On board monitoring of polluting emissions in sea shipping

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On board monitoring of polluting emissions in sea shipping

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Preface

This graduation thesis is the result of a research project for the completion of the Master's program Marine Technology at the Delft University of Technology. The research project has been carried out on behalf of TNO for a period of nine months. During this period I worked at the department Sustainable Transport and Logistics in the Hague.

Firsts of all I would like to thank Professor Eddy Van de Voorde and my daily supervisor Koos Frouws, for their constructive feedback and advice from the beginning of the graduation process. The feedback and the advice greatly enhanced the quality of my thesis. Secondly, I want to thank my daily supervisors Pim van Mensch and Ruud Verbeek from TNO a lot for their involvement. They helped me enormously with their experience, knowledge and feedback. Their help provided me a lot of guidance during the research project. I also appreciated the freedom and trust I received from both of you, especially during all the conversations with the stakeholders. Besides my daily supervisors of TNO, I would also express my special thanks to Dick Abma form TNO. He helped me a lot with topics that I did not know much about in the beginning. At the same time I want to express my gratitude to all the stakeholders who participated in this research.

I look back with great satisfaction on the past period with a result that I am proud of. This because the research was very aligned with my interest, which kept me enthusiastic and motivated. What I have experienced as very educational and enjoyable were the conversations with the stakeholders. Especially the different insights and interests per stakeholder that really made me think, which I enjoyed a lot.

Finally I want to thank my family, friends and everybody I have not mentioned here. I particularly want to gratitude my parents who have always supported me during my entire study time.

Robin de Jong
Den Haag, November 1, 2018

Summary

The International Maritime Organization (IMO) has been working on the reduction of emissions in sea shipping. This has been done by stricter regulations over the past years in the form of emission limits. An important element which determines the success of this reduction, is the enforcement of the emission limits. The task of the emission enforcement is assigned to the national inspection of each country. In case of The Netherlands, this is the Human Environment and Transport Inspectorate. They perform this task mainly through administrative and bunker sample checks. A drawback of the current procedure is that the inspectorate has insufficient insight in what happens at open sea or, for example, at the borders of an Emission Control Area (ECA).

TNO investigates if there are methods to improve the enforcement of emissions in shipping. Therefore, TNO started a research into an on board emission monitoring system. This report is the first step in this research and has the objective to recommend an on board monitoring system that is able to monitor pollutant emissions of seagoing vessels. The polluting emissions of seagoing vessels that are investigated in this report are: sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM) and black carbon (BC).

At the beginning of this research, a literature study has been done in order to get familiar with the above mentioned emissions, like their composition and impact on the environment and the human health. Another item that was investigated in the literature was the emission legislation of the IMO. This consisted of mapping the current and future emission limits including the associated regulations, such as the ECAs. The document that was used for this information primarily was MARPOL Annex VI (Regulations for prevention of air pollution from ships). The legislation study showed that there is no legislation for an on board emission monitoring system. This means that there is no obligation for the system in the near future. However, the IMO and the European Union want to investigate enforcement options in the future, which offers possibilities for the emission monitoring system. The legislation study therefore focused on the emission limits, so that these limits could be translated into requirements for the system. It turned out that there is no legislation for black carbon emissions in the MARPOL regulations. One of the reasons for this is that the definition of black carbon is still not officially confirmed by the IMO. At the moment, a measurement campaign is executed by the IMO to verify the definition of black carbon from Bond et al. (2013) and to define a robust measurement method. Because of the uncertainties regarding black carbon it is decided to remove this type of emission from the measurement scope of this research.

The research into the legislation has also revealed that there will be an important change in the future. Namely, the current global sulphur limit of 3.5% [m/m] will be adjusted to 0.5% [m/m] in the beginning of 2020. The consequence is that the shipping companies have to choose a strategy, so that they are compliant with this new legislation. This report shows the possibilities in the form of emission control technologies and fuels that can be chosen by the shipping companies to comply with the global 2020 sulphur regulation. The emission control technologies are: engine control technologies and after-treatment technologies (scrubbers). This is done in order to get a view on the extra emission control systems and fuels by which the on board monitoring system has to deal. These variables have been used subsequently to establish the requirements of the system.

The next step in this research was the search of possible sensors and systems that meet the requirements for an on board monitoring system. The sensors and systems were thereafter described in terms of specifications and working principles. The available systems were divided into two groups, the low-end systems and the high-end systems. The difference between the two groups is mainly based on working principles and price. It turned out that the low-end systems are not yet sufficiently developed to withstand the maritime conditions and could therefore not be used as an emission monitoring system in the near future, nevertheless they do have potential, because their low price and simple operating principle. The high-end systems showed to be suitable in the near future as an on board monitoring system. Therefore, the high-end systems were compared and assessed with each other on characteristics like: robustness, costs, accuracy, number of sample points, dimensions, emission measurement and maintenance. The assessment of the high-end systems was executed in the form of a multiple-criteria decision analysis. The on board emission monitoring system that scored the best was the Opsis M800 from Consilum. The main advantage of this system is that it operates with the UV/IR Differential Optical Absorption Spectroscopy principle. The big advantage of this principle is that the sensors

and the exhaust gas are separated, which causes much less maintenance. An additional benefit of this principle is that there is no need for a sample conditioning unit that ensures cooling and drying of the exhaust gas. The above mentioned on board emission monitoring system is therefore recommended, which means that the objective of this research is met. To improve this recommendation it will be desirable and recommended to test all the high-end systems in practice in order to determine and compare their performance for the above mentioned criteria.

Another subject that is treated in this research, is the opinion of the stakeholders towards an on board emission monitoring system. In short, it can be said that the stakeholders see potential in the system, especially with the task to create a level playing field, after the implementation of the 2020 sulphur limit. However, they also indicate that international legislation will be necessary to implement the system successfully. The shipping companies also indicated that they see potential for the on board emission system besides the enforcement task. Especially in the field of remote assistance with engine optimization as purpose.

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Abbreviations

AE	Auxiliary engine
BC	Black Carbon
°C	Degree Celsius
cSt	Centistokes
Ct	Coefficient of temperature resistance
DOAS	Differential Optical Absorption Spectroscopy
dwt	Deadweight tonnage
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EMEP	The European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
EU	Europeaan Union
Gg	Gigagram
HFO	Heavy Fuel Oil
HNO_3	Nitric acid
ILT	Inspectie Leefomgeving en Transport
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
kt	Kilotons
kWh	Kilowatt hour
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSHFO	Low Sulphur Heavy Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
ME	Main engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MRV	Monitoring, Reporting and Verification
N	Nitrogen
NDIR	Nondispersive infrared
NDUV	Nondispersive ultraviolet
NECA	Nitrogen Emission Control Area
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxide
O_2	Oxigen
PM	Particulate Matter
ppm	parts per million
rpm	revelations per minute
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SEMS	Smart Emission Monitoring System
SMO	Semiconductor Metal Oxides
SO_x	Sulphur oxide

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Introduction

1.1. Background

One of the environmental problems in Europe is air pollution caused by ships, in particular NO_x and SO_x pollution. It is even possible that these emissions from ships exceed the emissions from all other sources in the EU (Airclim, 2011). Besides this, air pollution from international shipping accounts approximately for 50,000 premature deaths per year in Europe, at an annual cost to society of more than €58 billion according to recent scientific studies. Through chemical reactions in the air, SO_2 and NO_x are converted into fine particles like, sulphate and nitrate aerosols (also known as direct particles). Besides these direct particles, ships are emitting particles such as black carbon and particulate matter (also known as secondary particles). These secondary particles are also bad for the environment and linked to premature deaths (Airclim, 2011).

One of the authorities that takes action in order to reduce the pollution of seagoing ships is the International Maritime Organization (IMO). This organization makes legislation, which should cause major health and environmental benefits for the world, particularly for populations living close to ports and coasts.

Also the European Union wants to reduce the polluting emissions as much as possible. That is why this subject is included in the Horizon 2020 programme. The horizon 2020 programme is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020) (European Commissions, 2018). One of the goals in this programme is to support the enforcement of current emissions legislation and potentially the development of future regulation and demonstrate a cost effective system to measure the airborne emissions of pollutants from a vessel under operational conditions.

Both the IMO and the European Union have the aim to reduce NO_x and SO_x emissions in shipping. Therefore, TNO wants to investigate the possibilities that may lead to a solution for such a monitoring system.

The monitoring system should make sure that, for example, port and coastal States can use the system to verify that the ship is compliant with the emission limits. In the Netherlands this is the responsibility of the Inspectie Leefomgeving en Transport (ILT). The Dutch inspection does not yet have the equipment to verify the emissions. That is why they have indicated they would like to cooperate with this research.

1.2. Objective

The objective of this thesis is to recommend an on board monitoring system that is able to monitor pollutant emissions of seagoing vessels, in relation with costs and benefits, robustness, accuracy, maintenance and future legislation for NO_x, SO_x and particulate matter/black carbon.

This objective is supported whit a number of sub-questions in order to give direction to this research. The following sub-questions are drawn up:

- What is the impact and contribution of SO_x, NO_x, PM and BC emissions from seagoing ships?
- What is the current legislation and what will be the future legislation regarding the emissions?
- What are the options for the shipowners to comply with the legislation?
- Which sensors are available for the measurement of emissions?

- Which low-end and high-end systems are available for the measurement of emissions?
- What are the options to send the data to the inspection?
- Which system is most suitable as an on board emission monitoring system?
- What is the opinion of the stakeholders according to an on board emission monitoring system?

1.3. Scope of work

The monitoring system that will be investigated in this research has to be suitable for seagoing vessels, which means that inland ships are outside the scope of this research. The monitoring of emissions of a seagoing ship could be done in several ways. One of the possibilities is to monitor the emissions by continuous monitoring on board of the ship and send the data to shore. Other possibilities are to monitor emissions with a satellite or with sniffing methods from shore when a ship enters the port, for example with a drone or a fixed station. This thesis will focus on the first option, on-board monitoring of the emissions, thus all other options are excluded. This option means that not only the measuring system is important, but also the method of monitoring and the data transmission from ship to shore.

The monitoring system should be able to monitor the following emissions: SO_x, NO_x, particle matter and black carbon. This means that all other types of emissions are excluded in this investigation. The impact of these emissions and the influence from international shipping on the total emissions will be briefly mentioned, in order to put the shipping emissions in perspective.

An important part of this research will be the current and future legislation regarding the emissions of seagoing vessels. Only the legislation for the previous mentioned emissions will be summarized. The regulations of the IMO will be leading in this thesis.

Part of this thesis will be a search to systems that are able to monitor the above mentioned emissions. This search will be a state of the art search. This means that the focus will be on the newest developments in monitoring systems. Within this search, a distinction will be made between high-end and low-end systems.

There will be a number of possible variables that affect the monitoring system, especially in the exhaust system after the engine. These variables will be researched, so that these are known before the requirement list is set up. Examples of variables are emission control technologies, like exhaust gas recirculation and exhaust gas scrubbers.

The working principles, emission components, characteristics and usage of the available systems will be described. Thereafter, an assessment on criteria such as costs, robustness, accuracy and maintenance will be made on the available systems.

Another topic that is within the scope and needs to be investigated is the data transmission, as mentioned earlier. The data regarding the emissions namely has to be transmitted to the inspection in the ideal situation.

Subsequently, there will be a consultation with stakeholders, in particular with the Dutch Inspection (ILT), ship-owners and, if possible, with suppliers of the most promising systems.

Finally, a recommendation will be made for the most suitable system and method that is capable of monitoring pollutant emissions of seagoing vessels.

2 Emissions in shipping

This chapter will describe the emissions that need to be surveyed by the monitoring system. This is done in a general form. The composition of the various emissions, will be mentioned here, in order to get familiar with the different components. This is meaningful for a next step of this research, the determination of the requirements of the monitoring system (see chapter 5). Also, the impact and the amount of the emission caused by international shipping will be illustrated in this chapter, in order to get an understanding of the consequences and to recognize the relevance of a monitoring system.

International shipping is one of the major sources of air pollution worldwide. The most principal pollutants in shipping are nitrogen oxides (NO_x), sulphur oxides (SO_x) and carbon dioxide (CO_2). Other pollutants released by seagoing vessel are particulate matter (PM) and black carbon (BC). An overview is given in figure 2.1, showing which combustion process causes the different pollutants.

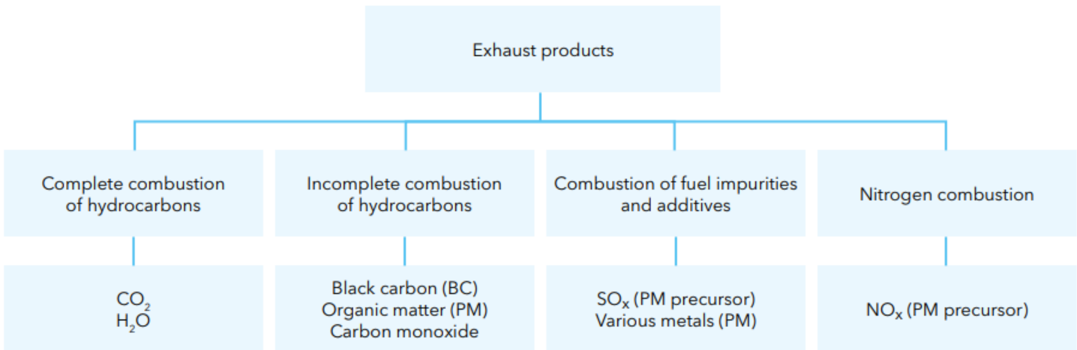


Figure 2.1: Exhaust gas products (DNV GL, 2016)

A reasonable number of studies has been carried out to NO_x, SO_x and PM emission in shipping. This results in sufficient available data and knowledge about these emissions. In the case of BC, there seems to be a lack of knowledge about the contribution that shipping makes to the overall BC emissions. This will be discussed later on in this chapter.

The overall impact of emissions from shipping on climate are complex. Nevertheless, (Lee et al., 2009) summarized the impact of shipping emissions in a conceptually form (see figure 2.2).

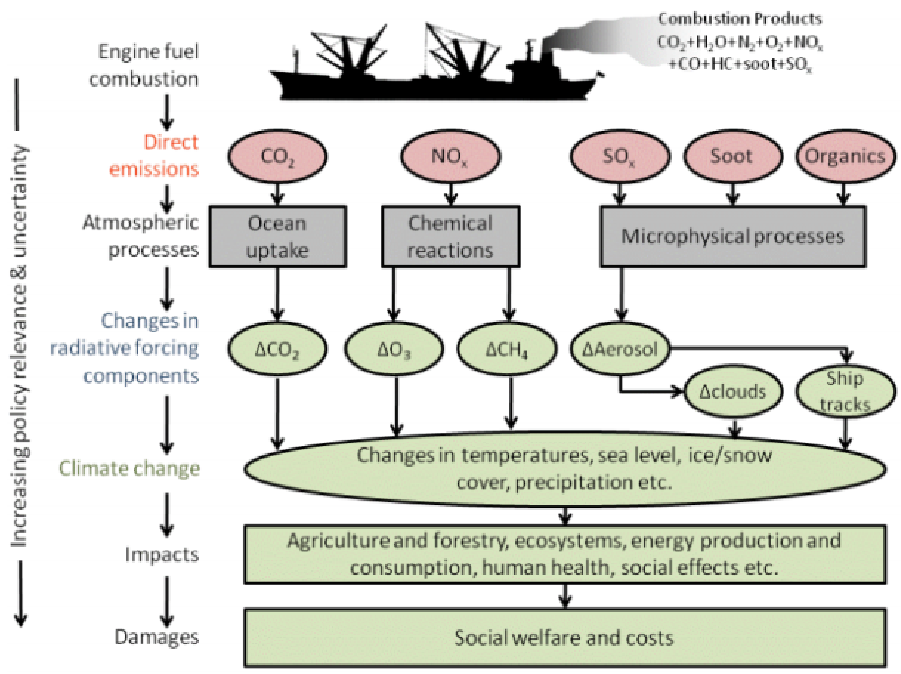


Figure 2.2: Schematic diagram of the overall impacts of emissions for the shipping sector (Lee et al., 2009)

Figure 2.2 shows that the combustion products of ships are causing changes in the following matters, namely: surface temperature, sea level, snow and ice cover, precipitation, etc. In turn, these physical impacts have societal impacts through their effects on agriculture, forestry, energy production and human health. This results in social welfare and costs.

2.1. Nitrogen oxides

Air and fuel need to be mixed during the combustion process of the marine diesel engine. Dry air consists of approximately 21% oxygen (O_2), 78% nitrogen (N_2) and small amount of other gases. The marine fuels, like HFO and MDO, are a complex mix of hydrocarbons. The NO_x emissions that are released by the diesel engine of a ship consists of roughly 95% nitric oxide (NO) and 5% nitrogen oxide (NO_2). It should be noted that the formation rate between the nitrogen oxides depend on peak temperatures of the engine (Latache, 2018).

The NO_x emissions are effecting the environment on several points. The NO_x reacts with ammonia and other compounds, which results in nitric acid (HNO_3) vapor and other small particles. These small particles can deeply penetrate into human lungs and damage it. In the most extreme cases it can lead to premature death. The inhalation of these fine particles may also cause or worsen bronchitis and emhysema and may also aggravate existing heart disease. Furthermore, the NO_x reacts with volatile organic compounds causing ozone in the presence of sunlight (Bobnar, 2018).

The IMO has performed a study to NO_x emissions from international shipping in 2009 (MEPC, 2009). The study shows the NO_x emissions over a period from 1990 to 2007 (see table 2.1). The values in the table are based on the fuel consumption of the international fleet in combination with emission factors.

Table 2.1: NO_x exhaust emissions (million tonnes) from international shipping, 1990–2007 (MEPC, 2009)

Period	1990-1992	1993-1994	1995-1996	1997-1999	2000-2002	2003	2004	2005	2006-2007
NO_x	12	13	14	15	16	17	18	19	20

The NO_x emission of international shipping have been increased since 1990, as can be seen in table 2.1. The increase that can be seen is due to the fact that the number of ships has increased in those years. The expectation is that the NO_x emission from international shipping will expand further, if there is no intervention in the form of legislation. Additional to this, the NO_x contribution of international shipping is estimated around 15% of global emissions (Eyring et al., 2005).

Figure 2.3 shows the estimated NO_x emission trends from international shipping in Europe (Norwegian Meteorological Institute, 2015). In this figure can be seen that the NO_x emission increased since the year 2000. There has been a decrease of NO_x emissions in the Baltic Sea and the North Sea after 2006 and 2011. The decrease of NO_x is not explained by the Norwegian Meteorological Institute. The most likely reason for this is the side effect of the SO_x emissions control area in these seas (see section 3.2).

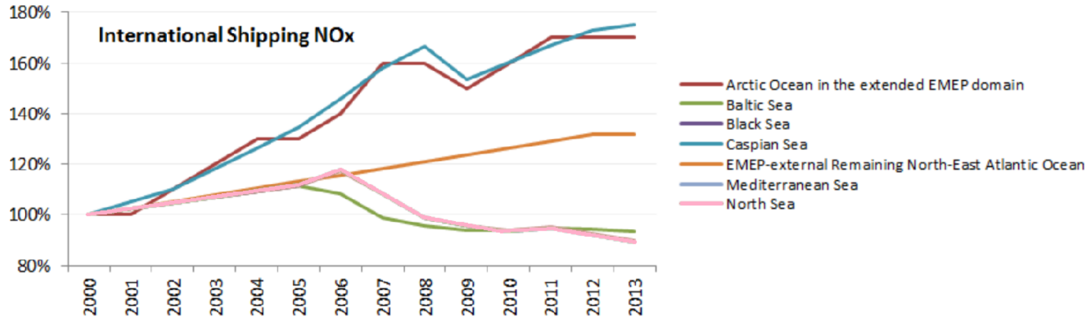


Figure 2.3: International shipping NO_x emission trends in Europe (Norwegian Meteorological Institute, 2015)

In the past few years, there have been several studies to NO_x emissions of ships. Especially a lot of research has been carried out to the Baltic Sea and the North Sea. The reason for this is that the countries around these seas are paying attention to the emission problem and therefore investigating the possibilities to establish a NO_x emission control area (NECA). An overview with the amount of NO_x emission for the North Sea and the Baltic Sea is made, as shown in table 2.2.

Table 2.2: Overview studies NO_x emissions in the North Sea and the Baltic Sea

Study	**Year of inventory**	**North Sea [ktonnes]**	**Baltic Sea [ktonnes]**
(Campling et al., 2013)	2005	518	220
(Kalli et al., 2013)	2009	878	
(Hammingh et al., 2012)	2009	427	314
(Norwegian Meteorological Institute, 2015)	2010	635	267
(Jonson et al., 2014)	2011	677	337
(Norwegian Meteorological Institute, 2015)	2013	644	271

This overview gives a valuable indication of the amount of NO_x caused by international ships in these seas. To put these emissions into perspective with other sources, figure 2.4 is included (Airclim, 2011). In this figure the emissions for NO_x are calculated under a business-as-usual scenario. According to this study it is expected that the NO_x emissions will enlarge by 40% towards 50% between the year 2000 and 2020. The expectation is that under this scenario, the NO_x emissions from international shipping around Europe will be equal or even surpass the total from all land-based sources in the 27 EU member states combined.

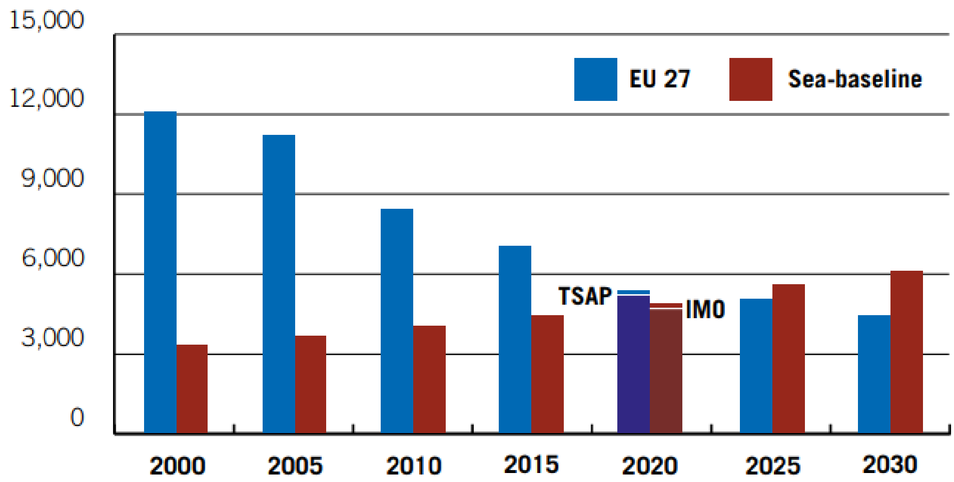


Figure 2.4: Emissions of NO_x 2000–2030 [ktonnes], (Airclim, 2011)

It can be concluded that it will be necessary to decrease the NO_x emissions from international shipping in order reduce the gap with respect to all other sources, as can be seen in figure 2.4. The on board monitoring system will be an option to achieve NO_x reduction in international shipping in the future. Also, the future legislation will play a crucial role to achieve this reduction.

2.2. Sulphur oxides

The sulphur oxides emissions are directly related with the sulphur content in fuel. During the combustion process of the fuel, the sulphur is oxidized in the combustion chamber. Which results in sulphur dioxide (SO_2) and sulphur trioxide (SO_3). The ratio between the (SO_2) and (SO_3) is generally 15:1. Thus, the SO_2 components emitted by ships are the most significant and have therefore the greatest impact on the environment. One of the environmental effects of SO_2 in the air is the contribution to acid rain. Another effect is that SO_x particles can react with other compounds in the atmosphere. Due to this, small new particles are formed. These small particles contribute to the formation of particulate matter (EPA, 2018a).

The European Monitoring and Evaluation Programme (EMEP) is a programme with the ambition to solve the transboundary air pollution problems in Europe. The programme is collecting emission information since 2010. One of the emissions that is collected by the EMEP are the sulphur oxides (SO_x). The EMEP also investigated the amount of SO_x emissions from international shipping in different European Seas (Baltic Sea, Black Sea, Caspian Sea, Mediterranean Sea and the North Sea). The results of this study are presented in the EMEP status report 1/2015 (Norwegian Meteorological Institute, 2015). Figure 2.5 is derived from this report and shows the international shipping SO_x emission trends over a period from 2000 until 2013 for the above mentioned European seas.

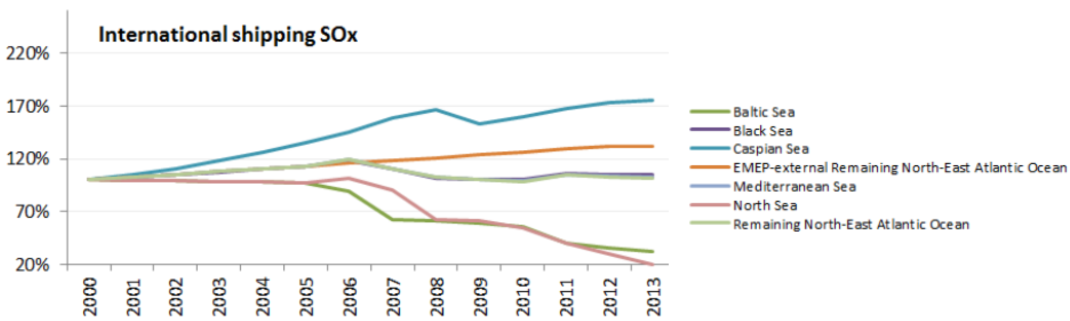


Figure 2.5: International shipping SO_x emission trends in Europe (Norwegian Meteorological Institute, 2015)

Figure 2.5 shows that there is a drop in sulphur emissions in some areas after 2006. This drop is caused by the impact of the economic crisis. Shipowners decided in that period to save fuel by slow steaming. Especially a drop in SO_x emissions can be noticed in the Baltic Sea and the North Sea. The reason for this drop is the implementation of the Emission Control Area by the IMO (see section 3.4).

Table 2.3 is included in this section to give an impression of the amount of sulphur emission emitted by ships. This table 2.3 shows the estimated sulphur emissions per ship type in the Baltic Sea, the North Sea and the English channel. The table is part of a study to long term emission projection (Kalli et al., 2013). It is clearly shown when the legislation has been implemented (see section 3.7).

Table 2.3: Estimated SO_x emissions of different ship types [ton] until 2015 (Kalli et al., 2013)

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Crude oil tanker	18,428	14,754	11,397	11,348	11,299	11,251	1,375
LPG tanker	4,155	3,279	2,466	2,456	2,445	2,435	340
Chemical tanker	27,792	21,986	16,605	16,534	16,463	16,392	2,245
Product tanker	7,604	6,017	4,546	4,526	4,507	4,488	616
Bulk ship	17,310	13,748	10,465	10,420	10,375	10,331	1,361
Container	62,793	51,196	38,987	39,443	39,905	40,373	5,492
LNG tanker	758	614	483	481	479	477	52
Ropax	58,461	46,810	36,452	36,166	35,882	35,601	4,582
Ro-ro	24,940	20,081	15,764	15,640	15,518	15,396	1,894
Vehicle carrier	9,165	7,292	5,632	5,587	5,544	5,500	668
General cargo	31,650	25,127	18,737	18,776	18,816	18,856	2,774
Cruise ship	8,951	7,212	5,632	5,588	5,544	5,500	615
Reefer	5,945	4,683	3,547	3,520	3,492	3,465	463

2.3. Particulate Matter

Particulate matter (PM) is a term for a mixture of liquid droplets and solid particles in the air. PM is categorized in three different scales, namely:

PM_{10}: particles with a diameter smaller than 10 micrometers and bigger than 2.5 micrometers.

