those emissions that are mainly dependent on combustion and engine characteristics. Our intention is to describe the enforcement gaps that relate to the most harmful environmental consequences. Since enforcement is tightly linked to fuels, combustion and abatement technologies there is a need also to include a description of what could be defined as regulatory gaps. This could be regulations on emissions that entail use of abatement technologies with detrimental side effects, or the design of engine type approval procedures, to give a few examples. Such regulatory gaps are in the following described separately from the enforcement gaps.

5.1 Sulphur and PM

5.1.1 Regulatory gaps

The sulphur regulations are effectively lowering the emissions of SO_2 to the atmosphere. Also, measurement studies on EGCS indicate in general good performance at proper operations. Potential gaps that became apparent in 2015 in Northern Europe relate to the placing on the market of hybrid fuel oils with low sulphur content. In water, these fuels have been shown to form stable emulsions making the oil difficult to recover at potential spills. Further, a guide or regulation on the use of hybrid fuels in the Arctic is needed when the use of residual fuels is banned in the region. **Gap**: **Regulations on other fuel characteristics than S-content are lacking.**

The international regulations do not contain limits on PM emissions relying on the relationship between decreasing particle emissions with decreasing FSC. When Sulphur limits are below 0.50%, this relationship is less apparent. This could also include limits of VOC to reduce formation of secondary aerosols. **Gap**: **Regulated limits on PM are lacking.**

The composition of particles influences their associated environmental risks. Black carbon has an impact on both global warming and health. PM (mass) can be an imprecise measure, and an elaborated PM regulation could consider for example BC emission limits. This would be a measure that approximates health and environmental risks from the particles. The measurement of the solid particle fraction BC also excludes uncertainties that arise from PM measurement related to the measurement method.
Gap: **Regulated limits of emission of the non-volatile particulate fraction BC are lacking.**

The acceptance to use EGCS to reduce SO_X emissions while burning heavy fuel oil is related to several side effects that are doubtfully in line with other regulations of the Marine Environmental Protection Committee. Two important ones are 1) scrubber emission requirements are not addressing particulate matter and measurements have concluded that particle emissions are higher at the use of HFO+scrubber than at the use of MGO in the same engine; 2) the scrubber emission requirements are not addressing toxicity of emissions to the marine environment. **Gap: Regulations on negative side effects of EGCS are lacking.**

Emissions of particulate matter in exhaust gas can be measured according to ISO standard 8178-1,2,4. Conditions that need to be fulfilled can be difficult to reach in the exhaust gas of marine diesel engines. Further, measurement standards for particle mass in cold exhaust gas, relevant for measurements downstream a wet scrubber, are lacking and makes comparisons with measurements in hot exhausts difficult.
Gap: PM emission measurement standards of emissions to air are insufficient.

5.1.2 Enforcement gaps

Remote measuring procedures are not described in the regulations. The use of remote sensing is a cost-efficient way to identifying those ships that should be targeted. Further development on the use of the technologies and prescribed approaches to their use in an enforcement context from an international perspective would possibly reduce the number of violations. Further, the conviction of a non-compliant vessel is based on the fuel sample analysis. Fuel samples are taken by inspectors (PSC, waterway police) when the ship is at berth, but not when the ship is in transit. It is not allowed to stop the ship for taking fuel samples. Hence, for a ship the probability to get a MARPOL inspection is higher when arriving at a port than when leaving or in transit.
Gap: **Regulatory prescribed approaches to the use of remote sensing technology is lacking.**

Enforcement is based on fuel sample taken on arrival in port, but not at sea or when leaving port/SECA. It is difficult or costly to prove the ships are not compliant at open sea or when leaving a port.