$PM_{2.5}$: particles with a diameter smaller than 2.5 micrometers and bigger than 1 micrometers.

PM_1: particles with a diameter of 1 micrometers and smaller.

Figure 2.6 is shown in order to get a feeling of the size of PM_{10} and $PM_{2.5}$. The fine particles, like the $PM_{2.5}$, can be inhaled by humans. Inhaling particles smaller then 10 micrometers can cause serious health problems, because the particles get deep into your lungs, and some may even get into your bloodstream (EPA, 2018b).

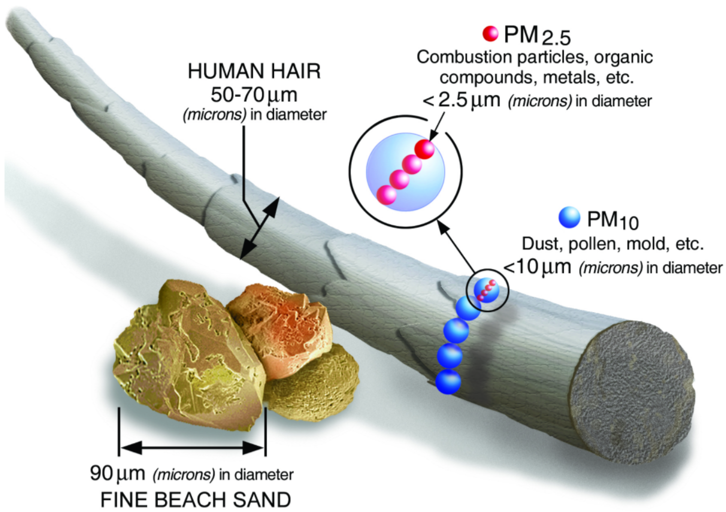


Figure 2.6: Size comparisons for PM Particles (EPA, 2018b)

The PM emitted by ship engines consists of sulphur, black carbon, organic carbon, inorganic compounds containing Ca, Ni, V, Zn and other metals associated with water (Agrawal et al., 2008), (Petzold et al., 2008), (Moldanová et al., 2009).

As described above, PM is a complex mixture of organic and inorganic compounds. The formation of PM depends on various factors, such as (Lamas and Rodríguez, 2012):

- Incomplete combustion
- Partly unburned lube oil
- Ash in the fuel and lube oil
- Thermal splitting of hydrocarbons from the fuel from the fuel and lube oil
- Sulphates
- Water

The contribution of particulate matter emissions of each sector is studied by Klimont et al. (2017). According to Klimont, this study was the first study that estimated the PM emissions using a uniform and consistent framework. Klimont estimated the PM emissions of each region and per sector for the year 2010. The results of the sectoral emissions are displayed in table 2.5. A percentage overview is made for PM_{10}, $PM_{2.5}$ and PM_1 of this table in figure 2.7. This overview is made in order to know the PM emissions content of international shipping relative to other sectors. This overview consists of all anthropogenic sources, so without forest and savannah fires. It can be seen in figure 2.7 that the PM emissions from international shipping contribute for about 3-4% of the global total. The total PM contribution of international shipping in the year 2010 was 5226 gigatonnes, so there is still a lot to be gained.

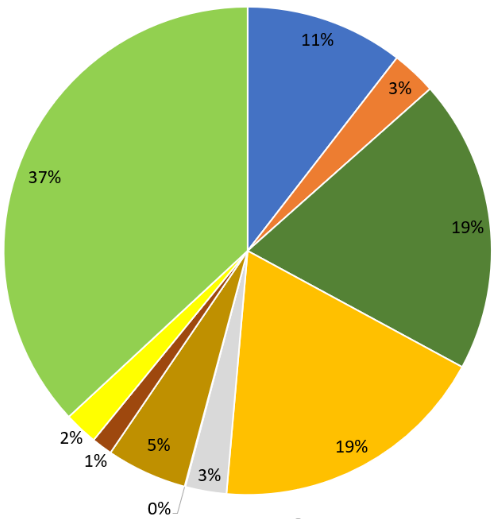
Kalli et al. (2013) investigated the emissions of shipping in the European Emission control area. Kali also estimated the $PM_{2.5}$ emissions per ship type in this area. The result of this can be seen in table 2.4. This table shows that the estimated $PM_{2.5}$ for the year 2015 is considerably lower compared to previous years. This is due to the legislation (see chapter 3). Furthermore, it can be seen that ropax, ro-ro and cruise ships are emitting substantially more PM than other ship types. These type of ships consume a large amount of hotel power, which will probably be the reason for the higher PM emission.

Table 2.4: Estimated $PM_{2.5}$ emissions [ton] of different ship types until 2015 (Kalli et al., 2013)

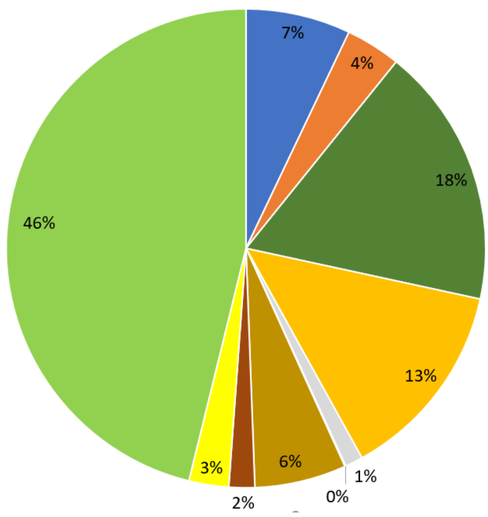
	2009	**2010**	**2011**	**2012**	**2103**	**2014**	**2015**	**ships**	**avg. ship**	**share [%]**
Crude oil tanker	4447	3909	3429	3414	3399	3385	1480	835	4.01	5.0
LPG tanker	1087	952	830	826	823	819	390	266	3.08	3.8
Chemical tanker	6729	5899	5148	5126	5104	5082	2391	1715	2.96	3.7
Product tanker	1845	1617	1411	1405	1399	1393	660	530	2.62	3.3
Bulk ship	4098	3596	3145	3131	3118	3104	1419	2316	1.33	1.7
Container	15383	13899	1217	12313	12457	12603	5917	1466	8.26	10.3
LNG tanker	203	179	158	157	156	156	63	61	2.51	3.1
Ropax	12557	11019	9722	9646	9570	9495	4346	433	21.89	27.4
Ro-ro	5392	4725	4165	4132	4100	4067	1773	273	14.84	18.5
Vehicle carrier	2167	1892	1660	1647	1634	1621	703	446	3.63	4.5
General cargo	7,329	6,488	5,649	5661	5673	5685	2806	3350	1.68	2.1
Cruise ship	1862	1633	1434	1423	1412	1401	578	127	10.96	13.7
Reefer	1419	1236	1080	1071	1063	1055	485	472	2.24	2.8
Total	**64518**	**57044**	**50002**	**49952**	**49908**	**49866**	**23011**	**12290**		

Table 2.5: Sectoral emission overview of PM in the year 2010 (Klimont et al., 2017)

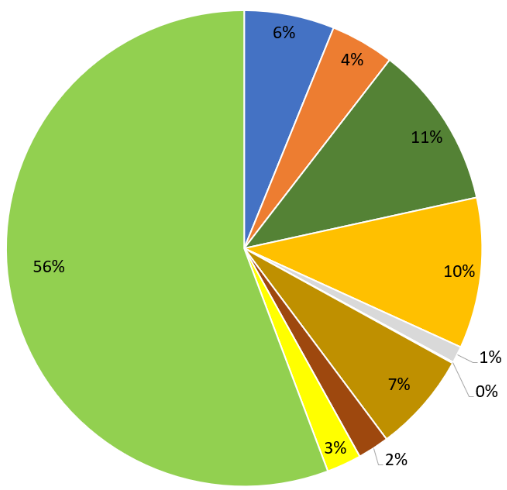
Sector	**PM_{10} [Gg]**	**$PM_{2.5}$ [Gg]**	**PM_1 [Gg]**	**Legend color**
Agriculture	6555	3348	2283	
International shipping	1856	1758	1612	
Residential combustion	23078	21857	20742	
Industrial processes	12162	8340	4135	
Large-scale combustion	11561	6420	3812	
Oil and gas, mining	1706	571	421	
International aviation	30	30	28	
Transport – road	3339	2925	2524	
Transport – non-road	861	823	795	
Waste	1388	1272	876	
Global anthropogenic	62537	47843	37819	×
Forest and savannah fires	48207	33014	33014	×
Global total	110744	80857	70833	×



(a) PM_{10}



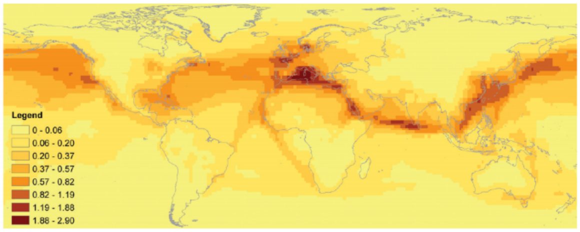
(b) $PM_{2.5}$



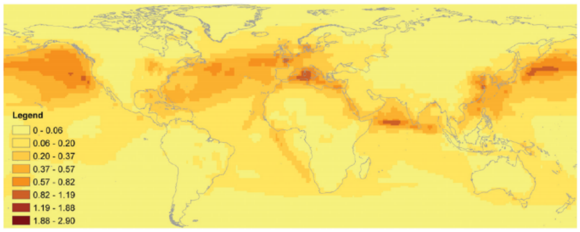
(c) PM_1

Figure 2.7: Sectoral emission overview of PM in the year 2010 in % (Klimont et al., 2017)

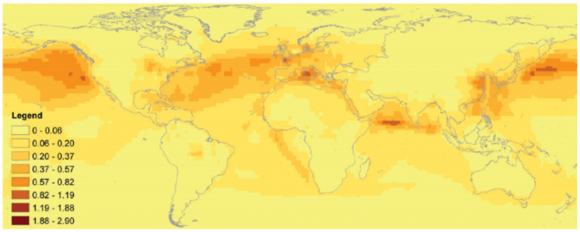
In the past, some studies has been carried out into impacts of pollution from oceangoing shipping. One of these studies investigated the changes in premature mortality due to emissions from ships under several sulphur emissions control scenarios (Winebrake et al., 2009). This study compared four different scenarios for the year 2012. One of the scenarios was a no control scenario, assuming 2.7% sulphur content in the fuel. The other three scenarios were with emission control. One scenario assumed that the marine fuel is limited to 0.5% sulphur content and the other assumed a 0.1% sulphur content in the fuel. The fourth control scenario represented a global limit of 0.5% sulphur content in the fuel determined the worldwide concentrations of $PM_{2.5}$ from oceangoing vessels and used this $PM_{2.5}$ in lung cancer and cardiopulmonary concentration-risk functions and population models, in order to estimate the annual premature mortality (Winebrake et al., 2009). Figure 2.8 shows the $PM_{2.5}$ concentration worldwide caused by oceangoing vessels for the four scenarios, the data in micrograms per cubic meter. Figure 2.9 shows the annual premature mortality for the no control scenario or the annual avoided premature mortality for the other scenarios.



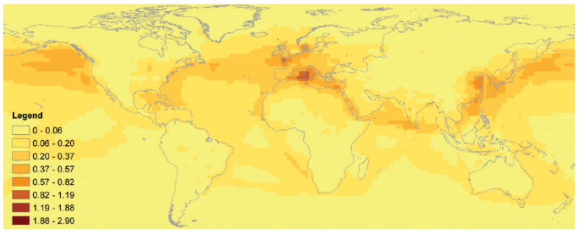
(a) No control scenario global 2.7% sulphur



(b) Control scenario coastal 0.5% sulphur

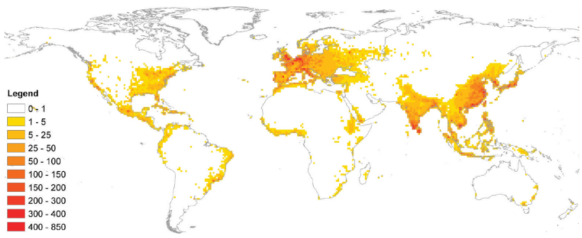


(c) Control scenario coastal 0.1% sulphur

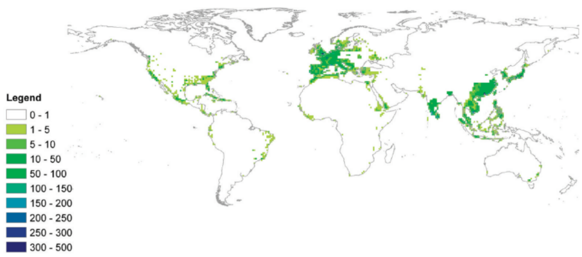


(d) Control scenario global 0.5% sulphur

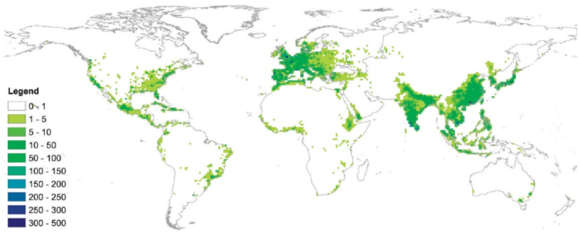
Figure 2.8: Concentrations of $PM_{2.5}$ for the four scenarios (Winebrake et al., 2009)



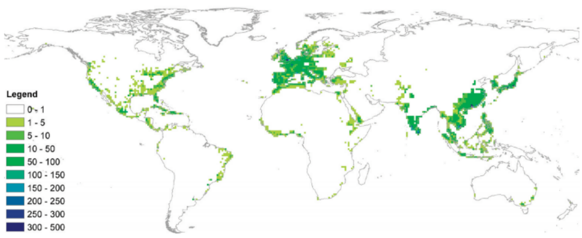
(a) Annual premature mortality for the no control scenario global 2.7% sulphur



(b) Annual avoided premature mortality for the control scenario coastal 0.5% sulphur



(c) Annual avoided premature mortality for the control scenario coastal 0.1% sulphur



(d) Annual avoided premature mortality for the control scenario global 0.5% sulphur

Figure 2.9: Mortality for the four scenarios (Winebrake et al., 2009)

The sulphur content in the fuel is from great importance for the emission of $PM_{2.5}$, just like the emission control areas as can be seen in figure 2.8. For example, figure 2.9a shows that there will be a lot more premature morbidity if there is no intervention. This indicates that it is necessary that measures must be taken. Here the monitoring system could play a supporting role.

2.4. Black carbon

Black carbon (BC) is a component of particulate matter with a diameter smaller than 2.5 µm. BC is formed trough the incomplete combustion of fossil fuels, biofuel and biomass. Figure 2.10 gives a valuable overview of the possible sources of BC and the effects on the climate (Bond et al., 2013).

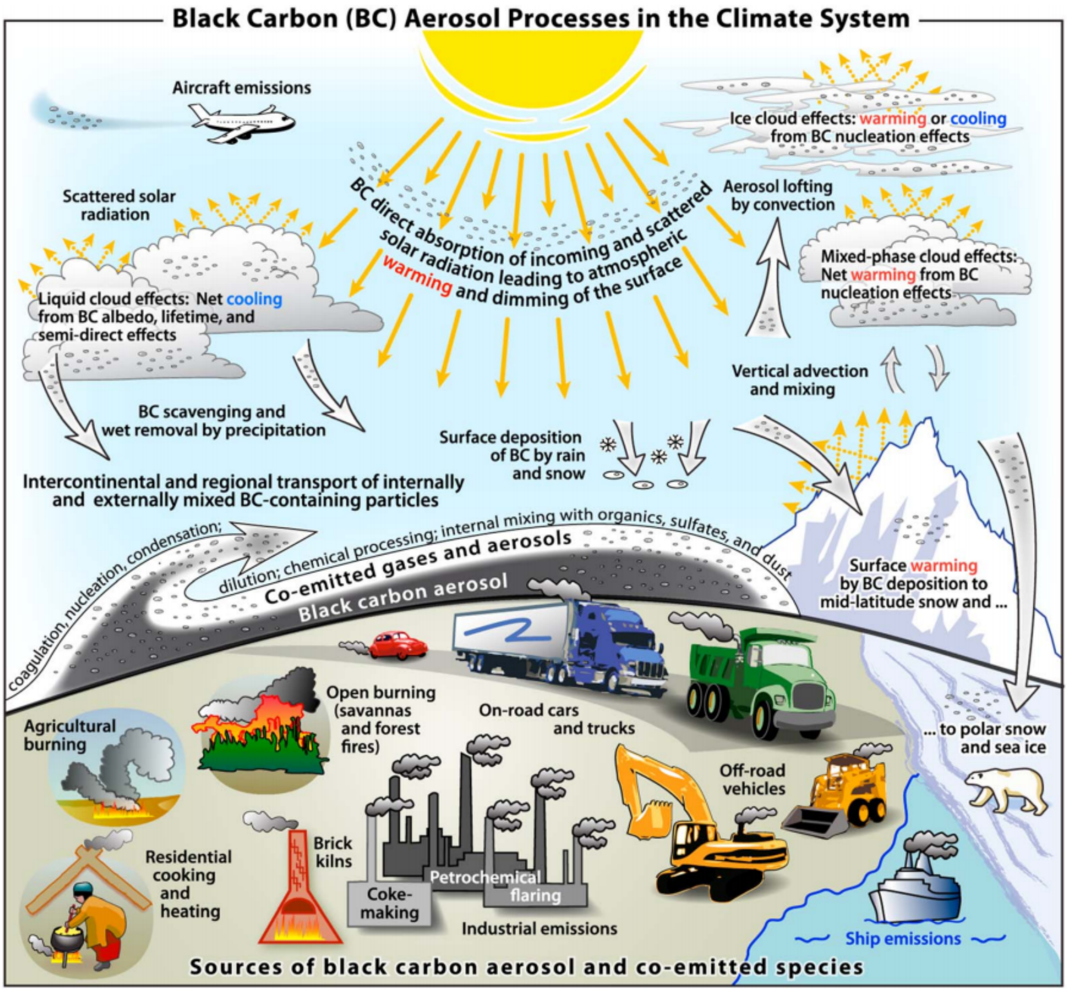


Figure 2.10: Schematic overview of the primary black-carbon emission sources and the processes that control the distribution of black carbon in the atmosphere and determine its role in the climate system (Bond et al., 2013)

More and more research is done the last few years into black carbon. One of the reasons for this is the increasing public attention for BC, because it affects the climate and human health. This public attention is fueled by the fact that the plumes of a ship are more often visible to crowded public areas. See figure 2.11a for an example of an arrival of an enormous cruise ship in the city center of Rotterdam. Another topic that gets attention in the news is the BC pollution on the Arctic (see figure 2.11b).

(a) Emission of a cruise ship in the city center of Rotterdam (NOS, 2018)

(b) Black carbon on the Arctic (Ostrander, 2018)

Despite all the attention for BC, there seems to be a lack of knowledge about the contribution that shipping makes to the worldwide anthropogenic emissions. According to (Klimont et al., 2017) the total BC emission is 9532 Gg in the year 2012, this includes forest and savannah fires, see table 2.6. This study has revealed that international shipping is responsible for 2% of the total global anthropogenic BC emission (see figure 2.12).

Table 2.6: Sectorial emission overview of black carbon in the year 2010

Sector	**[Gg]**
Agriculture	337
International shipping	120
Residential combustion	4163
Industrial processes	462
Large-scale combustion	136
Oil and gas, mining	226
International aviation	10
Transport – road	1349
Transport – non-road	363
Waste	97
Global anthropogenic	7264
Forest and savannah fires	2268
Global total	9532

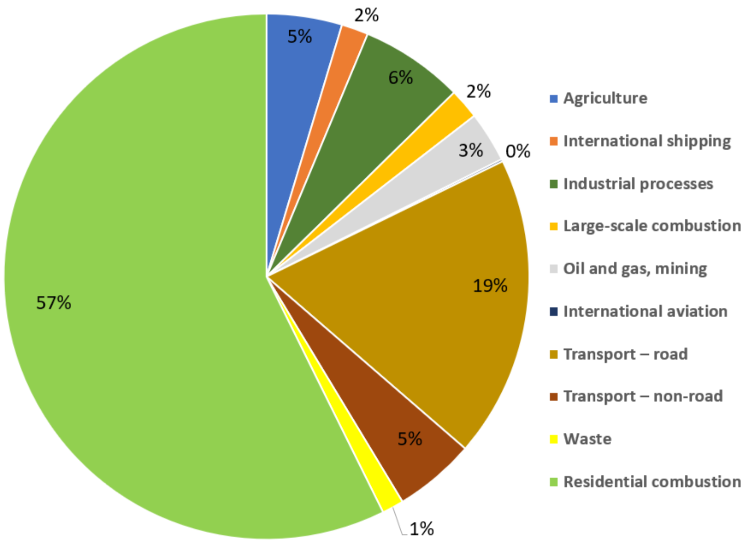


Figure 2.12: Sectoral emission overview of black carbon in the year 2010 in %

There are different definitions of black carbon in the scientific literature. The most prevailing definition of black carbon is from Bond et al. (2013), which suggested the definition in 2013. The IMO executes a measuring campaign in order to verify this definition at the moment. The definition reads as follows:

1. It strongly absorbs visible light with a mass absorption cross section of at least 5 m^2/g at a wave length of 550 nm.
2. It is refractory; that is, it retains its basic form at very high temperatures, with a vaporization temperature near 4000 K.
3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol.
4. It exists as an aggregate of small carbon spherules.

3
Legislation

This chapter will describe and summarize the most relevant legislation for this research. Section 3.1 will start with a description of the authorities that are involved in the legislation. These authorities that will be mentioned are responsible for drafting the legislation or for the enforcement of the legislation.

The legislation in this chapter is mainly from the International Convention for the Prevention of Pollution from Ships, also known as MARPOL (IMO, 2011). Especially, MARPOL Annex VI (Regulations for prevention of air pollution from ships) is used. Parts of this annex are included in appendix B. It is important to know that the legislation that will be described in this chapter will consist mainly of emission limits. This is because the fact that there is no legislation for an on board monitoring system at the moment, as mentioned earlier.

The IMO makes use of emissions standards, which are commonly referred to as Tier I, Tier II or Tier III standards. The Tier I standards were defined in the 1997 of Annex VI, while the Tier II and Tier III were introduced in the same annex in 2008. These Tier standards will be frequently mentioned in this chapter.

3.1. Authorities

This section will describe the authorities that are responsible for the legislation or involved with the legislation for international shipping. The most important authority in international shipping is the International Maritime Organization (IMO). This organization will be briefly described in section 3.1.1. Another important authority regarding the regulations is the European Commission of the European Union (see section 3.1.2). Within the Netherlands, the Inspectie Leefomgeving en Transport is held responsible for the enforcement of the regulations and will therefore be described briefly in section 3.1.3.

3.1.1. International Maritime Organization

The International Maritime Organization(IMO) is a United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. The main role of the IMO is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and implemented.

In other words, the role of the IMO is to create a level playing-field, so that ship operators cannot address their financial issues by simply cutting corners and compromising on safety, security and environmental performance. A direct result of the level playing-field is that it encourages innovation and efficiency (IMO, 2018).

MARPOL

In 1973 IMO convened a major conference to discuss the problem of marine pollution from ships. It resulted in the adoption of the first ever comprehensive antipollution convention, the International Convention for the Prevention of Pollution from Ships (MARPOL).

This Convention deals not only with pollution by oil, but also pollution from chemicals, other harmful substances, garbage, sewage and, under Annex VI adopted in 1997, air pollution and emissions from ships. A revised Annex VI was adopted in 2008 and it entered into force in 2010, phasing in a progressive reduction in sulphur oxide (SO_x) from ships and further reductions in nitrogen oxide (NO_x) emissions from marine engines (IMO, 2013). The regulations according the emissions from ships will be mentioned and described in the remainder of this chapter.

3.1.2. European Commission

The European Commission is the executive of the European Union (EU) and promotes its general interest. The Commission is the sole EU institution tabling laws for adoption by the parliament and the council that (European Union, 2018):

- protects the interests of the EU and its citizens on issues that can not be dealt with effectively at national level;
- get technical details right by consulting experts and the public.

The European Commission has started the biggest European Research and Innovation program ever with nearly €80 billion of founding available over 7 years (2014 to 2020), the name of this program is Horizon 2020 (European Commissions, 2018). Within Horizon 2020 a work program has been drawn up. The overall objective of this program is to achieve a European transport system that is resource efficient, resilient climate- and environmentally-friendly, safe and seamless for the benefit of all citizens, the economy and society (European Commissions, 2017c). The increased focus on innovation is one of the standout features so far of Horizon 2020, but there is still more to do, including addressing regulatory barriers to innovation, building synergies with other EU instruments and giving special attention to market-creating innovation (European Commissions, 2017b).

The research assignment of this thesis is indirectly formulated by the European Commission. Namely, the Horizon 2020 Work Program 2018-2020 describes a comparable objective in Chapter LC-MG-1-1-2018: InCo flagship on reduction of transport impact on air quality is implemented in the form of a proposal. This reads as follows (European Commissions, 2017a):

D) Cost effective enforcement of shipping related emissions legislation, both at the EU and global level, is essential for the expected environmental improvements to be achieved. To support the enforcement, assess their effectiveness and to identify potential future gaps it is necessary to develop, evaluate and demonstrate cost effective systems to measure the airborne emissions of pollutants from a vessel under real operational conditions (e.g. using on board systems) and to target ships for inspection and the enforcement of emission limits.

3.1.3. Inspectie Leefomgeving en Transport

The Inspectie Leefomgeving en Transport (ILT) monitors and encourages compliance with both national and European legislation and regulations in favour of a safe and sustainable human environment and a safe and sustainable transport. The activities of the inspectorate focus on good provision of services, fair enforcement and appropriate detection. If appropriate this is executed in collaboration with other inspectorates, this collaboration is risk-driven and based on mutual trust with the supervised organization. Policy-makers determine the rules; people and businesses are responsible for compliance and the inspectorate monitors and enforces(ILT, 2018).

The European legislation and regulations for shipping have been applied to the Dutch Ships Act. This act is applicable to all seagoing vessels sailing under the Dutch flag. It focuses on the safety of the ships, their operations and their cargo.

In the field of shipping, ILT monitors vessels that are sailing under the Dutch flag, foreign vessels, crews and shipping companies and classification societies. Vessels sailing a foreign flag are regulated in accordance with the Paris Memorandum of Understanding on Port State Control.

3.2. Emission Control Areas

The IMO has defined special Emission Control Areas (ECA) under MARPOL Annex VI "Regulations for the Prevention of Air Pollution from Ships". These ECA were devised to regulate emissions from ships. The objective of these areas is to prevent, reduce and control air pollution from NO_x and/or SO_x and/or particulate matter (PM) and their attendant adverse impacts on human health and the environment. Worldwide there are four ECA, namely:

- North Sea
- Baltic Sea
- North America
- United States

These four ECA, in combination with the corresponding type of emission, can also be seen in figure 3.1. More details are shown in appendix A. Important to know is that Emission Control Areas, where nitrogen emission limits are applicable are also known as NECA. Emission Control Areas where sulphur limits are applicable are also known as SECA. These abbreviations will return in the remainder of this report.

Figure 3.1: IMO Emission Control Areas (Hall, 2018)

3.3. Nitrogen oxide - Regulation 13

This section will describe the regulations for nitrogen oxides (NO_x) emissions in shipping. This is done using MARPOL Annex VI (Regulations for the prevention of air pollution from ships) (IMO, 2011) and the NO_x technical code (Marine Environment Protection Committee, 2008). Particularly, regulation 13 from MARPOL is used for this section. The full version of this regulation can also be read in annex B.1 of this report. The purpose of the NO_x technical code is to specify the requirements for the testing, certification and on board verification procedures of the marine diesel engine to demonstrate compliance with the applicable NO_x limits as mentioned in regulation 13 (see next paragraph).

The most relevant legislation in regulation 13 is about the maximum allowed amount of NO_x emissions. This regulation applies for ships that engaged in international voyages and of 400 gross tonnage and above. The maximum amount of NO_x emissions has been established in the Tier standards, as described in the beginning of this chapter. The maximums are dependent on the speed of the engine. An overview is made for the NO_x limits within the different Tier standards (see table 3.1). These limits are applicable for all installed marine diesel engines of over 130 kW output power.

Table 3.1: MARPOL Annex VI NO_x emissions limits (IMO, 2011)

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		$n < 130$	$130 \leq n < 2000$	≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{-0.2}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	1 January 2016	3.4	$9 \cdot n^{-0.2}$	2.0

The Tier III NO_x control is only applied to the specified ships while operating in Emission Control Areas, outside such areas the Tier II control applies.

Figure 3.2 shows the NO_x limit plotted against the rpm of the engine for the different Tier standard.

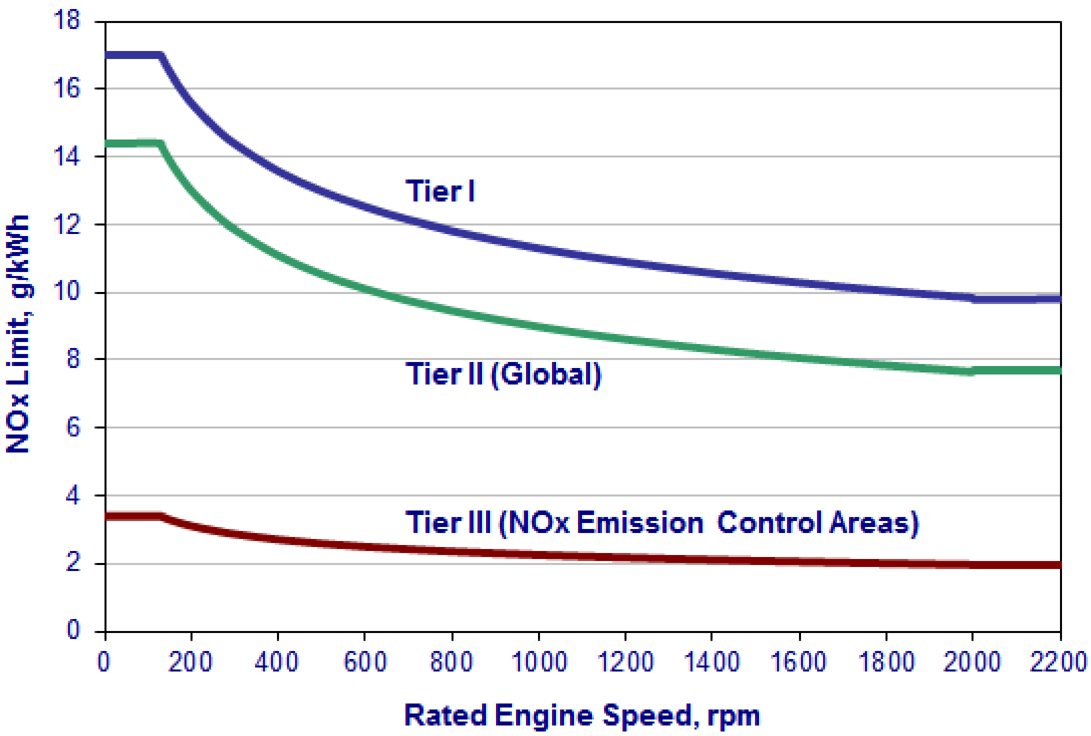


Figure 3.2: MARPOL Annex VI NO_x emission limits

It can be seen from figure 3.2 and table 3.1 that the limit for NO_x emissions are significantly lower within an ECA then elsewhere. The reduction in NO_x emissions between global and ECA corresponds to reduction of approximately 75%.

Supplementary, it is described in Regulation 13 that the NO_x limits are applicable for ships with a marine diesel engine with a power output of more than 130 kW. And that the regulation is not applicable for ships with a marine diesel engine that are solely used for emergencies, or solely to power any device or equipment intended to be used solely for emergencies on the ship on which it is installed, or a marine diesel engine installed in lifeboats intended to be used solely for emergencies.

Included in the technical code are procedures for on board NO_x verification. According to the technical code the on board measurement verification method contains the following parts:

1. Engine parameter check method to verify that an engine's component, settings and operating values have not deviated from the specifications in the engine's Technical File;
2. Simplified measurement method; or
3. Direct measurement and monitoring method.

Interesting to know is what the effect of the NO_x regulations will be. Therefore, Campling et al. (2013) estimated the impact of the above described regulations for European seas using a baseline scenario. This research used the year 2005 as starting point and estimated with a number of assumptions the amount of NO_x for the year 2020, 2030 and 2050. The results for NO_x emissions can be seen in table 3.2.

Table 3.2: Baseline emissions of NO_x from international shipping by sea region [kt] (Campling et al., 2013)

Sea regions	**Year**			
	2005	**2020**	**2030**	**2050**
Baltic Sea	220	183	202	250
Bay of Biscay	474	425	488	633
Black Sea	47	39	44	54
Celtic Sea	22	18	20	23
Mediterranean Sea	1294	1116	1255	1587
North Sea (+ English channel)	518	449	503	627
Rest of North-East Atlantic (EMEP grid)	54	48	54	69
Rest of North-East Atlantic (TNO grid outside EMEP)	192	172	196	250
Total	**2821**	**2450**	**2762**	**3494**

The above described regulations do have impact on the short-term, as can be seen in table 3.2. However, in the long-term can be seen that NO_x levels will be greater than the current NO_x emissions. This is due to the expectation the number of ships will increase. Other important factors for the future NO_x emissions are the possible new NECA's and the velocity with which the ships will be replaced.

The study of Yaramenka et al. (2017) estimated also the NO_x emissions of international shipping for Europe. This study compared the baseline scenario (table 3.3) and the ECA scenario including SCR (table 3.4). The two scenarios are plotted in figure 3.3. The figure shows that the NO_x emissions will drastically decrease, according the assumptions that are made by Yaramenka et al. (2017).

Table 3.3: Estimated NO_x emissions under baseline scenario [kt](Yaramenka et al., 2017)

Year	Boilers	Tier 0	Tier I	Tier II	Tier III (>2021)	LNG	Total
		No SCR	No SCR	No SCR	New SCR		
2021	1.54	118.6	367.6	304.0	-	0.25	792
2022	1.54	89.9	363.2	331.1	-	0.28	786
2023	1.54	61.3	358.7	358.3	-	0.30	780
2024	1.53	32.6	354.3	385.3	-	0.32	774
2025	1.53	4.0	349.8	412.4	-	0.34	768
2030	1.52	-	188.7	550.4	-	0.44	741
2035	1.51	-	23.6	690.3	-	0.54	716
2040	1.50	-	-	712.9	-	0.65	715

Table 3.4: Estimated NO_x emissions under ECA scenario [kt](Yaramenka et al., 2017)

Year	Boilers	Tier 0	Tier I	Tier II	Tier III (>2021)	LNG	Total
		No SCR	No SCR	No SCR	New SCR		
2021	1.54	118.6	367.6	277.1	2.1	0.25	767
2022	1.54	89.9	363.2	277.1	4.4	0.28	736
2023	1.54	61.3	358.7	277.2	6.6	0.30	706
2024	1.53	32.6	354.3	277.2	8.8	0.32	675
2025	1.53	4.0	349.8	277.3	11.1	0.34	644
2030	1.52	-	188.7	278.1	55.2	0.44	524
2035	1.51	-	23.6	279.4	99.0	0.54	404
2040	1.50	-	-	161.5	142.3	0.65	306

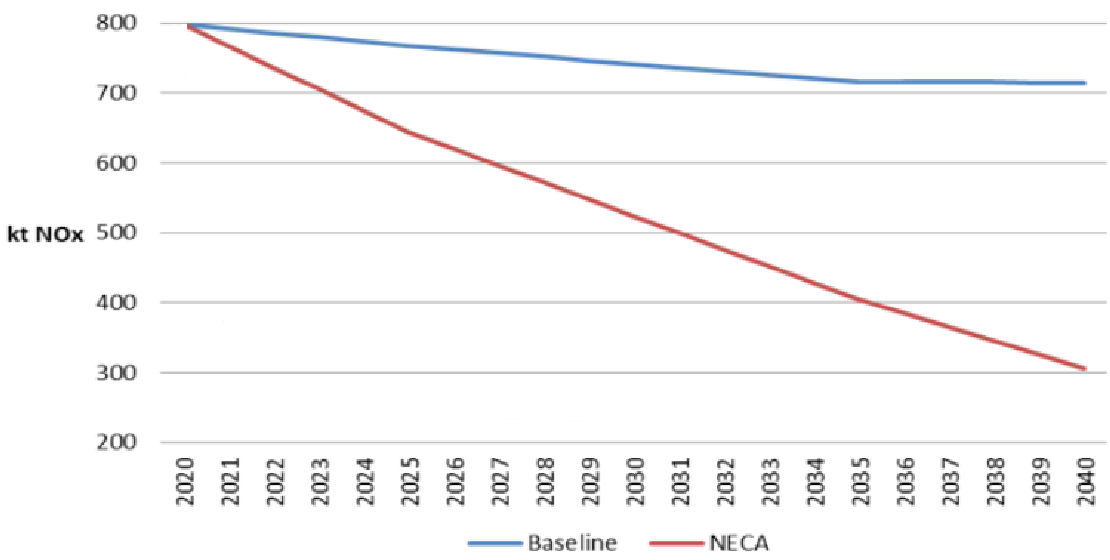


Figure 3.3: Projections of NO_x emissions according to the baseline and NECA scenarios [kt](Yaramenka et al., 2017)

3.4. Sulphur oxides and particulate matter - Regulation 14

This section will describe the regulations for sulphur oxides (SO_x) emissions and particulate matter (PM) in shipping. Mostly, regulation 14 (IMO, 2011) is used for this section. The full version of this regulation can also be read in annex B.2 of this report.

Also, the ECA apply for the control of SO_x and PM emission limits. These limits indicate how much sulphur content is allowed in the fuels that are on board of the ship. These fuel oil sulphur limits are expressed in terms of % mass by mass [m/m]. The limits for the sulphur content outside an ECA can be seen in table 3.5 and the limits within an ECA can be seen in table 3.6.

Table 3.5: Outside ECA sulphur content limits (IMO, 2011)

Date	**Limit** [m/m]
Prior to 1 January 2012	4.50%
On and after 1 January 2012	3.50%
On and after 1 January 2020*	0.50%

In table 3.5, there can be seen that 2020 is marked with an asterisk. The reason for this is that the global fuel sulphur limit is not yet established in regulation 14. After this regulation is released, a review of the availability of the required fuel oil was undertaken. The fuel assessment was executed during the 70th session of the Marine Environment Protection Committee MEPC in October 2016 and it was decided that the fuel oil standard (0.50% m/m) shall become effective on 1 January 2020 (IMO, 2016).

Table 3.6: Inside ECA sulphur contentlimits (IMO, 2011)

Date	**Limit** [m/m]
Prior to 1 July 2010	1.50%
On and after 1 July 2010	1.00%
On and after 1 January 2015	0.10%

The global and ECA sulphur limits are also plotted in figure 3.4. There can be seen that especially the global limits will be a lot stricter in the future compared to now.

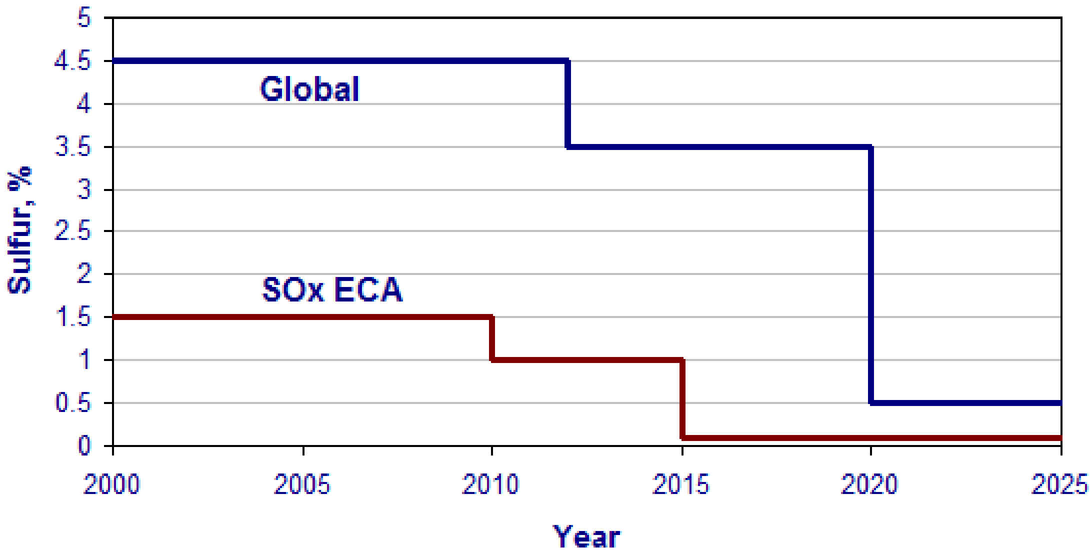


Figure 3.4: MARPOL Annex VI fuel sulphur limits

Most ships sail both inside and outside these ECA within one voyage and therefore can make use of two different types of fuels in order to comply whit the above mentioned limits. In such a case the ship is required to fully change over to the use of ECA compliant fuel when entering an ECA. Similarly, change-over from using the ECA compliant fuel oil is not to commence until after exiting the ECA. At each change-over it is required that the quantities of the ECA compliant fuel oils on board are recorded, together with the date, time and position of the ship when either completing the change-over prior to entry or commencing change-over after exit from such areas. These records are to be made in a logbook as prescribed by the ship's flag State (see Regulation 14.6 in appendix B.2).

The impact of these SO_x regulations are studied by (Campling et al., 2013), in particular the amount of SO_2 (see table 3.7). This study shows that a large reduction will be accomplished pertaining to 2005. However, there will be an increase in absolute sense.

Table 3.7: Baseline emissions of SO_2 from international shipping by sea region [kt] (Campling et al., 2013)

Sea regions	Year			
	2005	**2020**	**2030**	**2050**
Baltic Sea	130	6	7	9
Bay of Biscay	282	65	78	103
Black Sea	27	6	8	10
Celtic Sea	14	2	2	3
Mediterranean Sea	764	167	198	254
North Sea (+ English channel)	309	15	17	22
Rest of North-East Atlantic (EMEP grid)	31	7	9	11
Rest of North-East Atlantic (TNO grid outside EMEP)	1120	26	30	40
Total	**1668**	**293**	**349**	**452**

The impact of these IMO regulations on the amount of PM emissions in Europe is estimated by Campling et al. (2013) (see table 3.8). In table 3.8 can be seen that the PM emissions of ships will decrease on the short term when compared to 2005, but will be on the same level as 2005 on the long term.

Table 3.8: Baseline emissions of $PM_{2.5}$ from international shipping by sea region [kt] (Campling et al., 2013)

Sea regions	Year			
	2005	**2020**	**2030**	**2050**
Baltic Sea	14.2	8.7	10.1	12.8
Bay of Biscay	34.0	22.8	27.3	36.0
Black Sea	2.9	1.9	2.2	2.8
Celtic Sea	1.5	0.9	1.1	1.3
Mediterranean Sea	87.4	57.0	67.3	86.3
North Sea (+ English channel)	36.5	22.5	26.4	33.5
Rest of North-East Atlantic (EMEP grid)	3.7	2.5	2.9	3.8
Rest of North-East Atlantic (TNO grid outside EMEP)	13.8	9.2	10.9	14.2
Total	**193.9**	**125.5**	**148.3**	**190.7**

3.5. Black Carbon

Black carbon emissions from ships are not directly controlled by any IMO regulation today. However, the IMO agreed in MEPC 62 to a work plan to consider the impact on the Arctic of black carbon emissions from international shipping. The committee noted that there is a need for voluntary measurement studies to collect data of black carbon and to get experience with the definition and the related measurement methods. The definition of black carbon that is used by the IMO is from Bond et al. (2013) (see also section 2.4). The measurement methods that are included in the work plan are:

- Filter SmokeNumber
- Laser Induced Incandescence
- Photo-Acoustic Spectroscopy
- Multi Angle Absorption Photometry
- Thermal Optical Analysis

In response to the voluntary measurement studies, the working group prepared a draft protocol for the determination of black carbon. This draft protocol has to be reviewed in the future. However, the committee indicated that further consideration may be needed on measurement methods for black carbon, including revision of the draft measurement reporting protocol which was prepared at PPR 3, and also, if necessary, it should be considered to review the definition of black carbon itself.

3.6. Monitoring reporting verification

The Monitoring, Reporting and Verification (MRV) regulation is an European annual procedure and focuses on CO_2 emissions. This regulation is set out by the European Commission and has nothing to do with the IMO.

MRV can provide opportunities for the monitoring system and will therefore briefly described. The EU MRV regulation entered into force on 1 July 2015 and applies for ships larger than 5,000 gross tonnage calling at any European port (including Norway and Iceland). The regulation requires ship owners and operators to annually monitor, report and verify their CO_2 emissions in order to check compliance (see figure 3.6).

Figure 3.5: EU MRV regulation (DNV-GL, 2018b)

To give an overview of the EU MRV regulation, a timeline is included (see figure 3.6). The timeline shows that the first reporting period has started on January 2018 and will end the same year. Subsequently, a verification period will take place. Afterwards a CO_2 report over 2018 will be published by the European Commission on 30 June 2019.

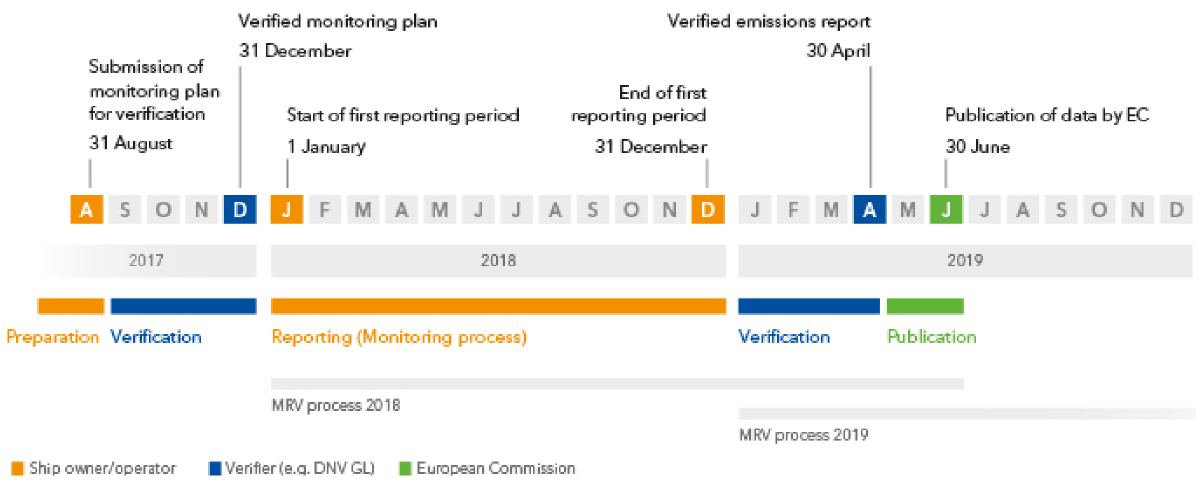


Figure 3.6: EU MRV regulation (DNV-GL, 2018b)

3.7. Overview emission regulations

The IMO regulations that are described in section 3.2 until section 3.4 are collected and depicted in the form of a timeline. This timeline is given in figure 3.7 and gives all the relevant IMO regulations in combination with the date of implementation.

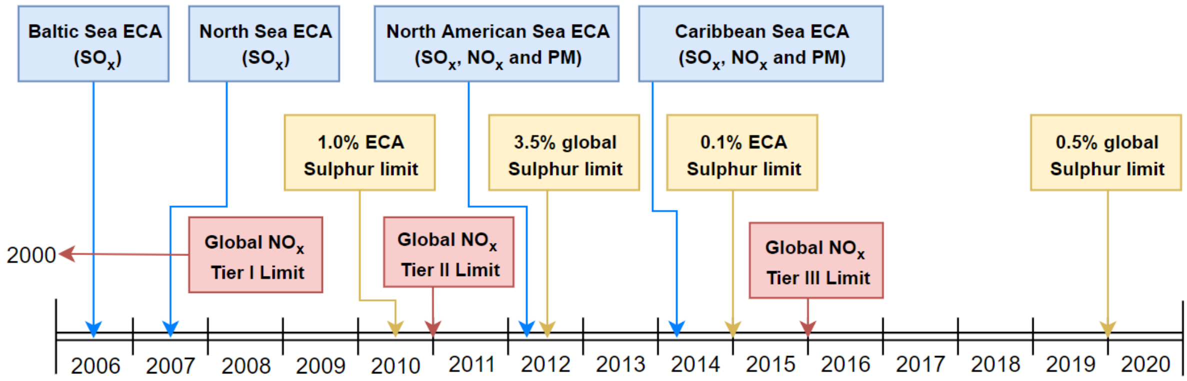


Figure 3.7: Timeline IMO regulations (own composition, 2018)

The implementation of the emission control areas are indicated with blue, the sulphur limits with yellow and the NO_x limits with red. The 0,5% global sulphur limit is the only regulation that is not into effect at the moment. It was uncertain for a long time when the global 0,5% sulphur limit would be introduced, but the two options for this global limit were the year 2020 or 2025. During MEPC 70 (see figure 3.8) is decided that the 0,5% will definitely come into effect on 1 January 2020. Before this decision was made, a review of the availability of the required fuel oil was undertaken by the IMO (IMO, 2018).

Figure 3.8 shows all critical plan meetings of the IMO. The yellow blocks are the Marine Environment Protection Commitee (MEPC) meetings and the blue are the meetings of the sub-committee on Pollution Prevention and Response (PPR).

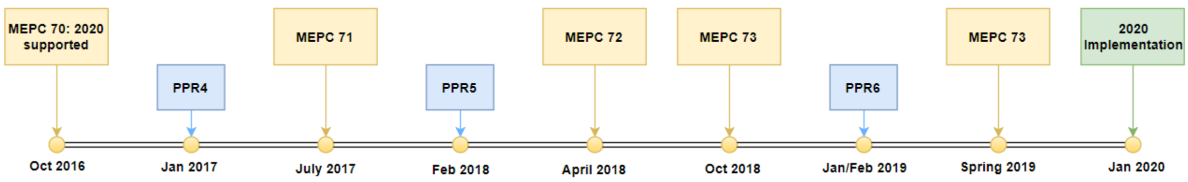


Figure 3.8: Timeline critical IMO meetings (own composition, 2018)

This section provides a good overview of the moment when the different regulations came or will come into effect. This is one of the topics that has been investigated in this chapter and will be used in the next chapters. The objective of this chapter was to search all relevant regulations for the emissions that need to be measured by the monitoring system. This worked for NO_x, SO_x, PM and unfortunately not for BC. It turned out that there is no regulation for BC. The most important reason for this is the lack of knowledge about BC in shipping. The definition of BC is unclear and the measurement of it is challenging. These factors makes it difficult to implement BC measurement in the monitoring system. This means for the remainder of this thesis that the focus will be on the monitoring NO_x, SO_x, PM and less on BC. This means that all the emissions limits that are described in this chapter for NO_x, SO_x and PM will be used for the monitoring system in the subsequent chapters.

4

Emission control technologies and fuels

To comply with the various IMO regulations as described in chapter 3, ships will need to take measures to control their emissions. For example, if the shipowner chooses to sail on HFO (see section 4.3), then the emission limits can no longer be met in the future. Therefore, some emission control technologies or other fuel choices are unavoidable to comply with the regulations. This chapter will describe both options for a shipowner, namely the emission control options (see sections 4.1 and 4.2) and the fuel options (see section 4.3). These options are combined and described in section 4.4. The remainder of this chapter will consist of topics that are related to fuels.

In addition, most of the existing fuel burning equipment and marine engines on board of a ship were specifically designed to burn HFO. This means that these emission control systems often have to be installed. Therefore a selection is made of the most used emission control technologies and these will be discussed in the above mentioned sections. Engine control technologies will be discussed in section 4.1 and 4.1.1, after-treatment technologies are briefly described in section 4.2 and the overview of the after-treatment technologies are given in section 4.2.1.

This chapter is important, because the monitoring system will encounter such emission control systems and fuels when operating. For example, the influence of a SCR system or an EGR system in combination with a scrubber(see figure 4.1). Namely, the emission control technologies take up extra space, especially around the exhaust system.

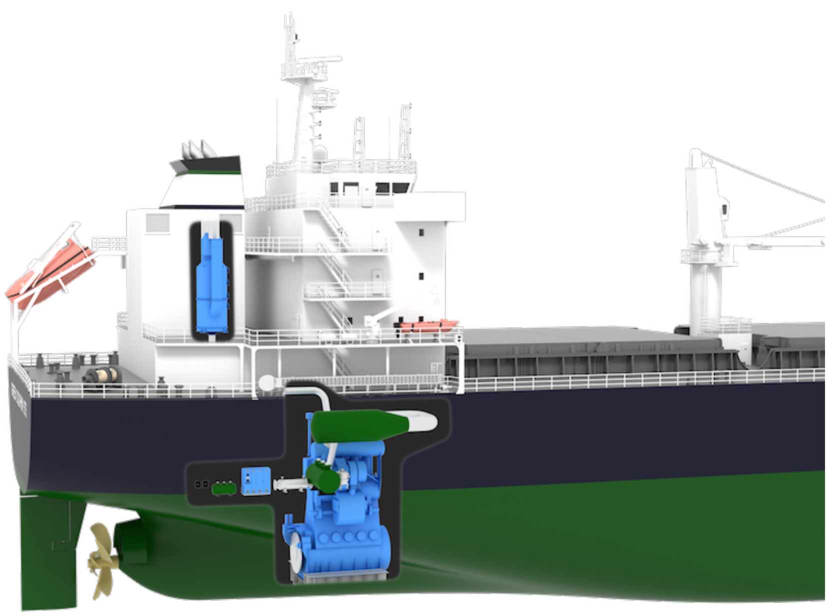


Figure 4.1: Ship including SCR, EGR and scrubber installation (DNV-GL, 2018a)

4.1. Engine control technologies

This section will describe the most common engine control technologies briefly, so it is clear which technologies the monitoring systems will encounter. The working principle will be described and the maximum achievable emission reduction of NO_x, SO_x or PM will be mentioned. In addition, a comparison will be made between the engine control in section 4.1.1. This will be done based on the achievable reductions, the applicable emission source and the possibility to retrofit. The possible reduction of black carbon per technology will be missing, because it is unknown.

Common-rail injection system

The common-rail injection system is a fuel supply system in which a single high-pressure pump supplies a common rail (see figure 4.2). The valves determine the timing and extend of the fuel delivery to the cylinder injectors. The benefits of a common rail system are: smokeless operation, lower stable running speeds and reduced fuel consumption at part load (Babicz, 2008).