Gap: **Cost efficient technologies for certifying compliance at sea are lacking.**

The EGCS equipped ships are overrepresented in the statistics on non-compliant ships from remote sensing studies. The reasons to this are not fully mapped. Suggested causes for non-compliance of ships with scrubbers are: elongated commissioning periods, causing non-compliance in scrubbers during installation: badly planned fuel changes when entering the SECA causing high sulphur fuel to be burnt also in the control area; unreliable SO_2/CO_2 sensors downstream the scrubber. The last issue is related to the maintenance and calibration of the sensors. **Gap: SO_2/CO_2 ratio from EGCS logs need are possibly not reliant over time.**

5.2 NO_X and other emissions depending on combustion characteristics

5.2.1 Regulatory gaps

The international NO_X regulations have an effect that is dependent on the phasing in of new ships. Only new ships are obliged to follow current regulatory limits. The Tier III regulations further only apply in the areas defined as NECAs. These circumstances have caused a disproportionate amount of keel-laid ships in 2015, after which the North American and US Caribbean Sea NECAs were introduced and fear that ship operators will use only old ships in these areas.
Gap: **NECA geographical scopes are possibly not enough to accomplish the technology demand from the industry that would be needed to have efficient NO_X-regulations.**

The test cycles used for marine engines for NO_X and other emissions are not necessarily giving an adequate picture of the engines' operational emission performance. Modern engines can be tuned to produce low amounts of NO_X at the engine loads specified as measurement points in a test cycle. Low levels of NO_X often indicate low efficiency of combustion and therefore low-cost efficiency. The cycle could also be optimized to keep emissions over the cycle below the limit although emissions at low and medium load conditions are high. As requirements at low load and transients are low, this is a way to beat the cycle. Further, transients are not addressed in the legislative test procedure and test cycle.
Gap: **Simple legislative test procedure allows for a substantial difference between test cycle emissions and real sailing emissions, especially using modern engine technology.**
A handful of technologies can comply with the Tier III NO_X emission limits. Side effects of these technologies are not covered by existing regulations. The SCR is a mature NO_X aftertreatment technology. A downside relates to the function of an SCR over time. A potential poisoning of the catalyst could cause a system deactivation. This can also be related to the tests for inland waterway vessels in the EU, since the durability period of 10 000 hours may not be the adequate time period to include a deactivation.
Gap: Control procedures to discover SCR deactivation are missing.

Another issue with SCR technology is the potential slip of ammonia. Ammonia should be precisely dosed in order to avoid a slip, however the emissions are not regulated or controlled. NH_3 may increase over time.
Gap: **Regulation on ammonia slip over time after SCRs are lacking.**

A third issue with the SCRs is that their function is dependent on medium and high temperatures and as sulphur content of the fuel increases the regular high temperatures are crucial to avoid poisoning. This causes the SCR function to decrease during operations on low engine loads that are often used in close to shore locations. The E3 and E2 cycles start at 25% power. Due to that, the manufacturer may decide to reduce or even withhold urea injection below 25% power even if this would technically very well possible. As a result, the NO_X emissions may increase below 25% power, an operational mode that is often used in port areas.
Gap: **SCR function in port areas and other close to shore locations are not well covered by the regulation.**

Onboard NO_X-sensors for SCR urea dosing are often used. These sensors indicate that there is technology available to measure NO_X continuously over long periods of time. It is important that such sensors offer the necessary robustness and the information required to assess compliance with limits, particularly under transient or low load operation or in cases of SCR catalyst degradation.
Gap: **Knowledge of NO_X sensor performance over time.**

The EGR technology is accompanied with scrubbers in order to spare the technology from exposure to the raw exhaust gas. Scrubber water is discharged over-board causing an environmental risk to the marine environment. The problem is less than that of EGCS described above and should likely diminish as sulphur regulations are increasingly strict.
Gap: **Side effects on the marine environment from the use of EGR scrubbers are not regulated.**

EGRs similarly to SCRs have a lower efficiency at low engine loads of the engine compared to high engine loads. Modern EGR system can however work very well at low load but systems are engineered and calibrated to fit the test cycles with emphasis on high load. EGR system might also become less effective due to fouling.
Gap: **EGR function in port areas and other close to shore locations are not well covered by the regulation.**

LNG engines are yet another technology reaching the Tier III NO_X emissions levels. Many LNG engines have a slip of unburnt methane through the engine. The methane slip is unwanted from all points of view and development work has reduced the slip considerably. The LNG-engines that are not coupled to a slip are using the diesel combustion cycle, in which case the NO_X emissions are high and after treatment of NO_X will be needed to reach Tier III levels.
Gap: **No regulation limits the methane slip from LNG engines.**