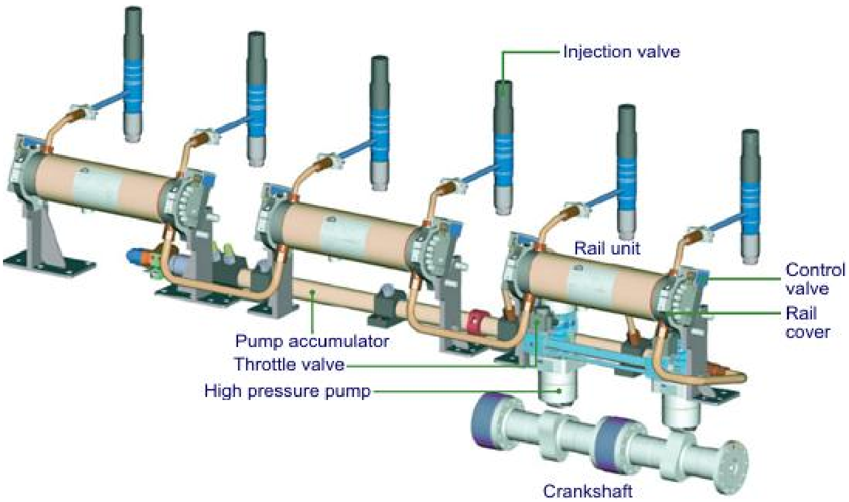
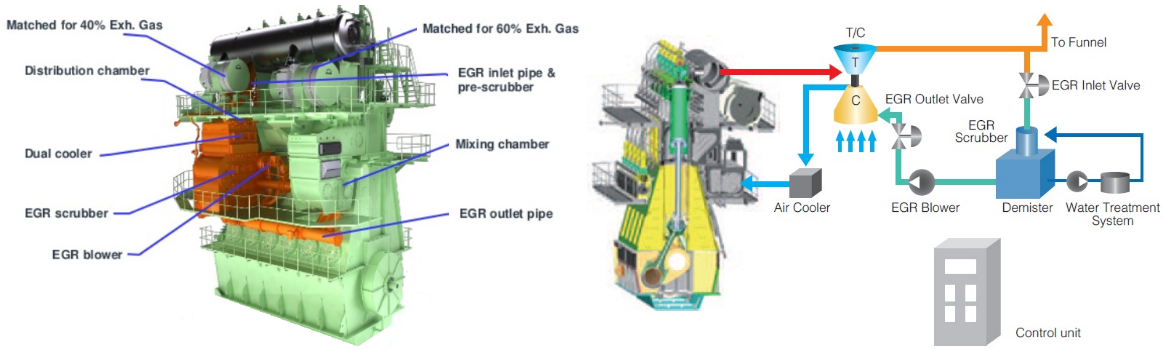


Figure 4.2: Common-rail injection system (Nelissen and Huigen, 2017)

Exhaust gas recirculation

Exhaust gas recirculation (EGR) is an effective method to control NO_x from diesel engines (Khair and Jaaskelainen, 2006). Figure 4.3 shows an example of an EGR system installed at a MAN B&W two-stroke diesel engine (MAN, 2015). For more detail, an example of an EGR system on a bulk carrier is included in appendix C.

In figure 4.3 can be seen that the exhaust gas is recirculated into the diesel engine, in order to achieve NO_x reductions. The EGR system ensures that the exhaust gas from the diesel engine is recirculated into the compressed air of the turbocharger. This causes a reduction of the oxygen content in the cylinder and increased heat capacity of the cylinder charge. Both conditions lead to lower combustion temperatures and this results in lower NO_x reductions. The EGR systems can achieve a NO_x reduction up to 60% although some EGR systems are showing a reduction up to 80% (Anderson et al., 2015). An important disadvantage which must be taken into account, is the increased chance of PM emissions, because of the lower oxygen concentration. More research has to be carried out in order to determine the exact extra PM emissions by installing an EGR system. Another disadvantage is that an EGR can lead to engine fouling (EGR cooler, EGR inlet system and acidity formation).



(a) (MAN, 2015) (b) (Mitsubishi, 2018)

Figure 4.3: Exhaust gas recirculation system

Electronically controlled lubrication systems

There are a few possible options for electronically controlled lubrication systems, especially from Wärtsilä and MAN. The combination of an efficient control system and a good quality cylinder lubrication can neutralize the sulphur in the fuel, which results in a reduction of PM emissions up to 20% to 30% from the diesel engine (Chopra, 2018). An example of an electronically controlled lubrication, is the Wärtsilä pulse system (see figure 4.4).

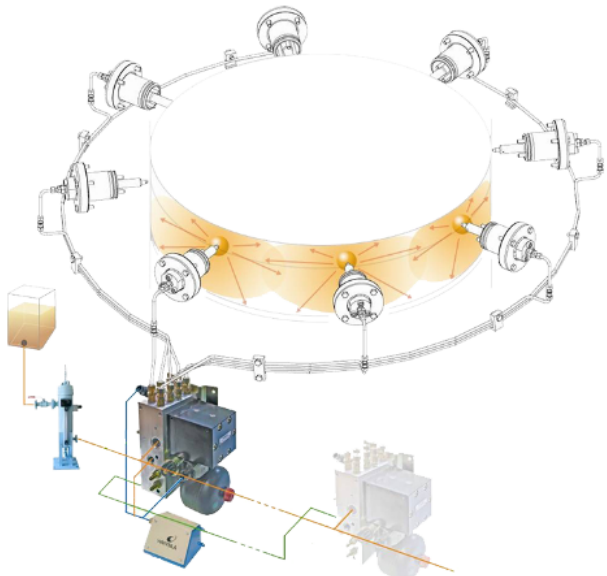


Figure 4.4: Wärtsilä pulse lubrication system (Walsh and Price, 2015)

Automated engine monitoring & control systems

Automated engine monitoring & control systems are often installed on ships with an electronically controlled engine. This automated system tunes or adjusts the engine parameters during various engine loads and operational conditions. Examples of what can be controlled by this automated system are: the compression ratio, the turbocharger shutoff, the engine fuel equipment, the exhaust valve timing, the fuel injection, the fuel system equipment and the engine fuel efficiency.

By adapting the above mentioned parameters engine efficiency can be improved and also the peak combustion temperatures of the engine can be diminished, in order to reduce NO_x emissions. The reduction of NO_x that can be reached is up to 20%. Also small SO_x and PM reduction are achievable by this system (Anderson et al., 2015). In this way Tier II emission limits can be achieved without the need of an EGR or a SCR system.

Continuous water injection

NO_x and PM emissions could be reduced by the use of continuous water injection. This works as follows: an injection of high quality water at a relatively low pressure takes place into the hot air stream after the turbochargers. Because of the injection of the water, the oxygen concentration and peak combustion temperatures are reduced. The potential reduction when using continuous water injection is up to 30% for NO_x and 5-18% for PM emission (Anderson et al., 2015).

Direct water injection

The purpose of direct water injection is to reduce the oxygen concentration, which causes lower temperatures in the cylinder before the combustion takes place. The water is directly injected under high pressure into the cylinder. The sulphur content of the fuel needs to be lower than 1.5% [m/m] in order to use direct water injection. The NO_x reduction that can be achieved is up to 50% and this reduction can be reached at all engine loads (Anderson et al., 2015).

Humid air motor or Scavenging air moistening

The human air motor (HAM method) is used to reduce the NO_x emissions and often installed in combination with four-stroke engines. In this HAM system the relatively hot and dry air from the turbocharger is saturated with water vapour that is produced by the ship itself, using engine heat and sea water (Babicz, 2008). By using this HAM system the peak temperatures are lowered in the combustion chamber, which is normally the main source of NO_x formation. This technology is able to reduce the NO_x emissions up to 65% (MAN PrimeServ, 2018). An example of a HAM system in combination with a main engine, can be seen in figure 4.5.

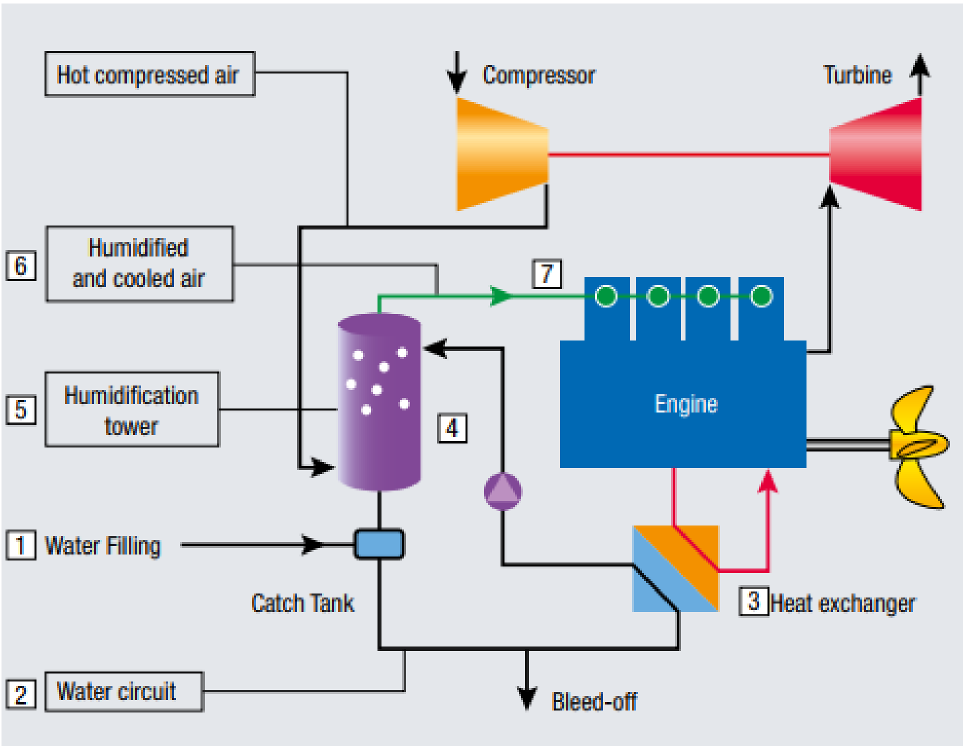


Figure 4.5: Engine with HAM principle (MAN PrimeServ, 2018)

The scavenging air moistening is a new method for the reduction of NO_x and is applicable for large two-stroke engines. The high humidity is induced in the scavenging air through evaporation of water in the hot turbocharger compressor outlet (Babicz, 2008). The result is a lower combustion temperature in the cylinder, and thus NO_x can be significantly reduced, up to 65% (Anderson et al., 2015). An example of a MAN B&W scavenging air moistening system is displayed in figure 4.6.

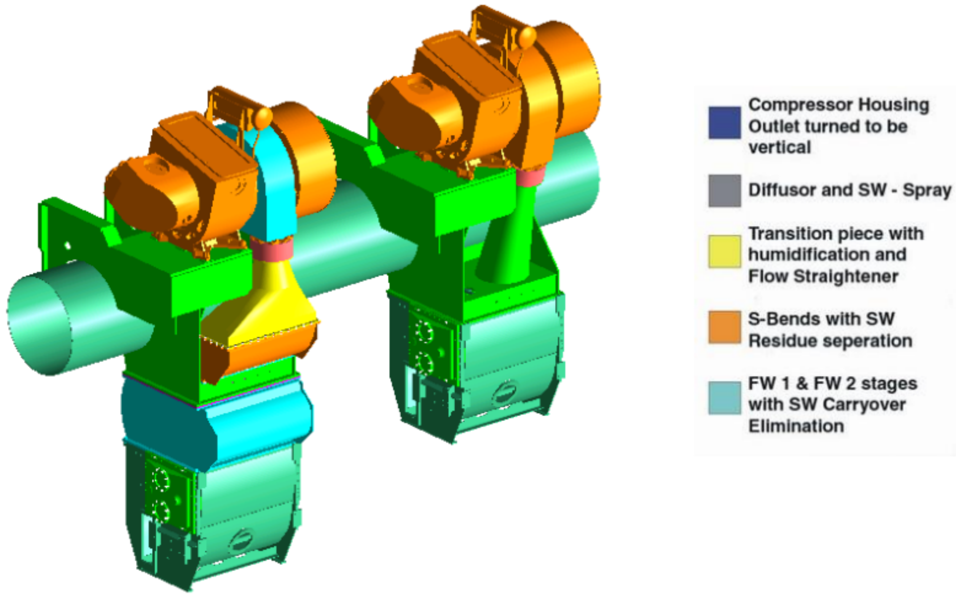


Figure 4.6: Scavenging air moistening (Skeltved, 2010)

Two-stage turbochargers

In case of two-stage turbocharging, the turbochargers are placed in series with the objective to increase the mean effective pressure (Klein Woud and Stapersma, 2002). A low pressure and a high pressure turbocharger are placed in series (see figure 4.7) causing, more airflow, increased air pressure and more efficient turbocharging effect. The NO_x reduction that can be reached by two-stage turbocharging is up to 40% (Anderson et al., 2015).

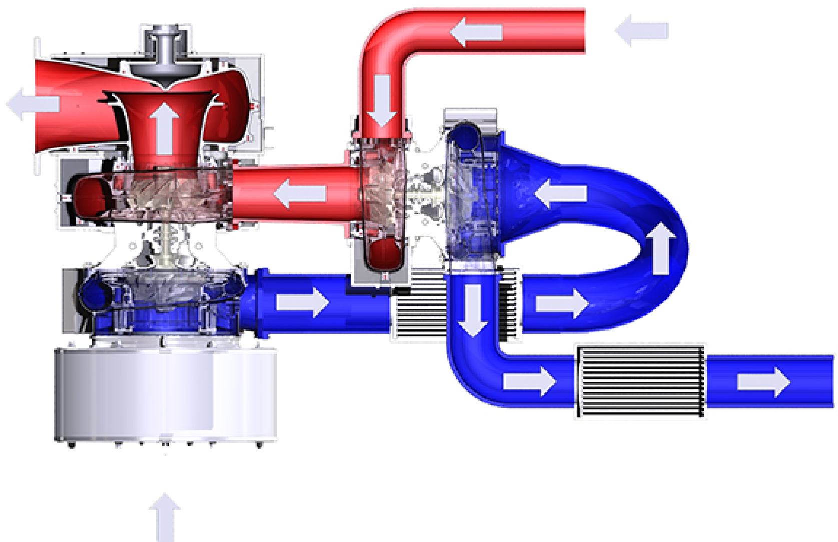


Figure 4.7: 2-stage turbocharging working principle (MAN, 2018b)

Turbocharger cut off systems

The turbocharger cut off system is designed to boost the engine performance and decrease the fuel oil consumption during low load operations (MAN, 2018a). Turbocharger cut off can be accomplished by installing a turbocharger cut of system with controls and swing gates (see figure 4.8). This system allows the ship operator to disable one of the turbocharges for low load operations. The NO_x reduction that can be achieved is up to 40% (Anderson et al., 2015)

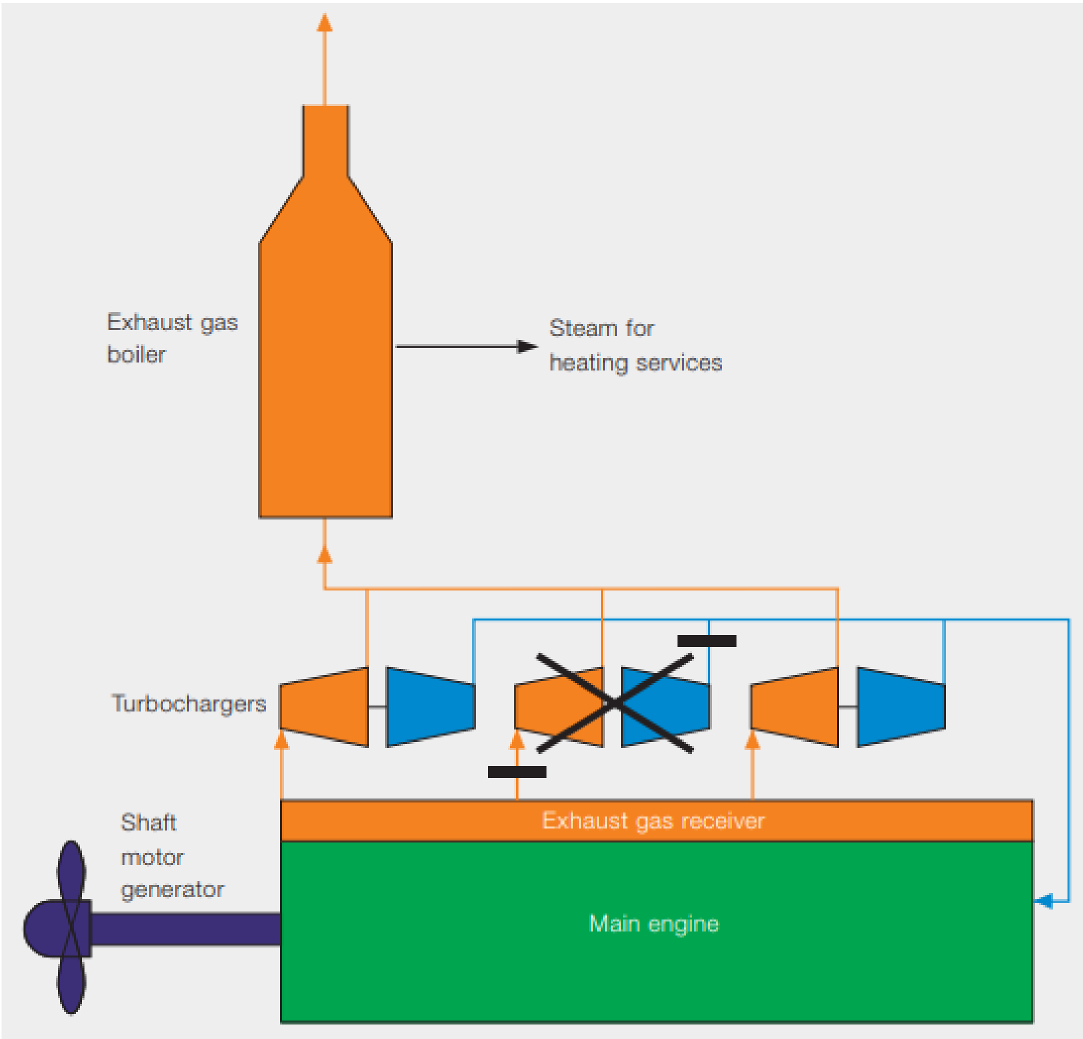


Figure 4.8: Example of a cut-out arrangement (Baechi, 2012)

4.1.1. Overview engine control technologies

This section gives an overview of all of the above mentioned control technologies. Table 4.1 shows all the possible reduction per emission type. The engine control technologies do have the most impact on the NO_x emissions as can be seen in table 4.1. Regards to the SO_x emissions, not much reduction can be achieved by using engine control technologies. For PM applies that reductions can be reached, but that for the most engine control technologies the precise reduction is unknown. Therefore, tbd (to be determined) and cbc (case-by-case) are given in table 4.1. The emission sources that are applicable on the different emission control technologies are also given in table 4.1. These sources are propulsion engines (P) and auxiliary engines (A). Finally, the last column of table 4.1 shows if it is feasible to install the particular engine control technology during a retrofit.

Table 4.1: Summary of engine control technologies (Anderson et al., 2015)

Engine Technologies	**NO_x**	**SO_x**	**PM**	**Applicable Emission Source**	**Retrofitable?**
Common Rail	≤25% ↓	-	↓cbc	P/A	Yes
Exhaust Gas Recirculation	≤60% ↓	-	tbd	P/A	Yes
Electronically Controlled Lubrication Systems	-	-	≤30% ↓	P	Yes
Automated Engine Monitoring/Control Systems	≤20% ↓	≤3% ↓	tbd	P/A	No
Continuous Water Injection	≤30% ↓	-	≤18% ↓	P/A	Yes
Direct Water Injection	≤60% ↓	-	↕cbc	P/A	Yes
Scavenging Air Moistening/Humid Air Motor	≤65% ↓	↑cbc	↑cbc	P/A	Yes
Two Stage Turbochargers	≤40% ↓	-	tbd	P/A	Yes
Turbocharger Cut Off	≤40% ↓	-	tbd	P	Yes

4.2. After-treatment technologies

After-treatment technologies are used to reduce the exhaust emissions. This is done by treating the exhaust gasses from the marine diesel engine. There are three different after-treatment options available on the market at the time of this research. Namely, selective catalytic reduction and two types of exhaust gas scrubbers: a wet scrubber or a dry scrubber. Both types of scrubbers and the selective catalytic reduction technology will be described in this section and compared with respect to emission reductions of NO_x, SO_x and PM. With regard to this section, some after-treatment configurations of different manufactures are included in appendix D.

Selective catalytic reduction

Selective catalytic reduction (SCR) is an after-treatment system that reduces the level of NO_x emissions from marine diesel engines. There are multiple options for a SCR system, depending on the manufacturer. The working principles are generally equivalent. The exhaust gases with the NO_x particles are converted with the aid of a catalyst. This catalytic process takes place in the SCR reactor (see figure 4.9). The exhaust gas enters the reactor, then the NO_x is reduced catalytically to water and nitrogen by adding urea or ammonia (MAN, 2017). The catalyst in the reactor consists of blocks with a substantial number of channels, providing a large surface area (see figure 4.10).

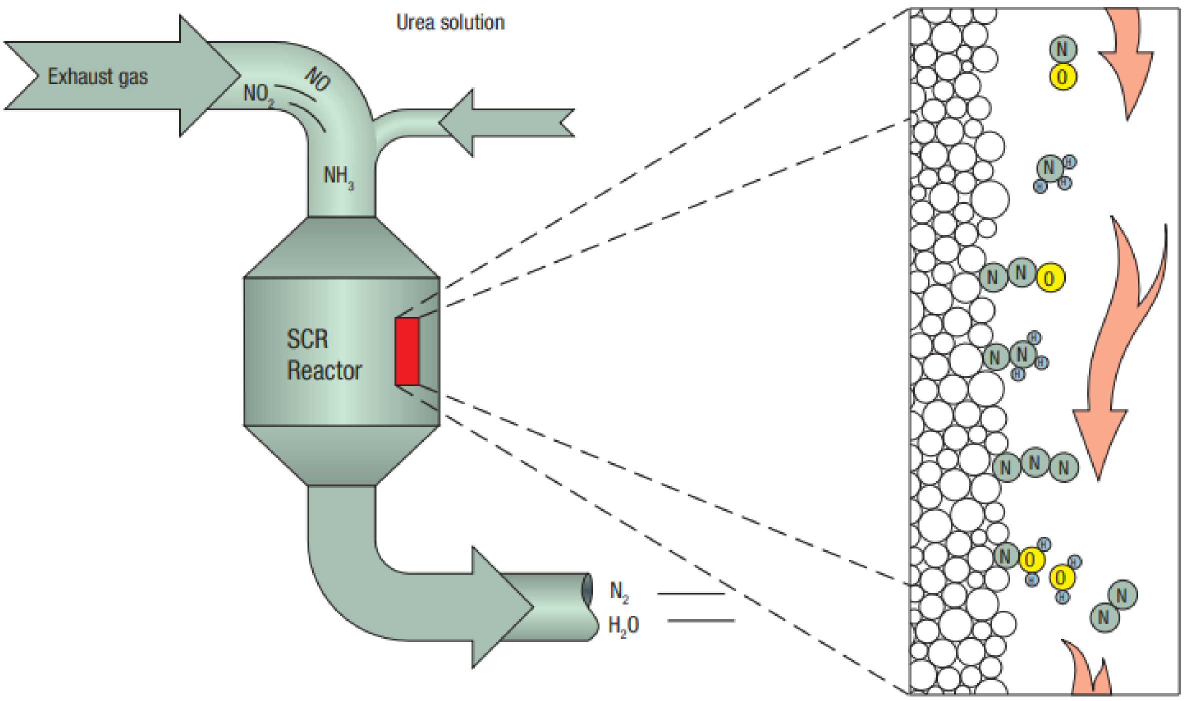


Figure 4.9: SCR working principle (MAN, 2017)

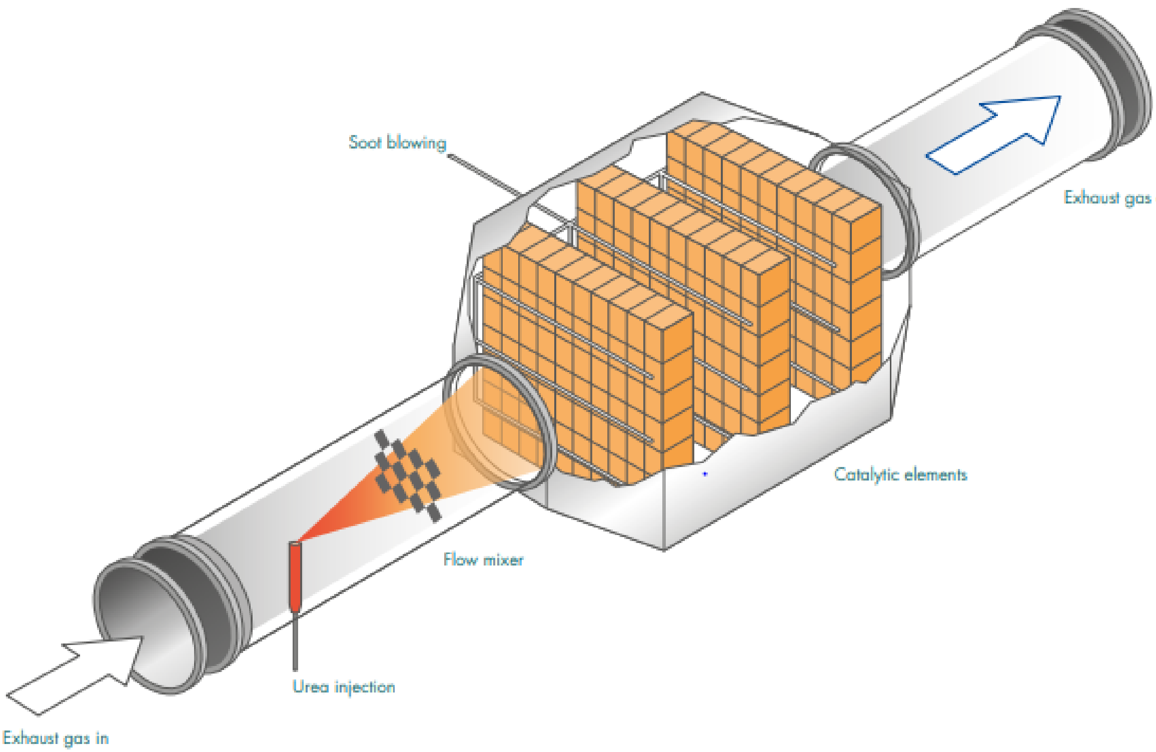


Figure 4.10: SCR unit (Gregory and Confuorto, 2012)

The catalytic process that takes places between these blocks, consists of the following chemical reactions:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$2NO + 2NO_2 + 4NH_3 \rightarrow 4N_2 + 6H_2O$$
$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

The limiting factor within this process is the exhaust gas temperature. The temperature that is fed through the reactor is normally greater than 250°C. The efficiency of this process will decrease when the exhaust temperature is too low. Namely, if the temperature is too low, the ammonia or urea will form a sticky product(ammonium bisulphate (NH_4HSO_4)). This product leads to congestion in the blocks of the catalyst, causing the lower efficiency. Thus, to secure a robust SCR process it is crucial to maintain the exhaust gasses within a certain temperature window. The minimum temperature that is required to avoid the formation of NH_4HSO_4 can be seen in figure 4.11. This figure is applicable for the unusual case when the SCR catalyst is placed in the high pressure exhaust gas between engine outlet valves and the turbo expander.

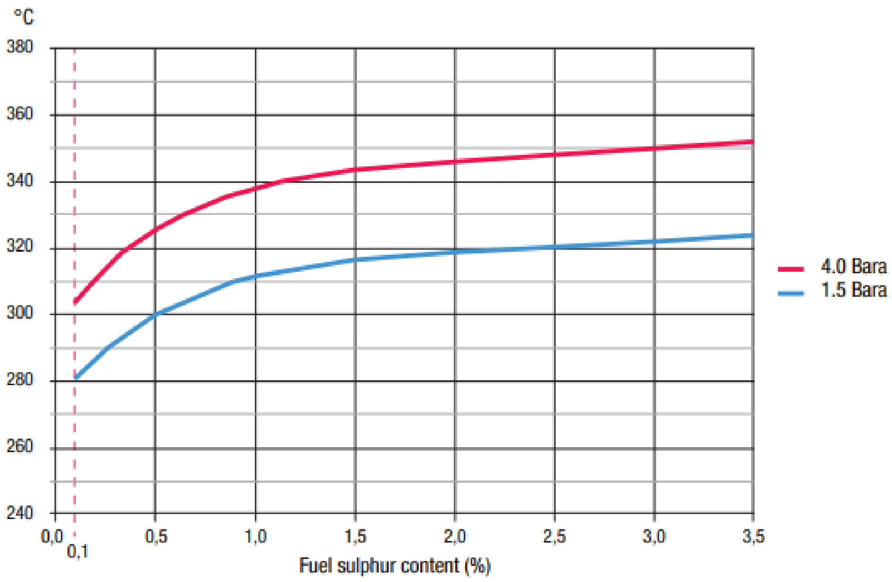


Figure 4.11: Required temperatures for SCR related to sulphur content and exhaust gas pressure (MAN, 2017)

Figure 4.11 shows a low pressure curve in blue and a high pressure curve in red, which represent the pressures at low and high engine load. In the figure 4.11 can be seen, that the sulphur content of the fuel also affects the required temperature.

The total SCR system is displayed in figure 4.12. It can be seen that the addition SCR system can have significant space requirements (see also appendix D.1). Besides the SCR reactor, an urea or ammonia tank together with a pump and a mixer needs to be installed. The total reduction of NO_x emissions that can be reached is between the 80% and the 98% (Anderson et al., 2015).

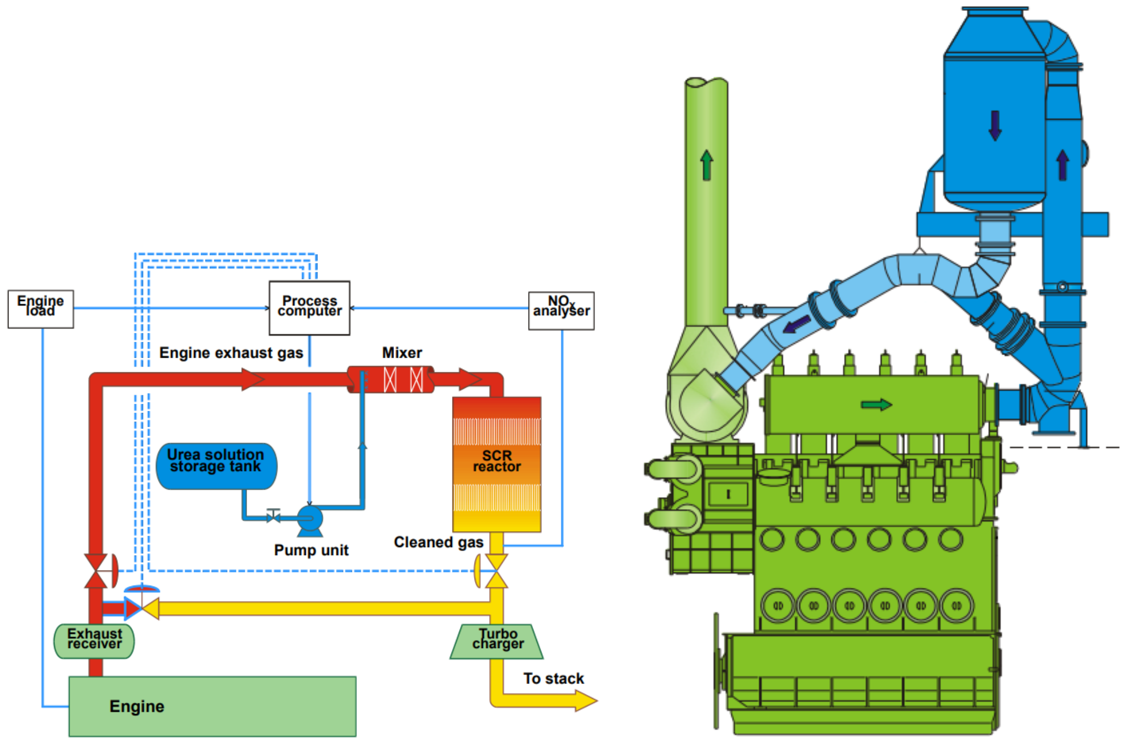


Figure 4.12: Selective catalytic reduction (Skeltved, 2010)

Wet exhaust gas scrubbers

Wet exhaust gas scrubbers are suitable for the discharge of SO_x and PM emissions from the marine diesel engine. The basic system components of a wet scrubber system can be seen in figure 4.13.

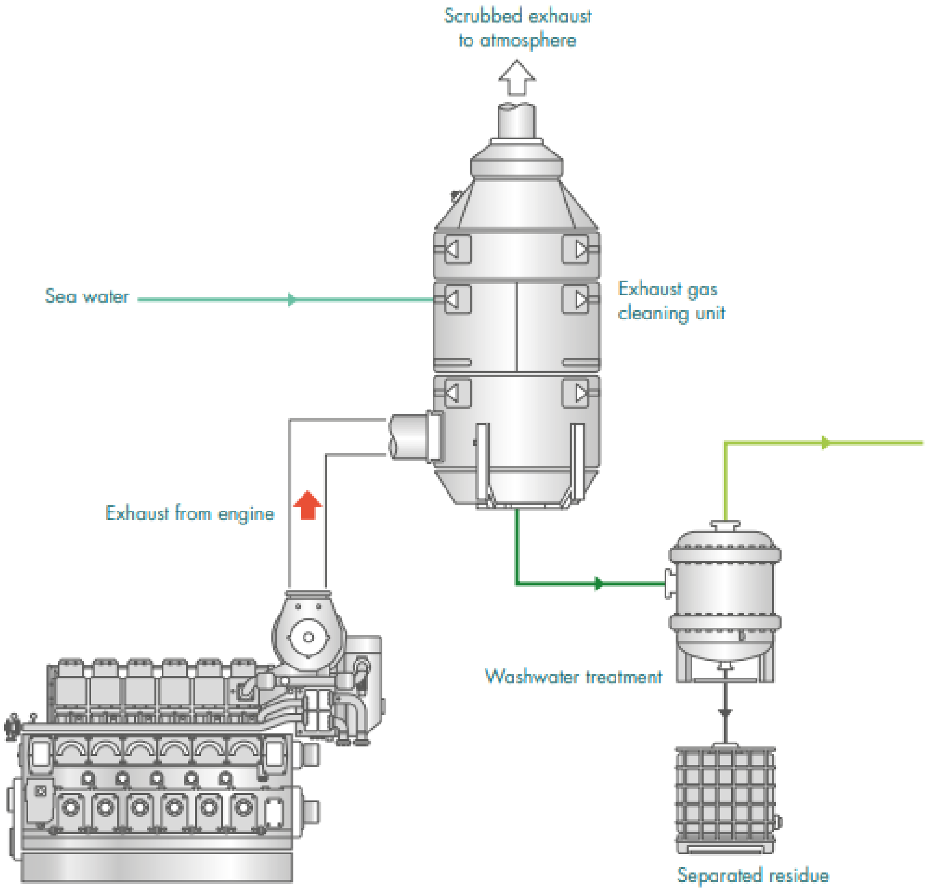


Figure 4.13: Wet exhaust gas cleaning system basic components (Gregory and Confuorto, 2012)

The scrubber system, as displayed in figure 4.13, can be utilized in an open loop, closed loop or hybrid configuration (see appendix D.2). The SO_x molecules that are released after the combustion of the diesel fuel are dissolved and eliminated by the water that is injected in the exhaust gas cleaning unit by the following simple chemical reactions (MAN, 2017):

$$SO_2 + H_2O \rightarrow H_2SO_3$$
$$SO_3 + H_2O \rightarrow H_2SO_4$$

The difference between a closed loop and an open loop configuration is the type of water use. The open loop configuration makes use of seawater in the scrubbing process and a closed loop makes use of freshwater. The hybrid configuration can use both, depending on the operational mode and the environment.

A benefit of an open loop system is that the natural chemical composition of seawater neutralizes the impact of SO_x in the scrubber water (MAN, 2017). The water for the scrubber is directly taken from the sea and supplied to the scrubber. Open loop configurations are often used in waters where the alkalinity of the seawater is high enough for adequate scrubbing. When a closed loop system is used, an addition of chemicals is essential.

These chemicals are needed to neutralize the sulphuric acid in the scrubber water. An example of such a chemical is sodium hydroxide (NaOH). Adding this chemical results in the following chemical reaction:

$$H_2SO_3 + 2NaOH + 1/2O_2 \rightarrow Na_2SO_4 + H_2O$$
$$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + H_2O$$

Besides the exhaust gas cleaning unit, a treatment unit is necessary in order to remove the pollutants from the washwater coming from the exhaust cleaning unit. This cleaning process is mandatory before the water can be discharged overboard. The residue that is left over from the washwater treatment must be retained on board for disposal ashore and may not be burned in the ship's incinerator (Gregory and Confuorto, 2012).

There are various types of wet scrubbers available on the market, often depending on the manufacturer. These different types of scrubbers are pictured in figure 4.14. Combinations of these different type of scrubbers are also possible.

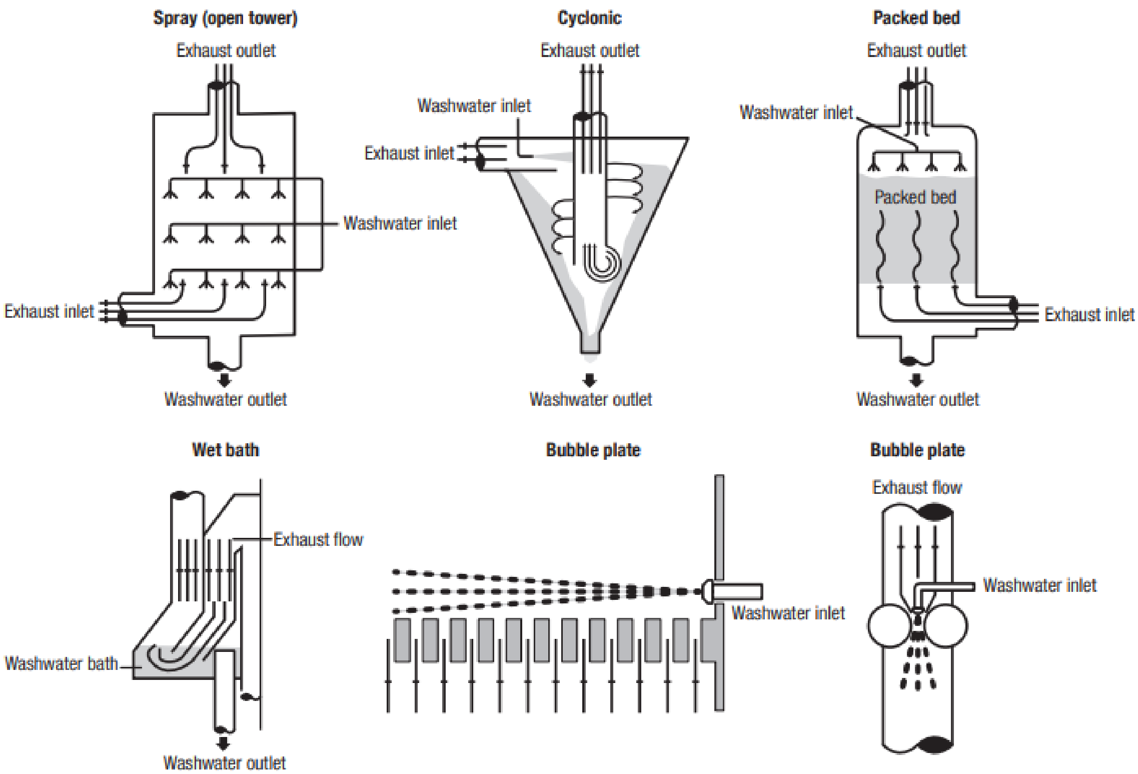


Figure 4.14: Different methods used for wet scrubbers (MAN, 2017)

The emission reduction that can be reached by using wet exhaust gas scrubbers is up to 98% for SO_x, up to 80% for PM and up to 5% for NO_x emissions (Anderson et al., 2015).

Dry Exhaust Gas Scrubbers

The most important component in a dry exhaust scrubber is the absorber. Marine dry scrubbers are using the absorber to remove the pollutant gases. This chemical absorption process is also known as chemisorption. This reaction ensures that the SO_x is converted into a stable compound (Gregory and Confuorto, 2012). The type of absorber that is regularly used in marine dry scrubbers is calcium hydroxide ($Ca(OH)_2$), in the form of granulated pellets. The SO_x reacts with the calcium hydroxide in the following way (Couple Systems GmbH, 2010):

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$$
$$Ca(OH)_2 + SO_2 + 1/2O_2 \rightarrow CaSO_4 + H_2O$$
$$Ca(OH)_2 + SO_3 + H_20 \rightarrow CaSO_4 + 2H_2O$$

Through the presence of calcium hydroxide in the scrubber, the SO_x will be reformed in Gypsum (calcium sulfate), as can be seen in the above given reaction. The calcium hydroxide is moved through the absorber with a certain speed depending on the engine load, and the gypsum is detached from the system and stored in a tank for removal from ship. An example of a dry exhaust gas scrubber can be seen in figure 4.15.

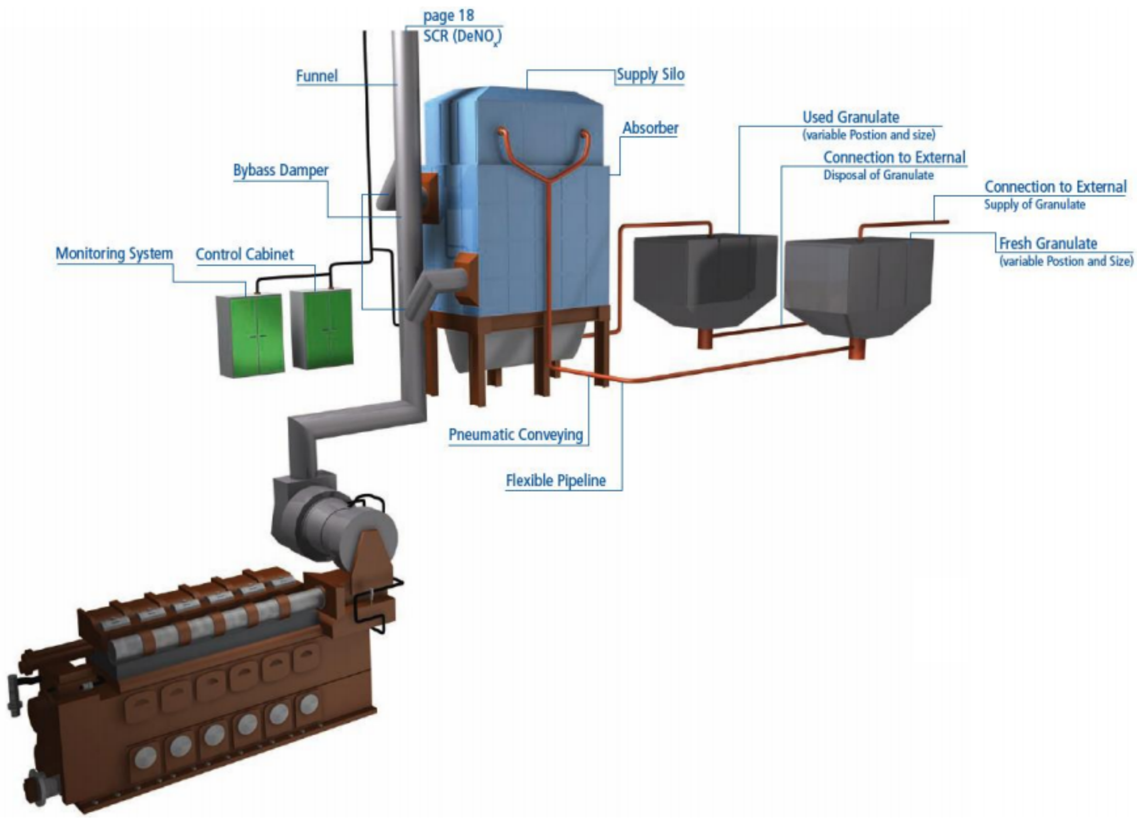


Figure 4.15: Dry exhaust gas cleaning system(Couple Systems GmbH, 2010)

The benefit of dry scrubbers over wet scrubbers is the relatively high temperature of the decontaminated exhaust gases, because the exhaust gas is not cooled in interaction with water. The relative high temperature of the exhaust gases by using a dry exhaust gas scrubber has the advantage that a combination with a small SCR system provides a high efficiency relative to other emission control systems. The SO_x reduction that be reached by applying dry scrubbing is up to 99% ((Couple Systems GmbH, 2010), (Gregory and Confuorto, 2012)). The PM reduction can reach up to 80% and the maximum NO_x reduction is 5%.

4.2.1. Overview after-treatment technologies

This section will give an overview of the after-treatment technologies and some extra information concerning the scrubbers. Interesting to know for the monitoring system is the rate of possible used scrubber systems in the future. Therefore, table 4.2 and figure 4.16 are included in this overview. Table 4.2 shows the estimated need for scrubbers and the number of ships that are suited for scrubbers per ship category. Important to realize is that container ships and bulk carriers together account for 76% of the world's DWT. Figure 4.16 shows the number of ships with scrubbers systems installed or on order at the time of May 2018.

Table 4.2: Estimated need for scrubbers (Schieldrop, 2018)

	Number of ships	mDWT	Average DWT per ship	Esimated need for scrubber	Number of ships suited for scrubber
Crude tankers	2017	387.6	192167	100 %	2017
Product tankers	8403	173.5	20647	70 %	5882
Chemical tankers	3686	43.7	11856	50 %	1843
Other tankers	405	0.9	2222	100 %	405
Bulk carriers	11113	817.2	73535	70 %	7779
Combos	12	1.4	116667	100 %	12
LPG carriers	1452	24.3	16736	70 %	1016
LNG carriers	504	40	79365	0 %	0
Containerships	5164	252.8	48954	80 %	4131
Multi-purpose	3183	29.3	9205	30 %	955
General cargo	15068	37.5	2489	30 %	4520
Ro-Ro	1662	7.7	4633	100 %	1662
Car carriers	782	12.4	15857	100 %	782
Reefers	1458	4.8	3292	100 %	1458
Offshore AHTS	4680	9.6	2051	30 %	1404
World cargo fleet	59589	1842.7	30923		
Others	34582	82	2371	15 %	5187
World fleet	94171	1925	20438	41 %	39054

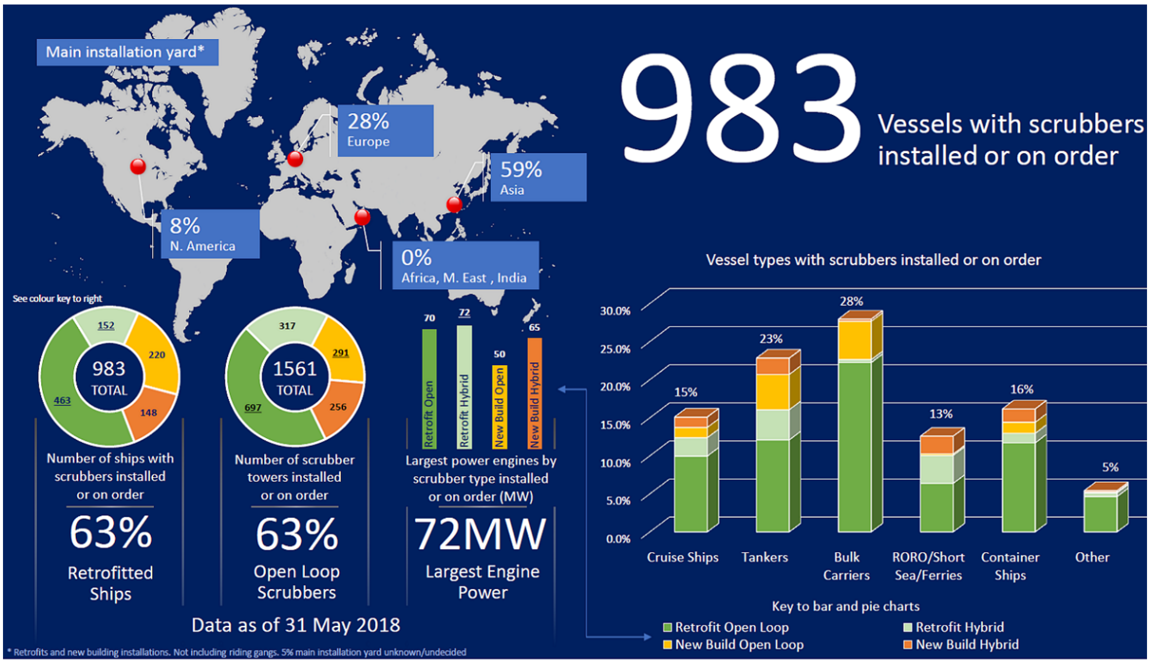


Figure 4.16: Numbers of scrubber systems installed or on order at the time of May 2018 (EGCSA, 2018a)

Table 4.3 shows the overview concerning the reductions that can be reached using the earlier described after-treatment technologies (see section 4.2). The after treatment-technologies are very effective for the reduction of NO_x, SO_x and PM, as can be seen in table 4.3. These technologies perform better than the engine control technologies (see section 4.1), when looking at the possible achievable reduction only.

Table 4.3: Summary of after-treatment technologies (Anderson et al., 2015)

Engine Technologies	**NO_x**	**SO_x**	**PM**	**Applicable Emission Source**	**Retrofitable?**
Selective Catalytic Reduction (SCR)	≤95% ↓	-	-	All	Yes
Wet Exhaust Gas Scrubbers	≤5% ↓	≤98% ↓	≤80% ↓	All	Yes
Dry Exhaust Gas Scrubbers	≤5% ↓	≤99% ↓	≤80% ↓	All	Yes

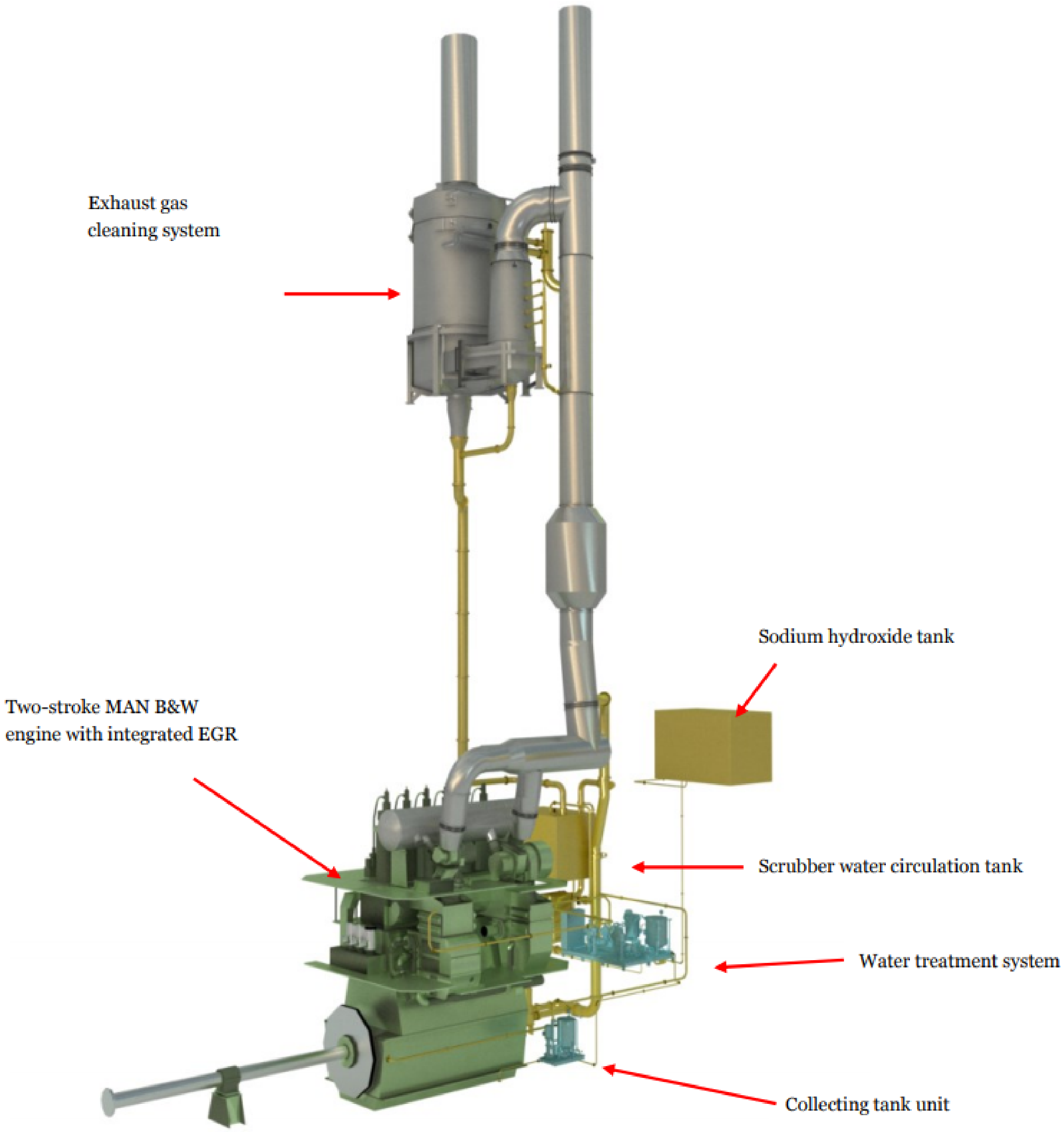


Figure 4.17: 3D arrangement of EGR engine, EGC scrubber, WTS and tanks(Hansen et al., 2013)

4.3. Marine fuels

Another option for the shipowners to meet the regulations that are described in chapter 3, besides the emission control technologies (see section 4.1 and 4.2), is the use of other fuel types. This section will further discuss the subject of marine diesel fuels to gain insight that can be used for the monitoring system. Namely, the amount of SO_x and PM emissions in the exhaust stream reduces significantly by burning cleaner. Fuels that can be used to comply with the regulations are low sulphur fuels. These types of fuels will be mentioned in this section. The impact of the 2020 global sulphur limit will be described briefly in section 4.3.1. After this, section 4.3.2 will describe the fuels in combination with their emissions. Section 4.3.3 will clarify what the consequences are for the monitoring system when the ship makes use of two different types of fuel during sailing.

The current shipping industry uses mainly two different types of fuels. Namely, marine gas oil (MGO) and heavy fuel oil (HFO), also known as marine fuel oil (MFO). HFO is a residual fuel and contains a maximum sulphur content of 3.5% [m/m], while low-sulphur MGO contains 0.1% [m/m] sulphur content or less (DNV GL - Maritime, 2018).

MGO is a distillate and therefore consists of components of crude oil, that are obtained by a distillation process and subsequently condensed into liquid fractions. Therefore, usually MGO consists of a blend of distillates. However, MGO is quite similar to diesel oil. Only the density and the viscosity of the oil differs. These characteristics of MGO will lead in the end to significantly less PM and BC, as well as low SO_x emissions (American Bureau of Shipping, 2018). Other used fuels in shipping are marine diesel oil (MDO) and intermediate fuel oil (IFO). An overview of these typical marine fuels, including some parameters, is given in table 4.4.