5.2.2 Enforcement gaps

Importantly, only a few incentive schemes in individual countries require onboard measurements to assure compliance. The existing regulatory enforcement requirements on emissions of NO_X, HC, CO, and PN, are not including obligatory measurements during the operational phase of the engine.
Gap: **Emissions of NO_X from the operational phase are not monitored.**

The monitoring procedures for NO_X emissions almost entirely rely on engine parameter checks during PSC. The duration between the controls can be long and could include changes to the parameters that increases emissions between the controls.
Gap: **Time intervals for parameter checks are not specified.**

The not-to-exceed limit in the NTC apply only for operational mode points specified in test cycles. The USEPA regulation are covering larger operational areas defined by the speed and power relationships. Further, the NTC is not applicable to Tier I and Tier II engines.
Gap: **The applicability of the NTE limit for international shipping is small.**

NO_X enforcement on open sea is difficult or costly. Since the engine parameters are important to determine compliance with regulation, the use or remote sensing for NO_X is less straight forward than for SO_2. The available technologies could however distinguish Tier III emission levels from previous standards. The background concentration of NO_X – particularly in trafficked areas – could however be too high to determine the absolute emission levels of Tier III ships.
Gap: **Regulatory prescribed approaches to the use of remote sensing technology for NO_X emissions is lacking.**

The use of abatement equipment is difficult to control by current enforcement regulation procedures. For example. the NTC states that records of urea consumption should be kept to as a proof of the use of an SCR installation, should a ship use that to fulfil NO_X emissions regulations. This do not suffice to shoe the operation of an SCR.
Gap: **Sufficient monitoring procedures at the use of NO_X abatement equipment for Tier III is lacking.**

Identified gaps:

- Regulations on other fuel characteristics than S-content are lacking.
- Regulated limits on PM are lacking.
- Regulated limits of emission of the non-volatile particulate fraction BC are lacking.
- Regulations on negative side effects of EGCS are lacking.
- PM emission measurement standards of emissions to air are insufficient.
- Regulatory prescribed approaches to the use of remote sensing technology is lacking.

- Cost efficient technologies for certifying compliance at sea are lacking.
- SO_2/CO_2 ratio from EGCS logs need are possibly not reliant over time.
- NECA geographical scopes are possibly not enough to accomplish the technology demand from the industry that would be needed to have efficient NO_X-regulations.
- Simple legislative test procedure allows for a substantial difference between test cycle emissions and real sailing emissions, especially using modern engine technology.
- Control procedures to discover SCR deactivation are missing.
- Regulation on ammonia slip over time after SCRs are lacking.
- SCR functioning in port areas and other close to shore locations are not well covered by the regulation.
- Knowledge of NO_X sensor performance over time.
- Side effects on the marine environment from the use of EGR scrubbers are not regulated.
- EGR function in port areas and other close to shore locations are not well covered by the regulation.
- No regulation limits the methane slip from LNG engines.
- Emissions of NO_X from the operational phase are not monitored.
- Time intervals for parameter checks are not specified.
- The applicability of NTE limit for international shipping is small
- Regulatory prescribed approaches to the use of remote sensing technology for NO_X emissions is lacking.
- Sufficient monitoring procedures at the use of NO_X abatement equipment for Tier III is lacking.

6 Continued work in the SCIPPER project

As a response to the identified enforcement gaps the SCIPPER project should as far as possible address among other issues also the ones described below.

6.1 WP1 – onboard systems and signal transmission

The development of onboard exhaust gas sensors that are reliable over time in exhaust downstream EGCS or at combustion of low sulphur fuel should be included in the project. Sensors for SO_2 exist but indications are that they, together with the CO_2 sensors used for scrubber compliance control, do not measure correctly or possibly need more frequent calibration. Possibly, recommendations could also be made for a standardization of CO_2 sensors.