Table 4.4: Typical parameters of marine fuels (American Bureau of Shipping, 2018)

Fuel types	**ISO category**	**Viscosity [cSt] (at 50° C for Residual and 40° C for distillate fuels)**		**Sulphur content (%)**
		Minimum	**Maximum**	
Heavy Fuel Oil (HFO)	Residual (RMA-RMK)	10	700	1.0 - 3.5
Marine Diesel Oil (MDO)	Distillate (DMB)	2	11	0.10 - 1.5
Marine Gas Oil (MGO, low sulphur distillate fuel)	Distillate (DMB and DMZ)	2	4	0.10 - 1.0
0.10% Heavy Fuel Oil (HFO, ECA fuel)	Not standardized	9	67	0.10
0.50% Heavy Fuel Oil (HFO, Global fuel)	Not standardized	No requirements defined	No requirements defined	0.50

The new IMO regulations and restrictions have led to the development of new marine low sulphur fuels. Examples of such fuels can also be seen in table 4.4, like HFO ECA fuel and HFO global fuel. These new developed fuels will contain less sulphur like MGO, but the difference is in the viscosity and the higher flash point. An overview of all possible 0.10% HFO's with their associated characteristics is included in appendix E.1. Additionally, it is interesting to see how the sulphur limits of the fuels that are used for ships relate to fuels used for land sources. Therefore, figure 4.18 is included, which shows that the limits for ship fuels are much less strict compared to, for example, road transport.

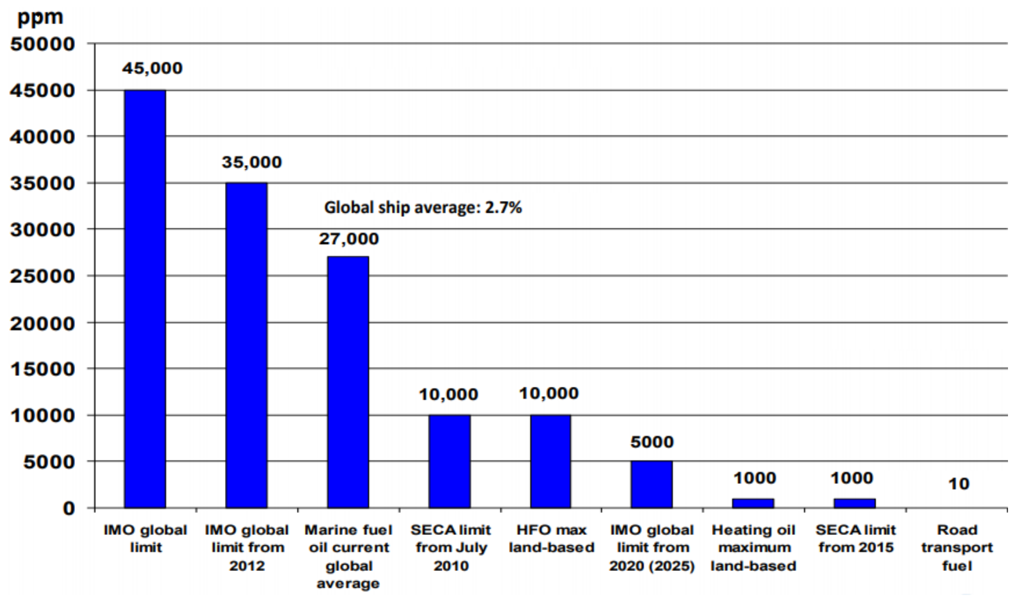


Figure 4.18: Sulphur content limits in ppm for various fuels (Airclim, 2017)

4.3.1. Impact 2020 global sulphur limit

The direct consequence of the 2020 global sulphur limit (sulphur content < 0.5%), is that only ships equipped with the right emission control technologies can sail on HFO. The expectation is that 4000 ships will operate with scrubbers in the year 2020. This means that no more then 11% of the ships will use high sulphur fuel (DNV GL - Maritime, 2018). This also means that the demand for high-sulphur HFO will be strongly reduced. Shell has investigated the future bunker demand and concluded that the transition to 0.5% sulphur content will cause more changes to the global marine industry than the 0.1% sulphur content ECA regulation from 2015. The impact of the 2020 transition will be approximately 75% of the global demand of marine fuel demand when compared to the demand of ECA fuel (Shell-marine, 2018). To illustrate the expected global fuel demand, figure 4.19 is used. The figure indicates that the impact of the 2020 global sulphur implementation in the field of fuel demand will be enormous. To illustrate, the daily consumption of shipping lies around the 750.000 barrels per day of MGO and the 3,2 million barrels per day of HFO. The prognosis is that this distribution will change to 3,4 million barrels per day MGO and 70.000 barrels per day HFO (Lee Hong Liang, Asia Editor and Seatrade Maritime News, 2018).

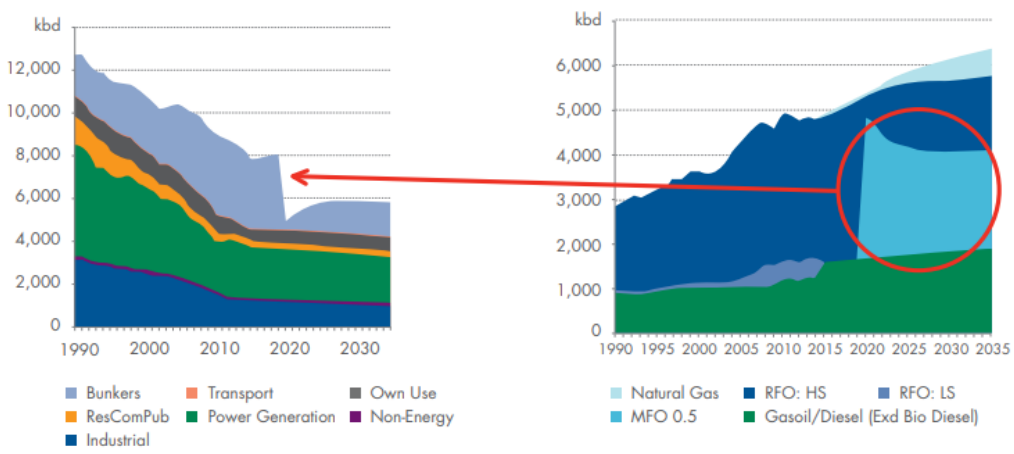


Figure 4.19: Global residual fuel oil demand by sector (left) & Bunker demand (right) (Shell-marine, 2018)

The sulphur 2020 limit will also have a considerable impact on the fuel prices. Ship & Bunker monitored the Rotterdam bunker prices of IFO380 (3.5%sulphur content) and MGO (1.5% sulphur content) over a period of 5 years (1 march 2012 - march 2017) (see figure 4.20). The average bunker price in Rotterdam over this period was around the $255 per metric ton. The figure shows that the bunker prices dropped around the year 2015, relative to the previous years. The reason for this price drop is probably the implementation of the stricter SO_x regulation within ECA in the beginning of 2015. Nevertheless, the fuel price will ultimately be determined by supply and demand. Appendix E.2 is included to show the prices in detail over the past period.

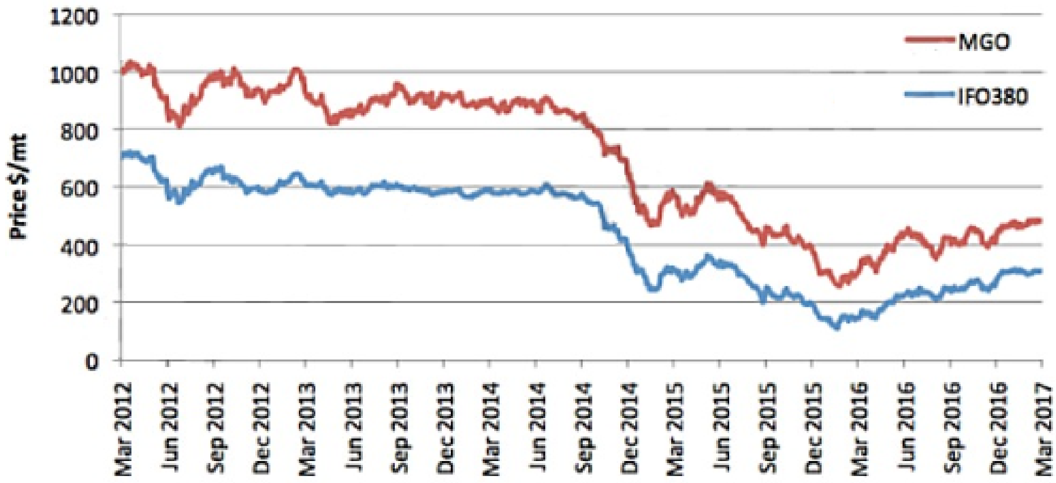


Figure 4.20: Rotterdam bunker prices IFO380 vs MGO (Ship & Bunker, 2017)

The expectation is that the prices of fuels with a low sulphur concentration will increase drastically after the sulphur 2020 implementation (figure 4.21 shows the current prices of low sulphur fuels compared with IFO380 with a sulphur content of max 3.5%). Namely, switching to a low sulphur fuel (sulphur content < 0.5%) will be a costly solution for shipping. The prospect is that the higher costs that will be made by the shipping companies will be calculated to the final customers. These higher prices can also lead to a choice for a cheap fuel, like for example IFO380, in combination with emission control technologies, like scrubbers as a more attractive solution. More about this subject can be read in section 4.4.

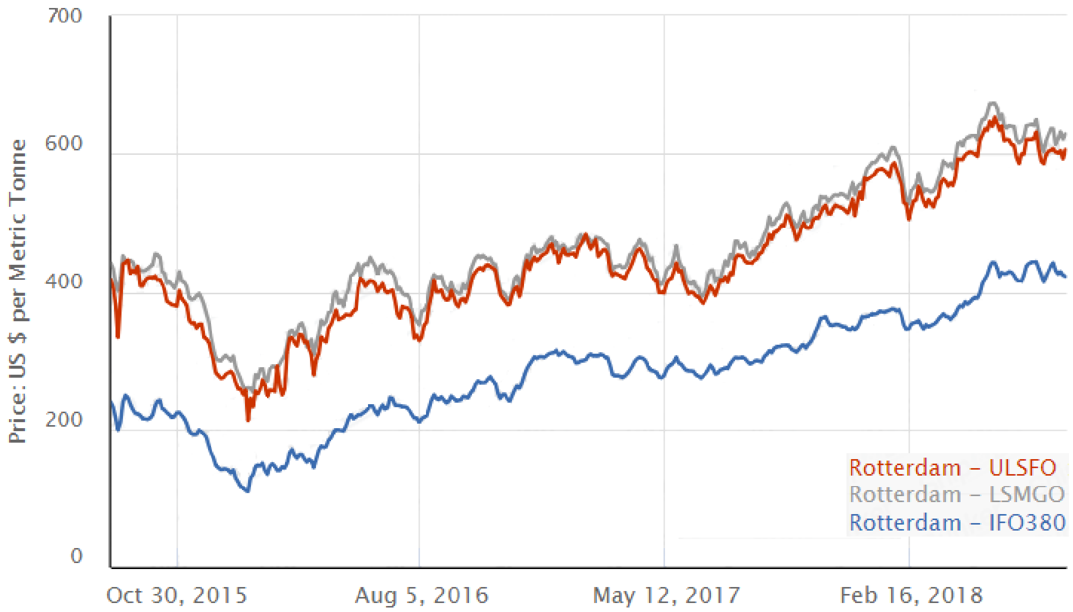


Figure 4.21: Rotterdam bunker prices ULSFO, LSMGO and IFO380 (Ship & Bunker, 2017)

4.3.2. Fuels in combination with emissions

It is clear that the type of fuel burned by a ship's engine affects the amount of emission. In the past, research has been executed on the amount of emission in relation to the sulphur content of the fuel. An example of such a study can be seen in figure 4.22. The values for PM and BC emissions are subtracted from the plot and also presented in table form in figure 4.22.

	Sulphur content (%)				
	0.1	**0.5**	**1**	**2**	**3**
PM_{10}	38	57	76	124	176
$PM_{2.5}$	37	54	73	120	167
BC	8.8	8.8	8.8	6	4

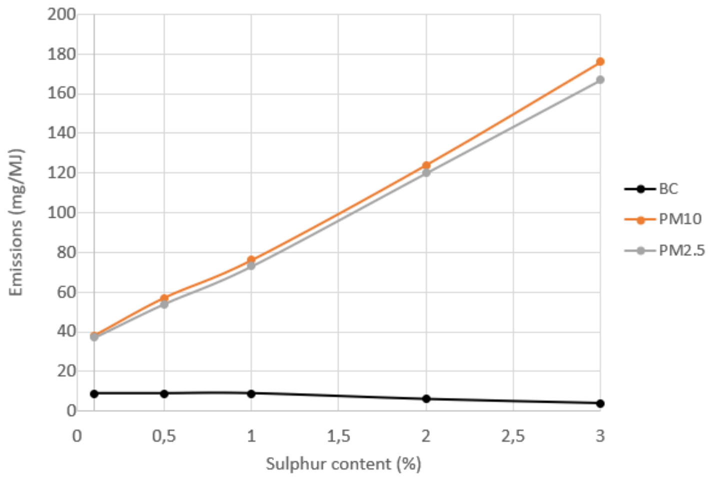


Figure 4.22: Particulate matter and black carbon emission factors for shipping used in he GAINS model (Klimont et al., 2017)

Logically, it can be seen that the amount of PM increases when the sulphur content in the fuel also increases. This observation is confirmed in other studies (see figure 4.23). The reason for this is that a few percent of the SO_2 is converted to H_2SO_4 which is adsorbed by the PM particles together with additional H_2O. Consequently the PM mass strongly increases.

An approximation of a PM emission factor is made by Kristensen based on the data from Carlton and Ristimake. This PM emission factor in [g/kWh] reads as follows, with S for % sulphur content in fuel :

$$PM = 0.26 + 0.081 \cdot S + 0.103 \cdot S^2$$

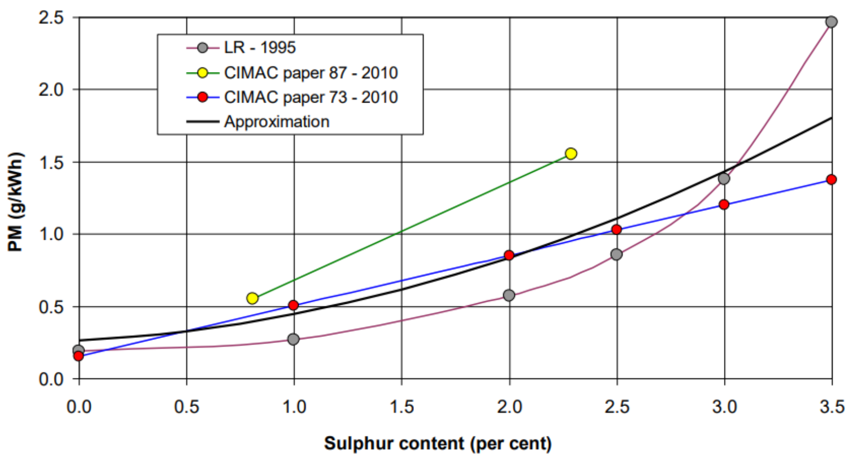


Figure 4.23: Relationship between fuel sulphur content and PM emissions (Carlton et al., 1995) (Ristimaki et al., 2010) (Kristensen, 2015)

This trend does not apply for BC. It appears that a higher sulphur content causes a lower BC emission. This occurs in a BC measurement campaign carried out by The International Council of Combustion Engines (see figure 4.24 (CIMAC, 2012)).

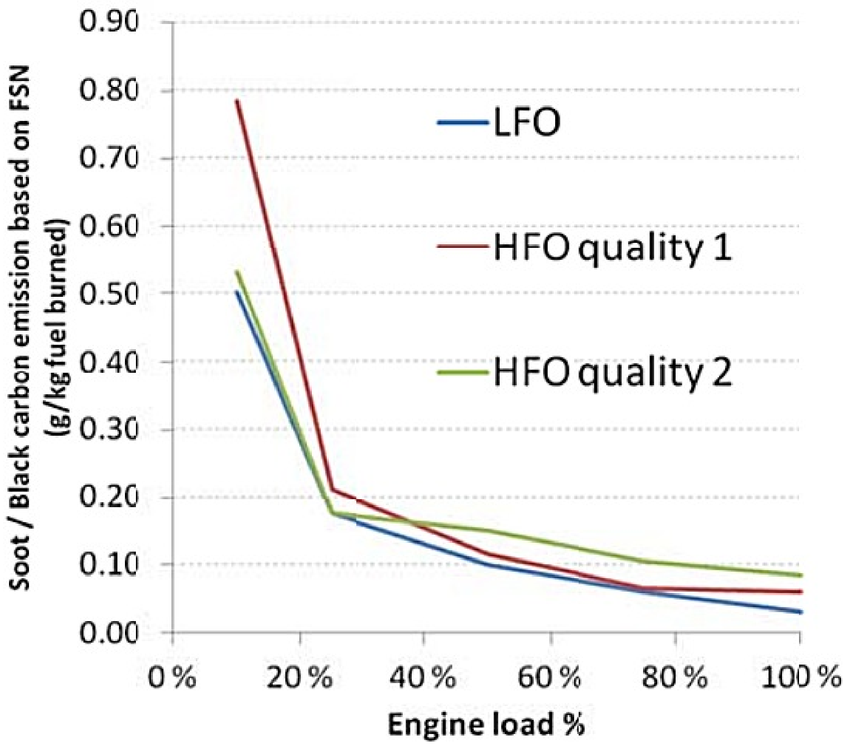


Figure 4.24: Reported black carbon emissions as a function of engine load percent (CIMAC, 2012)

The CIMEC executed a BC measurement on a medium speed 4-stroke large diesel engine based on the filter smoke number. The filter smoke number is a type of measurement at which a clean filter is used in the exhaust stream. The degree of blackening of the clean filter in a given column leads to data. This measurement is done with three different fuels, namely distillate/light fuel oil (LFO) with a sulphur content below the 0.05%, HFO quality 1 with a sulphur content of 0.89% and HFO quality 2 with a sulphur content of 2.42%. It can be seen in figure 4.24 that the BC emissions are plotted against the percentage of the engine load. It is found out that the BC emissions are non-linear with the engine load for the tested fuels. An interesting observation can be noticed. Namely, the LFO may not have the expected benefits compared with HFO. So, the CIMEC concluded that switching to fuels with a low sulphur content may not result in reduced BC emissions and more research is needed on BC emission.

An overview of the combination of fuel type and emission control systems for SO_x and NO_x in order to meet the regulations is given in table 4.5.

Table 4.5: Overview fuel in combination with engine system and emission (DNV GL - Maritime, 2018)

	HFO	**LSHFO/MGO**
SOx	Scrubber	Compliance
NOx	Tier III: EGR/SCR	Tier III: EGR/SCR

It is logical that a higher sulphur content results in higher SO_x emissions. See figure 4.25 for the sulphur content SO_2 emission ratio. Therefore, a scrubber is necessary when a ship sails on HFO and nothing is needed when using LSHFO/MGO with the appropriate sulphur content in the future. In the case of NO_x emissions, measures must be taken, like EGR or SCR for TIER III compliance for all types of fuels.

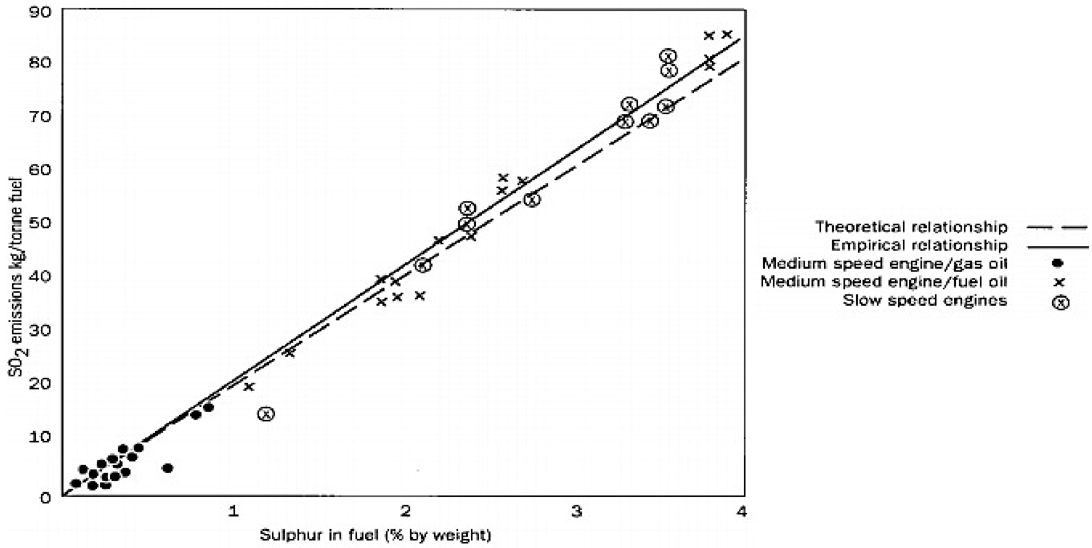


Figure 4.25: Relationship between fuel sulphur content and SO2 missions for marine diesel engines (Kristensen, 2015)

4.3.3. Fuel switching

Ships that sail inside and outside an ECA mostly use two different types of fuels (see figure 4.26). Outside the ECA's they often use the cheaper HFO fuel and inside the ECA's they use LSHFO or ULSFO to satisfy the 0.1% limit. When a ship uses different types of fuels during a trip, an on board procedure has to be written, an example can be seen in appendix E.3. This document shows how the fuel change over is accomplished. So this document must demonstrate that sufficient time was allotted for the fuel change. The time is necessary so all noncompliant fuel can be flushed away before entering an ECA. The date, time and exact location must be logged of the fuel changeover together with the volume of low sulphur fuel in each tank, when entering or leaving the ECA (American Bureau of Shipping, 2018). It is difficult for the inspection to verify if this procedure has been done correctly. The on board monitoring system could offer a solution for this problem. The system then have to be equipped with a GPS tracker, more about this can be read in chapter 8.

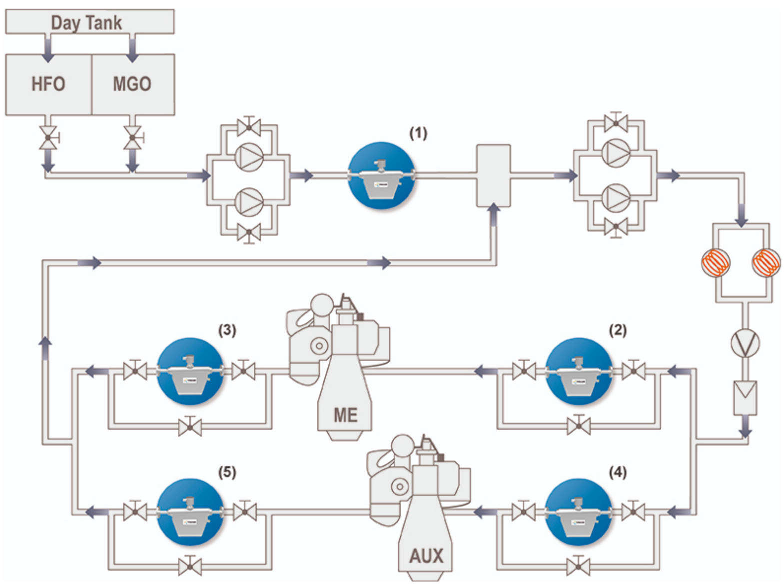


Figure 4.26: Example of a configuration with two different types of fuels (TCM-Marine, 2017)

4.3.4. Influence of fuel on the emission monitoring system

The previous sections are used to gather information about marine diesel fuels, where the emission monitoring system must deal with in the future. A description was given of the most common marine diesels, including fuels which probably will be developed. The reason for the development of these new fuels is the 2020 sulphur regulation. The expectation is that this regulation will cause an immense impact in the world of marine fuels. However, every scenario has to be taken into account, because it is complex and difficult to forecast what will be usual regarding this topic after 2020.

An important matter for the monitoring system according to the fuel is the rate of deterioration of the sensors. Namely, the composition of the fuel will be responsible for the degradation of the sensors. The expectation is that metals, like vanadium and possibly SO_x, may cause deterioration of the sensors. The rate of degradation of the sensors per fuel type is still unknown at the moment. This means that this can not be taken into account in the requirements in chapter 5.

The fuel price will indirectly also be of influence for the emission monitoring system, especially in the location where it should be installed. The price of the oil will play a role in the decision to install a scrubber. Indeed, it is very likely that shipowners will choose for emission control technologies in combination with a cheaper fuel, more about this decision in section 4.4. For the monitoring system, this means that it has to be installed after scrubber.

Another factor which must be taken into account, is the possibility that ships will use multiple types of fuels. When the monitoring system is working properly, it should appear in the data when a ship has switched to another fuel. However, this will have to be done at the right locations, according the IMO regulations (see section 3.2). An option to enforce these location regulations will be the addition of a GPS tracker, more about this solutions will be explained in chapter 8.

4.4. Combined measures and options for compliance

The previous sections were about the subjects emission control technologies and marine diesel fuels. This section will combine these two subjects in the form of a brief overview of the combined measures that can be taken by shipowners, so they meet the future legislation. The underlying idea behind this section is that the monitoring system has to deal with the consequences of the regulations and the choices that will be made by the shipowners, as is explained earlier. This will give an insight in the combinations that are possible currently and in the future.

The overview has been made in the form of a table, regarding the compliance for vessels inside and outside an ECA (see table 4.6). This table shows the possible control technology measures (see section 4.1 and section 4.2) that can be taken in combination with the type of marine diesel fuel (see section 4.3) that can be used. This will give an insight in the combinations that are possible in the future.

Table 4.6: Overview of fuel and technological options for various environmental requirements (own composition, 2018)

		Global	
Fuel type	**Sulphur content**	**<2020 (Tier II and Sulphur <3.5%)**	**>2020 (Tier II and Sulphur <0.5%)**
HFO/IFO380/ IFO180	<3.5%	(optional engine control technologies)	Wet or dry exhaust scrubber (optional engine control technologies)
LSHFO	<0.5%	Complies	Complies
MDO/MGO	<1.5%	Complies	Wet or dry exhaust scrubber (optional engine control technologies)
ULSFO/LSMGO	<0.1%	Complies	Complies

		ECA	
Fuel	**Sulphur content**	**SECA (Tier II and Sulphur <0.1%)**	**SECA + NECA (Tier III and Sulphur <0.1%)**
HFO/IFO380/ IFO180	<3.5%	Wet or dry exhaust scrubber	Wet or dry exhaust scrubber Tier III engine or Tier II engine + SCR or EGR
LSHFO	<0.5%	Wet or dry exhaust scrubber	Wet or dry exhaust scrubber (optional engine control technologies) Tier III engine or Tier II engine + SCR or EGR
MDO/MGO	<1.5%	Wet or dry exhaust scrubber	Wet or dry exhaust scrubber (optional engine control technologies) Tier III engine or Tier II engine + SCR or EGR
ULSFO/LSMGO	<0.1%	Complies	Tier III engine or Tier II engine + SCR or EGR

Table 4.6 shows that it will be necessary to use emission control technologies according to SO_x emissions, when using the cheaper HFO or MDO/MGO in the future. The wet or dry scrubber will be the most obvious choice for shipowners (see chapter 4) and is therefore mentioned as option in table 4.6. Other options are also possible and are mentioned under the heading 'engine control technologies'. An example of this is direct water injection for the reduction of PM. The table shows that use of ULSFO or LSMGO are the two options without further adjustments outside a NECA. It must be noticed that the maximum possible sulphur content is indicted per fuel type. So it could be that the sulphur content of LSHFO is lower than 0.1% (see appendix E.1).

The options to comply with the NO_x limits are mainly dependent on the ship construction date (see section 3.3). Ships constructed after 1 January 2011 have to comply the Tier II standard and ships constructed after 1 January 2016 have to comply the Tier III standard within a NECA. The options for shipowners within a NECA are therefore: a Tier III engine or a Tier II engine in combination with a selective catalytic reduction system or an exhaust gas recirculation system.

Table 4.6 shows that the implementation of emission control technologies are strongly dependent on the fuel choice of the ship owner. This is one of the reasons why it is difficult to predict which combination between fuel and emission control technologies will be widely used. So, the future will have to point out the most common and chosen combination of fuel and emission control technologies. This choice depends on many things, like fuel price and availability, company image and the share of time the ships sails in Emission Control Areas. The more time a ships sails in a ECA, the higher the payback of a scrubber system.

For example the choice between the option of a low sulphur fuel and a scrubber with a high sulphur content fuel, based on price is further elaborated below. This example is worked out in a very simple way for a specific ship type. The price difference between IFO380 (sulphur content 3.5%) and ULSFO (sulphur content 0.1%,) expressed in profit per year, will be compared with the investment costs of a scrubber.

One of the most important variable in this calculation, is the fuel consumption. The fuel consumption of a ship depends primarily non-linearly on the ships payload and the sailing speed. Nevertheless, the influence of the following examples are also important on the fuel consumption: hull shape, ship size and engine type. For this calculation is chosen to use a container ship, because the fuel consumption is available of this type of ship (see figure 4.27). This figure shows the fuel consumption of container ships in tons per day depending on the ship speed in knots.

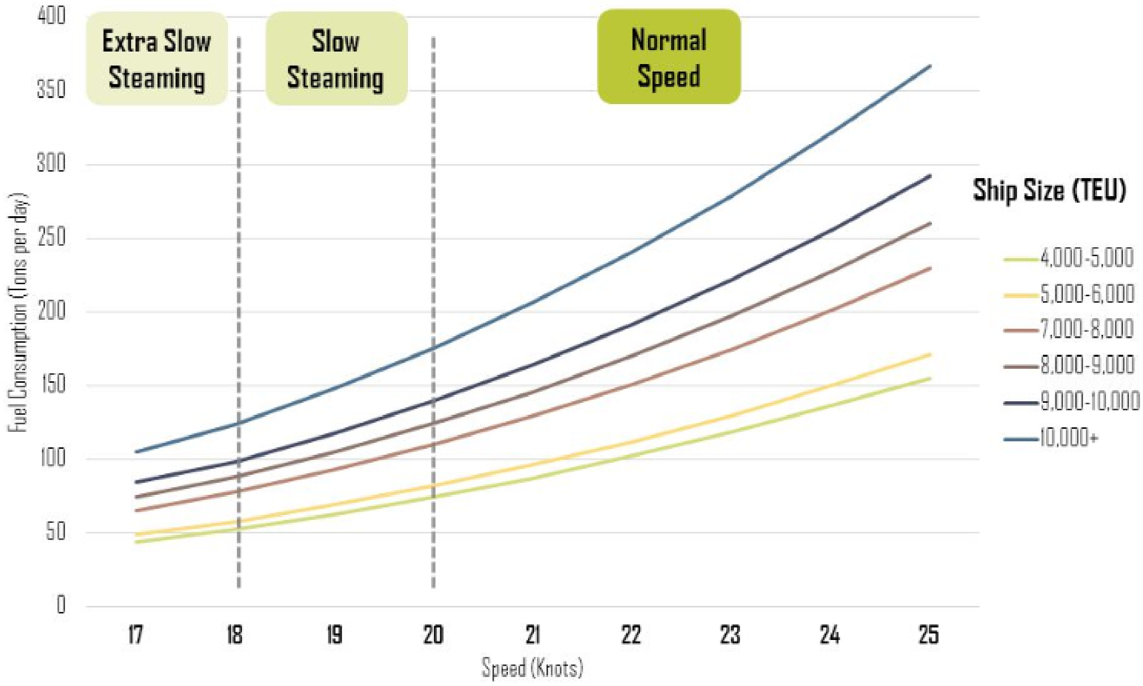


Figure 4.27: Fuel consumption by container ship size and speed (Rodrigue et al., 2016)

A valuable parameter to determine which option will be the best, is the payback period in this case, that of the scrubber installation. In order to calculate this parameter, it will be necessary to know the profit of the scrubber installation and the investment costs. The profit in this case is the price difference per ton fuel between IFO380-ULSFO and the investment costs of a scrubber installation, which lies between the $1.20 million to $8 million for the equipment alone, so without installation (Reuters, 2018). These scrubber prices are also verified with the stakeholder of chapter 9. The profit per year is calculated and displayed in figure 4.28. In this figure it is assumed that the ship will sail for 300 days per year. And a 7000-8000 TEU ship is used for this example calculation.

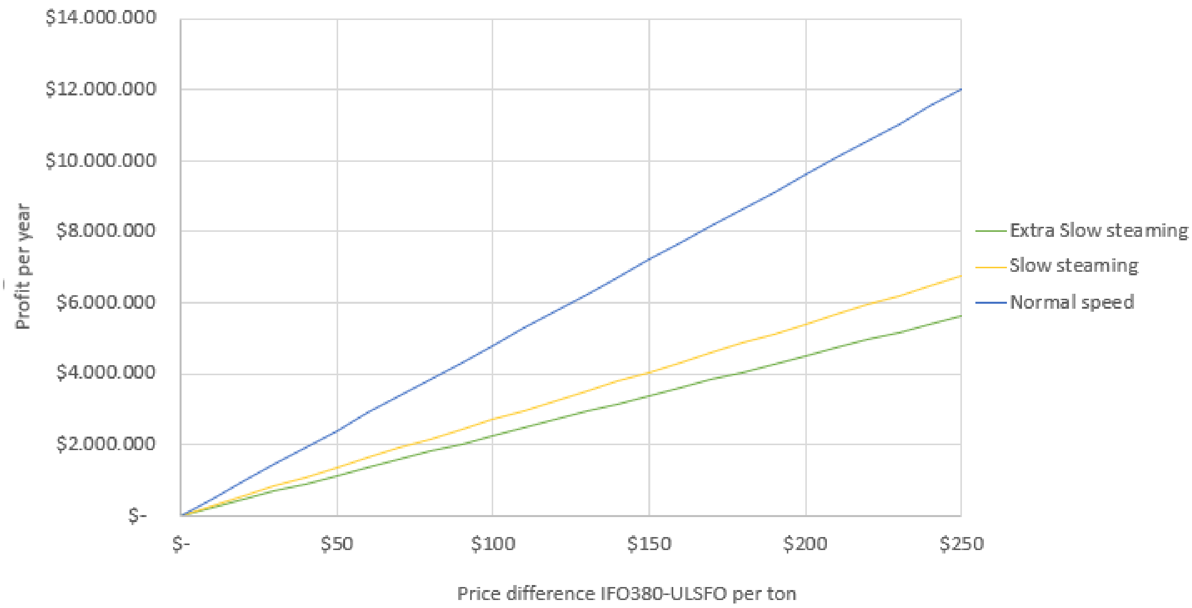


Figure 4.28: Profit per year for a 7000-8000 TEU container ship that sails 300 days (own composition, 2018)

The price of a scrubber for a container ship that is used in figure 4.28, is estimated around the $7 million. This means that the payback period will be 9 months, based on a price difference between the two fuels of $200 and a normal sailing speed. This reveals that in this scenario, with this type of ship, the payback period will be quite short. To rule out that this specific scenario is only due to coincidence, more scenarios will be calculated.

Four different ships are selected for these scenarios, namely: a container ship with a capacity of 20.000 TEU, a container ship with a capacity of 1000 TEU, a bulk carrier of 170.000 dwt and a tanker of 200.000 dwt. These ships are randomly selected, with the precondition that all necessary parameters are available for this calculation. Because there is also a strong degree of uncertainty, three different scenarios will be used based on price difference per ton fuel between IFO380 and ULFSO. Namely, an optimistic scenario in favor of a scrubber, this means a price difference between the fuels of $240, a central scenario with a price difference of $200 and a pessimistic scenario with a price difference of $160. Note that the current difference in price lies around the $160 per ton fuel and it is expected that the price difference will increase after the sulphur cap of 2020 (see section 4.3.1). Furthermore, it makes sense that the sailing time of a ship will be of great importance for the fuel consumption. Therefore, a calculation is made based on 300 sailing days per year and another calculation is made based on 200 sailing days per year. The result of the calculated scenarios are shown in table 4.7.

Table 4.7: Overview payback period for various scenarios and ship types for a scrubber in combination with IFO380 (own composition, 2018)

Ship type	**Fuel consumption [Ton per day]**	**Scrubber costs [$]**	**Sailing time per year [days]**	**Scenario**	**Fuel profit per year [$]**	**Payback period [months]**
Container 20.000 TEU	250	8.000.000	300	Optimistic	18.000.000	6
				Central	15.000.000	7
				Pessimistic	12.000.000	8
			200	Optimistic	12.000.000	8
				Central	10.000.000	10
				Pessimistic	8.000.000	12
Container 1000 TEU	30	2.250.000	300	Optimistic	2.160.000	13
				Central	1.800.000	15
				Pessimistic	1.440.000	19
			200	Optimistic	1.440.000	19
				Central	1.200.000	23
				Pessimistic	960.000	29
Bulk 170.000 dwt	80	4.000.000	300	Optimistic	5.760.000	9
				Central	4.800.000	10
				Pessimistic	3.840.000	13
			200	Optimistic	3.840.000	13
				Central	3.200.000	15
				Pessimistic	2.560.000	19
Tanker 200.000 dwt	110	5.000.000	300	Optimistic	7.920.000	8
				Central	6.600.000	10
				Pessimistic	5.280.000	12
			200	Optimistic	5.280.000	12
				Central	4.400.000	14
				Pessimistic	3.520.000	17

Table 4.7 confirms that the payback period is not too long for the calculated cases. Which should be taken into account is that only the scrubber costs are included and not the installation cost or the maintenance costs. An additional fact, which applies for the installation of a scrubber (new buildings excluded) is that the ship can not earn money during the installation. Thus it can be concluded that the payback period will be longer, when the installation costs with all related matters will be included.

From table 4.7 can also be concluded that the payback period will be faster with bigger ships relative to smaller ships. It seems that with this information a shipowner will be inclined to choose for the scrubber option.

However, it must be taken into account that this is not the case. To the fact that shipowners, especially in the container business, will try to charge the extra costs of low sulphur fuel to the final costumer. The benefit of this choice is that the shipowner does not have to worry about having a scrubber installation, with additional disadvantages like operation costs, loss of space, weight gain and operational related problems. The future will have to prove if the shipowner is able to pass the additional costs to the final costumer. If not, than the scrubber will surely be seen as an alternative.

The objective of this chapter is to determine whether a scrubber cleaning system has to be taken into account for the monitoring system. Because of the above mentioned uncertainty, it can be concluded that both options have to be taken into account for the monitoring system. This information will be used for the requirements for the monitoring system in chapter 5.

The information of the previous chapters is also summarized in the form of a flowchart (see figure 4.29). By following the arrows in this figure, it will become clear what the reason for the system is. There are also a few open choices in the figure. These choices must be made by the shipowners. For example, the selection of a fuel type in combination with an emission control technology. The final choice of the shipowner should always be within the emission limits of the IMO (see chapter 3). This enforcement element is exactly one of the intended functions of the emission monitoring system, as shown in the bottom part of figure 4.29.

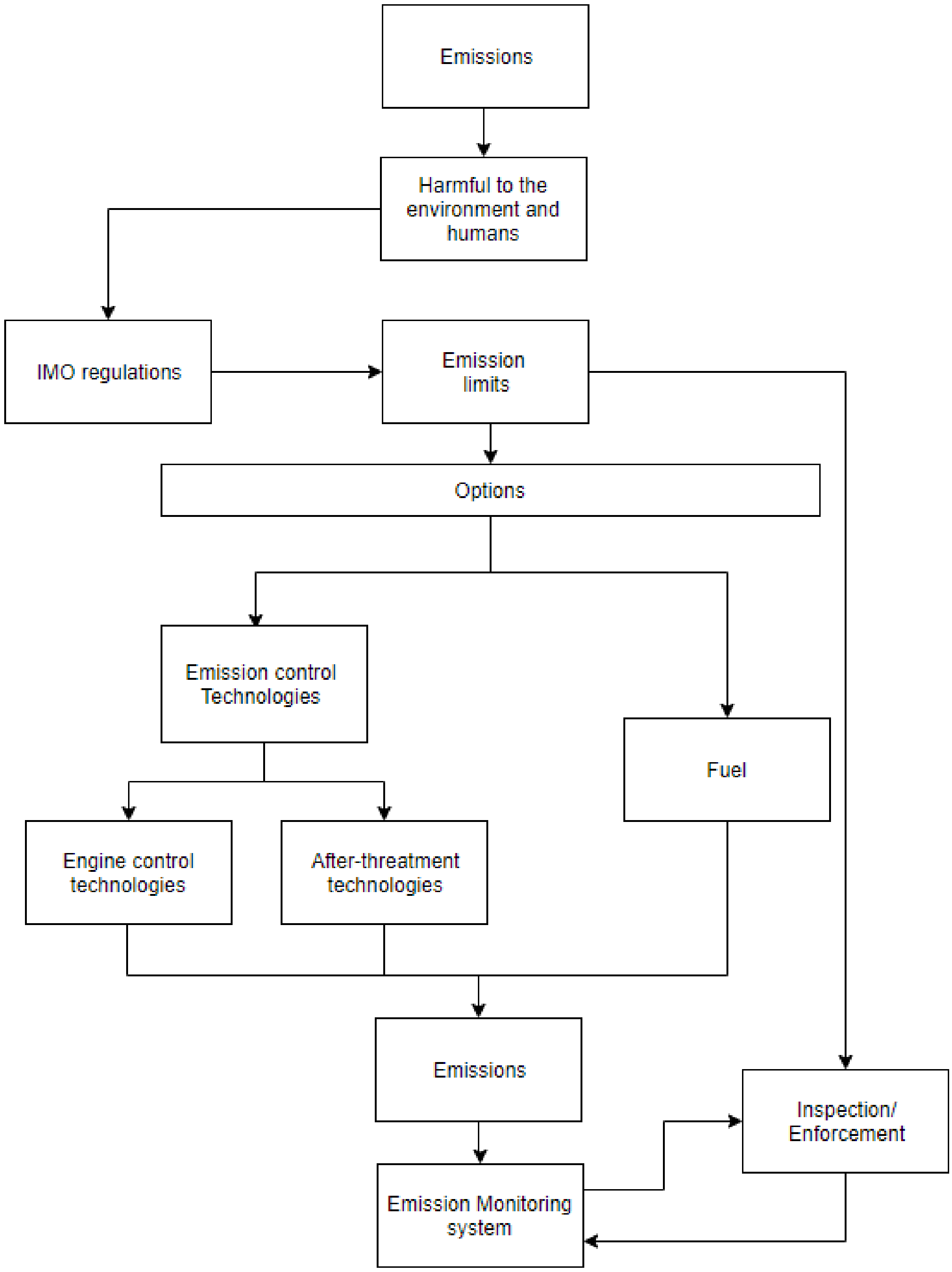


Figure 4.29: Flowchart overview (own composition, 2018)

5

Requirements on board emission monitoring system

One of the objectives of the emission monitoring is that the system should be able to measure NO_x, SO_x, PM and BC. This chapter will define the basic requirements to which the system must comply. These requirements will be used in chapter 6 and especially in chapter 7, in which the possible monitoring systems will be reviewed.

What needs to be taken into account, is that each ship has been built differently. This means that it will not always be possible to measure under exact the same conditions. This chapter must ensure that a demarcation takes place so that a uniform measurement method can be carried out, on which the systems are selected and reviewed in the next chapters.

The investigation of chapter 2 and chapter 3 has shown that there is not enough knowledge available in the field of BC measurement. For this reason, it has been decided that BC measurement will not be included in the requirements for the on board monitoring system.

5.1. Location of the monitoring system

It is evident that the location of the sampling will be of great importance for the measurement of emissions. Namely, the data has to be reliable in order to check the compliance of the vessel. It also applies for the location that the available space within the engine room will not always be the same (see figure 5.1). The objective of establishing suitable locations, is that the available on board monitoring systems can be reviewed on the feasibility, when it comes to the amount of space they occupy.

Figure 5.1: Examples of two different engine rooms (James Hamilton, 2018), (Netwave Systems B.V, 2018)

The monitoring system will presumably consist of multiple components. For example, a sample part and processing part, which includes the storage and sending of the data (see chapter 8). The location for the sample part is of great influence for the success of the system. This part needs to be installed after the engines and, if applicable, after emission control systems, as described in chapter 4. The expectation is that many ships will install some kind of emission control techniques. Hence, it is sensible to place the sampling part towards the end of the exhaust system as much as possible. The benefit of this location is that the sampling part will not be in the way if a shipowner decides to install a scrubber at a later point in time. By taking this into account in the form of a requirement, it means that there will be two possible locations for the sampling system. The first option is in the exhaust pipe (see figure 5.2). This figure shows a probe in the exhaust duct and this is one example of the sampling principles (see section 6.4.5). Chapter 6 will discuss the possible options in combination with this location.

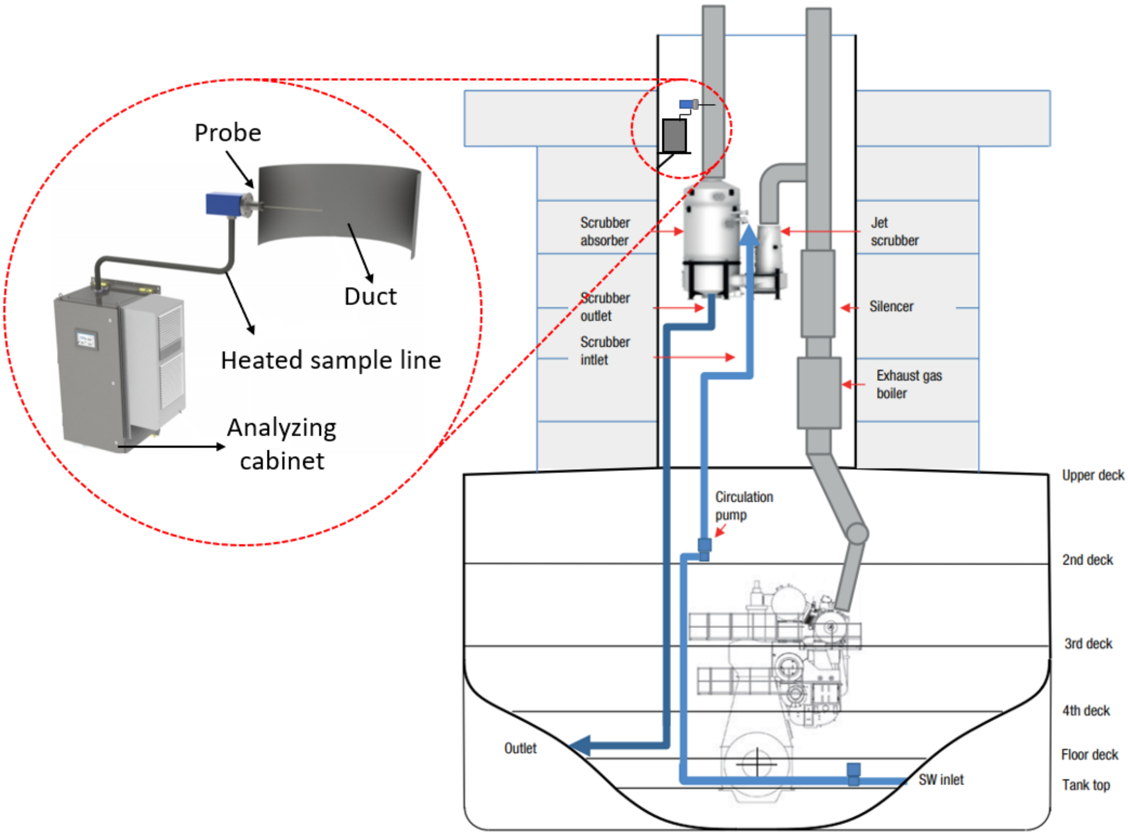


Figure 5.2: Example of location in the exhaust plume (own composition, 2018)

The other possible location for the sampling system of the on board monitoring system, is outside the ship. One of the options could be measuring in the exhaust plume with a sensor box (see figure 5.3).

Figure 5.3: Example of location in the exhaust plume (own composition, 2018)

5.2. Measurement ranges and calculations for the monitoring system

It is important that all measurements could be compared with each other similarly, in order to determine the compliance of the vessel. Therefore, it will in advance be decided in which units the system has to measure. This is done in combination with the range. The legislation has been described in chapter 3 and will be used in this section for the determination of the ranges.

The NO_x emissions have to stay within the Tier limits (see section 3.3). These Tier limits are in g/kwh and are based on the rpm of the marine diesel engine. The direct consequence of the location choice is that the emissions have to be measured in the exhaust pipe or exhaust plume (see section 5.1). Therefore, it is necessary to convert the NO_x emission limit of g/kwh into parts per million (ppm). This is done according the following formula from (Pilusa et al., 2012):

$$NO_x(g/kwh) = 6.636 \cdot 10^{-3} \cdot NO_x(ppm)$$

Figure 5.4 is obtained by applying the formula on the NO_x emissions limits of the IMO.

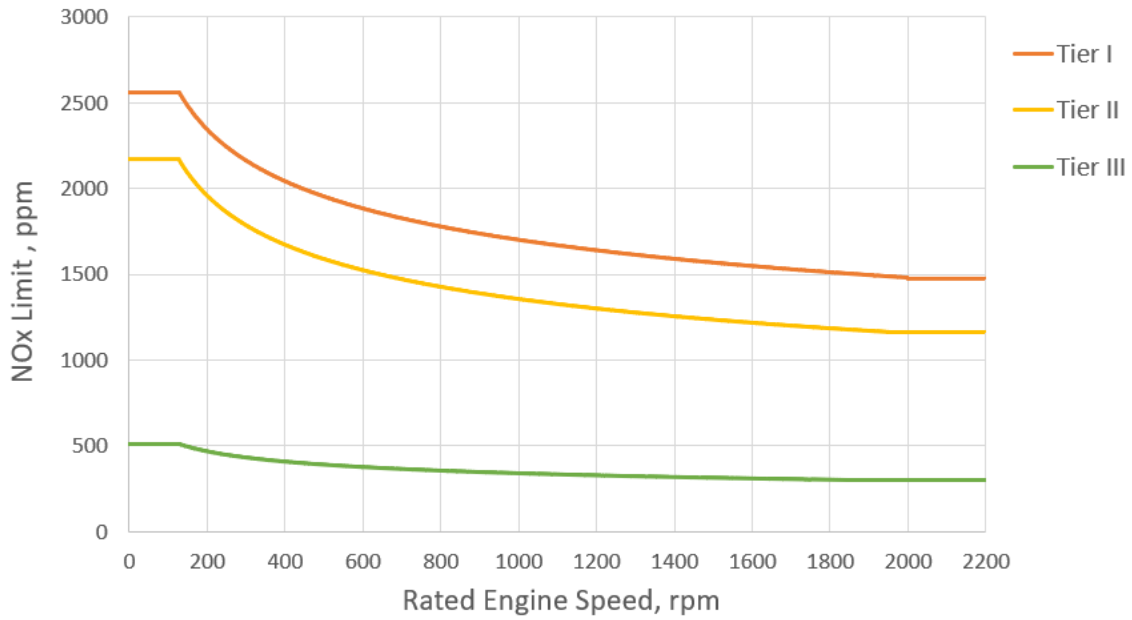


Figure 5.4: NO_x limits in ppm (own composition, 2018)

The figure 5.4 shows that the range of the sensors has to be at least between 0 ppm and 3000 ppm. Chapter 6 will investigate the possible sensors and analyzers that are able to measure NO_x emissions within this range.

One of the options in order to determine the NO_x emissions in g/kwh, is to use the NO_x/CO_2 ratio, as shown in the following formula (Balzani Lööv et al., 2014):

$$NO_x \quad (g/kwh) = \frac{c[NO_2](ppm)}{c[CO_2](ppm)} \cdot \frac{46}{12} \cdot 0.87 \cdot e(g/kwh)$$

In this formula the c[NO_x] and c[CO_2] stands for the measured net volume in order to determine the mixing ratio between the components. Furthermore, the molecular weight of nitrogen (14 g/mol), oxygen (16 g/mol) and carbon (12 g/mol), together with the carbon mass percent in the fuel (87% (m/m)), can be read. Without the term e(g/kwh), the NO_x emission is calculated in g/kg. This value has to be converted to engine power weighted NO_x (g/kwh), as is prescribed by the IMO. Therefore, the typical fuel efficiency that differs from 160 g/kwh to 210 g/kwh, depending on the engine parameter ((Cooper, 2005), (Dalsøren et al., 2009)).

The SO_x emission limit, as described in section 3.4 depends, on the sulphur content of the fuel. Because of this, it will be necessary to recalculate the emissions back to sulphur content of the fuel. This can be done with the SO_2/CO_2 ratio method. This method is mandatory for ships that are using an exhaust scrubber, because they have to prove that scrubber meets the requirements and the limits. The formula that is used, looks as follows (MEPC, 2015):

$$Sulphur \quad content(\%m/m) = \frac{[SO_2](ppm)}{[CO_2](\%v/v)} \cdot \frac{32}{12} \cdot 0.87 \cdot 100$$

Here, the SO_2 is measured in parts per million and the CO_2 in percentage by volume. The '32' in this formula indicates the molecular weight of sulphur in g/mol and the '12' is the molecular weight of carbon. Also the carbon mass percent of (87% m/m) is used.

This SO_2/CO_2 ratio is independent of fuel-to-air ratios. This means that the measurement result is not affected by changes in excess air. The benefit of this independence is that the ratio can be used and calculated at any point in operation, also at an operation point where no brake power is generated. Important to know is that the CO_2 should be measured only at a dry basis.

In order to determine the ranges of the sensors for the monitoring system, figure 5.5 is used. This figure shows the measuring range of SO_2 in ppm in combination with the volume percentage CO_2 for all the sulphur limits, that are described in section 3.4.

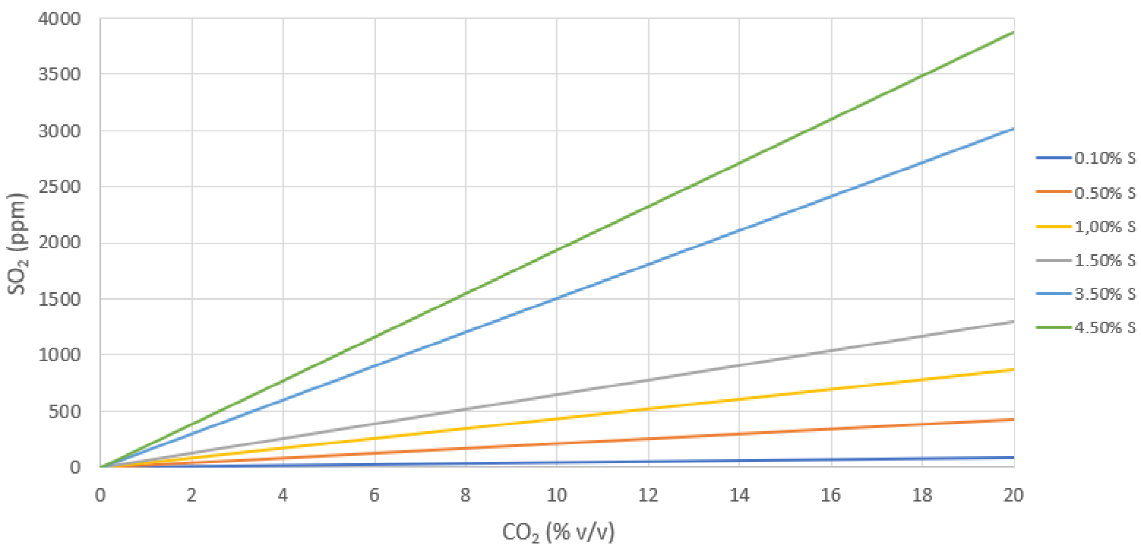


Figure 5.5: SO_2 (ppm) and CO_2 (% v/v) combination for the different IMO limits (own composition, 2018))

The expectation is that only the global limit of 0.50% and the 0.10% will be applicable at the time the emission monitoring is working. Therefore, it was chosen to focus on the range for these two sulphur contents (see figure 5.6). The key range for the CO_2 volume (3-12% v/v) is also implemented in this figure. It can be seen that the key range will be around 0-250 ppm. This range will be a requirement that has to be satisfied in the search for suitable sensors.