We have also identified a need for the development of onboard sensors for NO_X, for use in ship exhaust gas. It is important that these sensors function over time and give reliable data from all operational modes. The potential to confound the test cycle should be reduced. There is also a need to investigate if NO_X sensors could provide monitoring at the specific conditions downstream use of NO_x abatement equipment for Tier III compliance. Testing of this might however not be accomplished within the project.

The expected abatement technologies that fulfil Tier III requirements for NO_X have side effects. It would be valuable if SCIPPER could address these issues with aim to provide policy makers with state-of-the-art performance of sensors for marine use. For SCRs, NH_3 sensors are relevant. Together with a NO_X sensor, an NH_3 sensor could contribute to procedures to discover SCR deactivation. For LNG engines, CH_4 sensors are relevant to test and develop for the specifics of marine applications.

Regulations of PM are still lacking in international shipping, but discussions are ongoing in the IMO and emission standards for PM, or parts thereof can be expected. A characteristic of particles that is interesting from an environmental perspective and that is discussed in a policy context is BC. Development of BC sensors for use in marine exhaust gas would be good to include in the project.

Consideration of and the description of relevant calibration and maintenance procedures in the context of a marine application is also needed. Something that could be addressed in WP1.

Another aspect that is important for all the listed sensors in the sense of enforcement practices relate to the communication of the measured results. In order to assure compliance also at remote locations a reliable system for signal transmission is needed. It is important that the data to be reported include the relevant information but is also simple to judge and interpolate. This could also be elaborated upon in the project.

6.2 WP2 – remote measurement techniques

The remote sensing technologies for monitoring of SO_2 emissions from ships are used by many countries to facilitate directed compliance checks by PSC. The further development of sensors within this project will provide policy makers with state-of-the-art performance of sensors for marine use. Technology platforms as well as sensors are investigated. Platforms with a potential to measure at offshore locations also needs to be investigated.

Further, regulatory approaches to the use of remote sensing technology for NO_x emissions are lacking but as far as this study has concluded possible to include in enforcement regulations in individual European states from a legal perspective. The SCIPPER project can in this context provide policy makers information on the technical potential to use sensors. Remote sensing of NO_X emissions relies on relevant "not to exceed" emission limits. The existing "not- to-exceed" limits are not directly applicable for remote sensing measurements since they all require certain knowledge of the operation of the engine at the time of the emission.

Other valuable measurements from remote locations include PM and BC, in the light of expected regulations; NH_3, as a potential complement to sensors onboard at the use of SCRs; and CH_4 as a potential complement to sensors onboard at the use of LNG as fuel. These emissions all relate to combustion characteristics or operational modes and the issue of not-to-exceed limits therefore needs to be addressed for all of them.

Also, for remote sensing equipment it is important for the enforcement practices to communicate measured results. In order to assure compliance also at remote locations a reliable system for signal transmission is needed.

6.3 WP5 – Results synthesis and recommendations

The result from this report will provide input to work package 5 on synthesis and recommendations. Several of the gaps addressed in WP1 and WP2 and the findings from these studies are expected to be used in the final recommendations. Examples of this are findings on technical potential for onboard and remote sensors for all or some of SO_2, NO_X, CO_2, NH_3, and CH_4.

The regulatory approaches to the use of remote sensing will rely on a thorough comparison of different measurement techniques that have been tested and evaluated against each other. All input from other WPs should ideally contain a detailed description of what metadata is relevant in order to evaluate the values. For example, remote sensing data could be accompanied by weather data and ship parameters like type of ship, size, speed, course etc. From the tests in the WP1 and WP2, these metadata needs will be assessed. In WP1 from tests onboard ships during elongated test periods and sensor development, and in WP2 from measurements of as many ships as possible to improve knowledge on plume characteristic.

For the final recommendations it is important that aspects of the maturity and cost-efficiency of different measurement techniques are considered. A joint analysis of all findings will aim at filling the gap of providing policymakers state of the art knowledge of the technical potential to monitor emissions from ships. Recommendations on which sensors are best to be used, the signal transmission technology, and the reporting structure of the measurement data can also be an output.

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