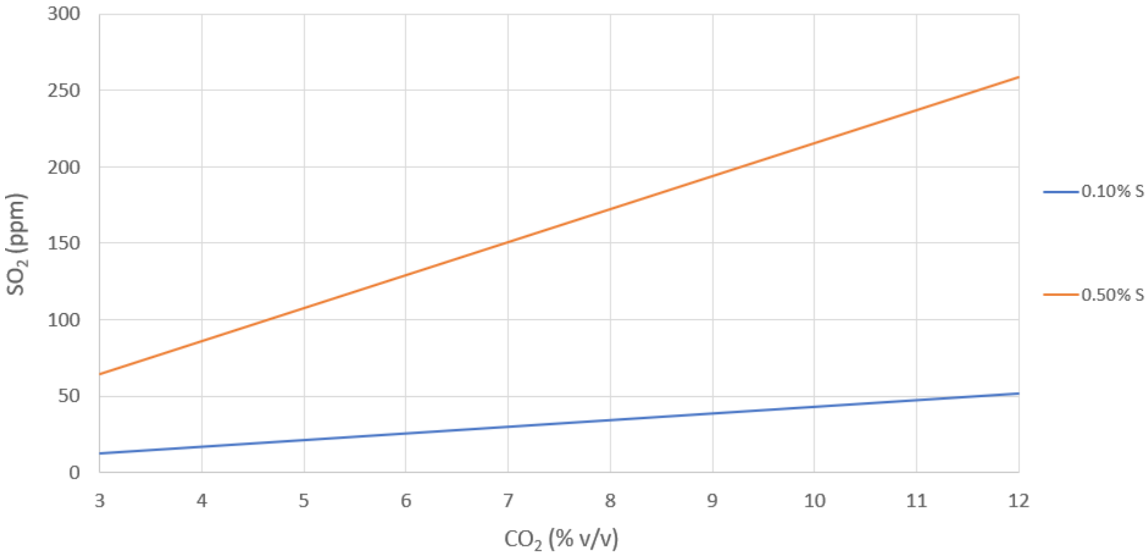


Figure 5.6: Key range SO_2 (ppm) and CO_2 (% v/v) combination for the ECA and global IMO limit (own composition, 2018)

Regarding the PM requirements for the sensor, it can be stated that the regulations are based on the sulphur content in the fuel. Nevertheless, figure 5.7 is included in order to give an impression of the measurement range of $PM_{2.5}$ and PM PM_{10} in mg/kwh.

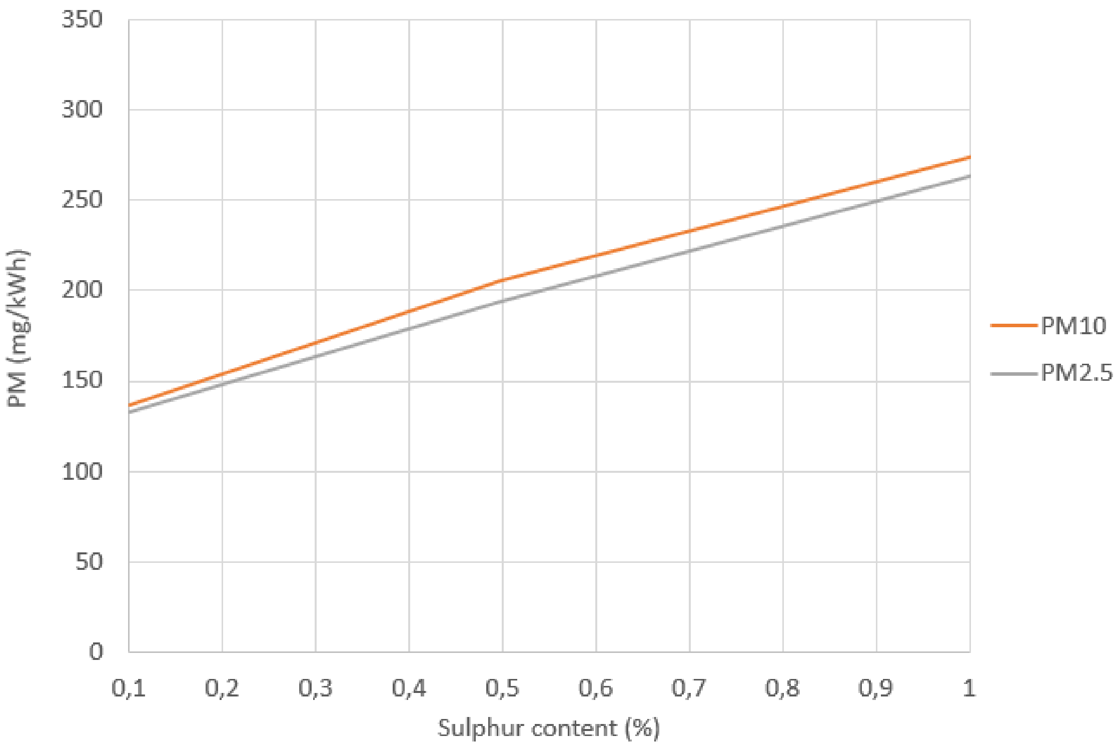


Figure 5.7: Range for particulate matter measurement in (mg/kWh) in combination with the sulphur content of the fuel (own composition, 2018)

5.3. Additional requirements

This section will mention the additional requirements, including the measurement ranges for the various emission components. The monitoring systems that meet these requirements will be mentioned in chapter 6 and reviewed based on these requirements. The output of the system must be digital to process the data in a computer, for which an Ethernet connection will be required, (see chapter 8). The minimum lifetime is determined at 5 years, which has to do with the docking schedule. Namely, each ship is obliged by the IMO to dock once every 5 years (IMO, 2007). This means that the system has to function for a minimum time of 5 years. The annual uptime in hours of the sampling part still needs to be determined. A combination must be found between proper enforcement and degradation of the sensors. However, the degradation differs per type of sensor, whereby the sample frequency could not be determined in advance. Nevertheless, the expectation is that the sampling system will have an uptime of around 2500-8000 hours per year (see green line in figure 5.8).

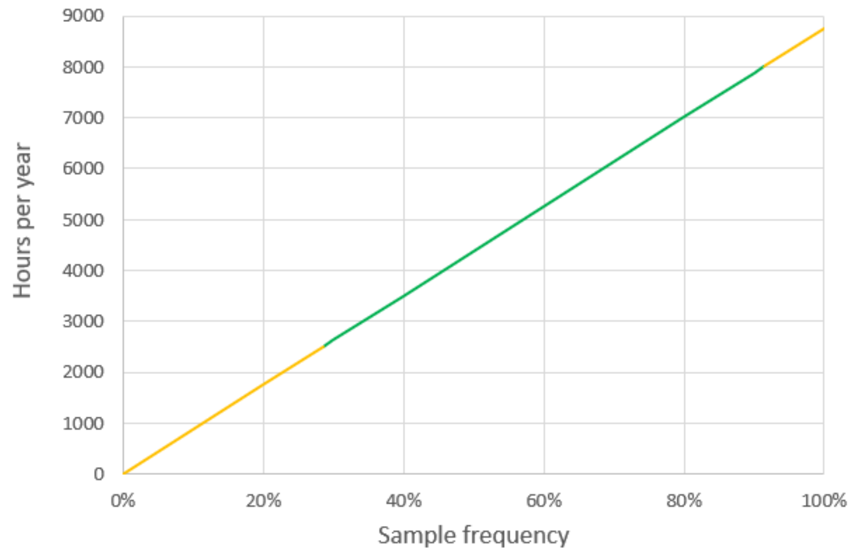


Figure 5.8: Uptime sample system (own composition, 2018)

The measurement time of a single measurement has to be less than five minutes. This time is related to the frequency of 0.0035 Hz. This frequency is retained, as it also applies for monitoring for exhaust gas cleaning systems (IMO, 2009). All remaining requirements are displayed in table 5.1. The same applies for the measurement ranges regarding the different emissions. As can be seen in table 5.1, the temperature is based on the engine load and after-treatment configuration. This will mainly apply to a sensor that will be installed in the stack (see section 5.1).

Table 5.1: Requirements and ranges emission monitoring system (own composition, 2018)

	Requirements system
Output system	Digital, wired using Ethernet
Lifetime	>5 years
Measurement time	<5 minutes
Uptime	2500 -8000 hours per year
Frequency	0.0035 Hz
Pressure	Atmospheric / max 10 kPa overpressure
Temperature	30°C - 400°C depending on engine load and exhaust after-treatment configuration
Available power	230 V AC, 50/60Hz two-phase
Location	Post after-treatment system
Maintenance	To be determined
Resilience to exhaust gas	Sensor should not fail after exposure to out-of-range gasses

Emission	**Range**
NO_x	0-3000 ppm
SO_x	0-300 ppm
CO_2	0-20 %v/v
PM	0-250 mg/kwh

6

Sensors and on board emission monitoring systems

The objective of this research is to recommend an on board emission monitoring system. To achieve this, an investigation in the form of a state of the art search will be executed on the available systems. This means that the focus will be on the newest developments in emission monitoring systems. This chapter will describe the results of this search in the form of possible on board emission monitoring systems. This is done with the purpose to be able to assess and compare the systems in chapter 7.

There will be a distinction in this chapter between low-end systems (see section 6.3) and high-end systems (see section 6.4). This distinction is based on the price of the system.

The possible systems mainly make use of sensors and will therefore also be described in this chapter (see section 6.2). By describing the working principles of the sensors, it should also be easier to assess the sensors and systems in chapter 7. Before this, the chapter will start with a description of the possible gas sampling principles in section 6.1 in order to show which sensors are suitable for the measurement of NO_x, SO_x and PM emission on board a ship.

The location of the detection equipment will also be of great influence for the monitoring system. Chapter 5 indicated that there are two locations that are suitable for emission measurement, namely: measurement in the exhaust pipe (see figure 6.1) or measurement in the exhaust plume. This chapter will describe per system which measurement location is desirable.

The possible monitoring systems that are investigated in this chapter are not just originated from the shipbuilding sector, but also from other sectors. An example of this, is the automotive industry.

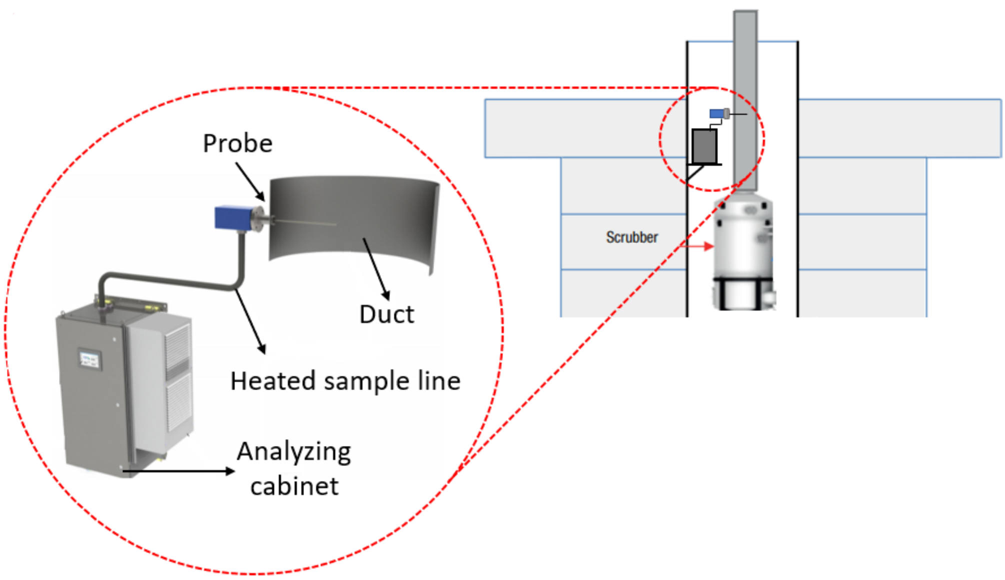


Figure 6.1: Example of a measurement at the location of the exhaust pipe (own composition, 2018)

6.1. Gas sampling principles

This section will outline the possible gas sampling principles in order to know which principles are suitable for measurement of emissions. The development of gas sensors has gone fast in the past decades. This has led to a wide variety of available sensors based on different sensing methods and materials. The available sensors are distinguished in a number of ways in the literature. When these sensors are, for example, based on sensing methods (Liu et al., 2012), it results in two groups: methods based on electrical variation with different materials and methods based on other kind of variation. An overview of the different gas sampling principles, is shown in figure 6.2.

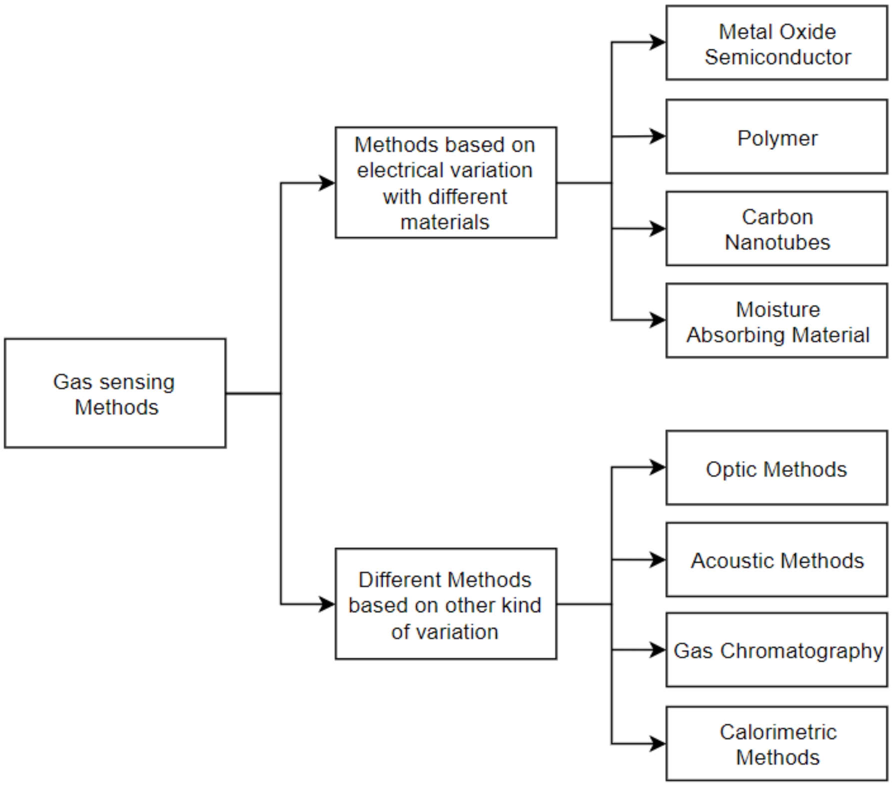


Figure 6.2: Overview of gas sensing methods (Liu et al., 2012)

Various gas sensing methods are available, as can be seen in figure 6.2. However, not all methods are suitable for measuring on board a ship. To provide insight which methods are able to measure on board a ship, an overview of these gas sampling principles is given in the form of a table (see table 6.1). Table 6.1 shows the advantages and disadvantages per sensor type/method and can be seen as a summary of the sensing methods according Liu and colleagues (2012). A number of indicators are used in this table in order to make a good comparison between the different methods. The following indicators are used:

- **Sensitivity**: the minimum value of target gases.
- **Response time**: the period of time that it takes from the detection of the signal until the sensor generates a warning signal.
- **Reversibility**: the extent to which the material could return to original state after detection.
- **Selectivity**: the ability to identify a specific gas among a gas mixture.
- **Energy consumption**: the extent to which the sensor uses energy.
- **Adsorptive capacity**: the extent to which the sensor can adsorp the molecules.
- **Fabrication**: the costs that are invalided during manufacture.

Table 6.1: Summary of basic gas sensing method (Liu et al., 2012)

Sensor/Material	Advantages	Disadvantages	Target Gases and Application fields
Metal Oxide Semiconductor	- Low cost - Short response time - Wide range of target gases - Long lifetime	-Relatively low sensitivity and selectivity - Sensitive to environmental factors - High energy consumption	-Industrial applications and civil use
Polymer	- High sensitivity - Short response time - Low cost of fabrication - Simple and portable structure - Low energy consumption	- Long-time instability - Irreversibility - Poor selectivity	- Indoor air monitoring - Storage place of synthetic products as paints, wax or fuels -Workplaces like chemical industries
Carbon Nanotubes	- Ultra sensitive - Great adsorptive capacity - Large surface area-to-volume ratio - Low weight	-Difficulties in fabrication and repeatability - High cost	-Detection of partial discharge (PD)
Moisture Absorbing Material	- Low cost - Low weight - High selectivity to water vapor	- Vulnerable to friction - Potential irreversibility in high humidity	-Humidity monitoring
Optical Methods	- High sensitivity, selectivity and stability - Long lifetime - Insensitive to environment change	- Difficulty in miniaturization - High cost	- Remote air quality monitoring - Gas leak detection systems with high accuracy and safety - High-end market applications
Calorimetric Methods	- Stable at ambient temperature - Low cost - Adequate sensitivity for industrial detection	- Risk of catalyst poisoning and explosion - Intrinsic deficiencies in selectivity	- Most combustible gases under industrial environment - Petrochemical plants - Mine tunnels - Kitchens
Gas Chromatography	- Excellent separation performance - High sensitivity and selectivity	- High cost - Difficulty in miniaturization for portable applications	- Typical laboratory analysis
Acoustic Methods	- Long lifetime -Avoiding secondary pollution	- Low sensitivity - Sensitive to environmental change	- Components of Wireless Sensor Networks

Based on table 6.1 and additional research, it can be concluded that some gas sampling techniques are not suitable for on board emission measurement. The measurement principles that are useful for on board measurement are: metal oxide semiconducters, optical methods, calorimetric methods and gas chromatography. These methods will be further investigated and used in the remainder of this report. The methods that are not suitable will be described in the next paragraph.

Polymers are not suitable due to the fact they are mainly used as moisture sensors (Cichosz et al., 2018). That is why polymer sensors are principally used to determine the relative humidity value in the environment. However, polymers can measure a few types of emission, but this can only be done for very low concentrations.

Carbon nanotubes are not suited, because they have a long sensitive element recovery time. The time it takes to recover for a carbon nanotube varies from several minutes to several hours (Zaporotskova et al., 2016). This property is not desirable when the monitoring system has to measure with a short time interval or even continuously.

Moisture absorbing sensors are mentioned for detecting water, as the name already suggests. These type of sensors are especially used to measure water vapor concentrations, since their dielectric value depends on the water content of its surroundings (Liu et al., 2012). As a result, the sensor is able to express the determined water concentration in terms of the surroundings air humidity.

Sensors based on acoustic methods are not also not suitable for on board monitoring, because the measurement with these sensors is extremely difficult in practice, especially in a process environment (Liu et al., 2012). Due to this reason, the acoustic sensor has not been widely applied in commercial applications.

Another method to classify the sensors is given by Korotcenkov (2007). He classified the following types of gas sensors: Semiconductor metal oxides sensors, catalytic combustion sensors, electrochemical sensors, thermal conductive sensors and infrared absorption sensors. These sensor types are all suitable for on board measurements and will therefore be described in section 6.2 in order to get familiar with the working principles and the characteristics. Before that, a comparison can be seen for the sensors based on a number of indicators. This comparison is made by Korotcenkov (2007) and can be seen in table 6.2.

Table 6.2: Comparison of various types of gas sensors (Korotcenkov, 2007)

Parameter	**Type of sensors**			
	Semi-conductor	**Catalytic combustion**	**Electro-chemical**	**Infrared absorption**
Sensitivity	Excellent	Good	Good	Excellent
Accuracy	Good	Good	Good	Excellent
Selectivity	Poor	Bad	Good	Excellent
Response time	Excellent	Good	Poor	Poor
Stability	Good	Good	Bad	Good
Durability	Good	Good	Poor	Excellent
Maintenance	Excellent	Excellent	Good	Poor
Cost	Excellent	Excellent	Good	Poor
Suitability to portable instruments	Excellent	Good	Poor	Bad

6.2. Possible sensors

Sensors are devices with the function to detect events or changes in its surroundings. Besides this, they are able to send information to other electronics, for example, a computer processor. This section will describe the working principles of the sensors that are suitable for the measurement of NO_x, SO_x and PM emissions on board of a ship. Most of the sensors that will be described are from section 6.1.

6.2.1. Semiconductor metal oxide sensor

The semiconductor metal oxide (SMO) sensor is one of the most used sensors. This has to do with the advantages, like high sensitivity and low costs (Liu et al., 2012). An SMO sensor usually exists out of a sensor body with a sensing element inside (see figure 6.3). The sensing element is the most important part of the sensor. This sensing element is a porous sintered block with a surface of polycrystalline resistors made of semiconducting oxides such as, for example: ZnO, $SnO_2$2, In_2O_3 and WO_3 (Yamazoe et al., 2003). For more information about the operating parameters of the various metal oxides, appendix G is included.

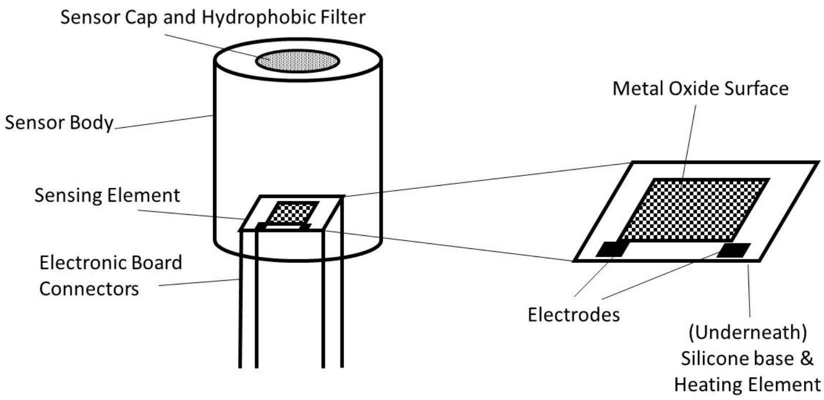


Figure 6.3: Example of an semiconductor metal oxide sensor (Evikon, 2018)

It is essential to note that the gas sensing mechanisms are not straightforward for this type of sensors. This has to do with the complex nature of the polycrystalline sensing element. Therefore, it will not be described in to depth. Nevertheless, figure 6.3 is included to show the basic processes that take place inside the sensor.

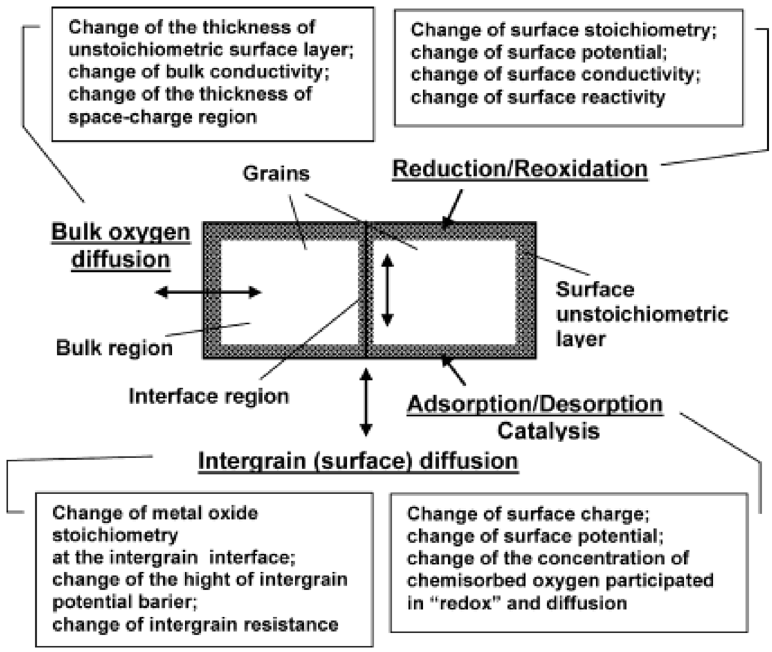


Figure 6.4: Diagram illustrating processes taking place in metal oxides during gas detection and their consequences for polycrystalline metal oxides properties (Korotcenkov, 2007)

The working principle of a SMO sensor consists of two important functions (see figure 6.5). One of these functions is the recognition of a gas through interaction between the gas and the SMO, which induces an electronic change of the oxide surface (receptor function). The other important function is the transduction phenomena into an electrical change of resistance of the sensor (transducer function) (Yamazoe et al., 2003).

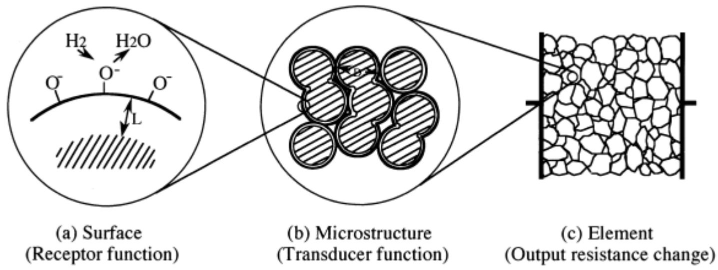


Figure 6.5: Receptor and transducer functions of the semiconductor sensor (Yamazoe et al., 2003)

Besides these two functions, a distinction could be made between two groups based on temperature. Namely, sensors which follow surface conductance effects and sensors which follow bulk conductance effects (Dey, 2018). The surface conductive sensor operates at low temperatures (400°C - 600°C) and the bulk conductance sensor operates at higher temperatures (>700 °C) (Moseley, 1992).

6.2.2. Catalytic combustion sensor

The catalytic combustion sensor is considered as a calorimetric sensor (see section 6.1). Calorimetric implies that the sensor measures differences in thermal conductivity in comparison with, for example air. In other words, the sensor measures the heat transfer, which is correlated with the changes in the environment under specified constraints.

This type of sensor is already in use for more than 50 years and also known under the name pellistor sensor. The catalytic combustion sensor is primarily used for the measurement of combustible gases, as the name already suggests. These sensors are produced by many different manufactures almost everywhere in the world. This results in a great variation in reliability and performance of the sensors (Chou, 2000).

Figure 6.6 shows a catalytic combustion sensor. What stands out is the simplicity of the design. The most important part of the sensor is the ceramic bead, which consists out of: a porous refractory shell with inside a catalyst and also a platinum wire. The wire of a catalytic combustion sensor is often made of platinum, because of the magnificent chemical characteristics of this metal. Namely, platinum has a great coefficient of temperature resistance in comparison with other metals. This coefficient expresses the change in degree Celsius as a percentage. Another advantage of platinum is the resistance against corrosion, which ensures a very long operation time. Because of this, the sensor will be able to give a reliable signal over an extended period of time (Chou, 2000).

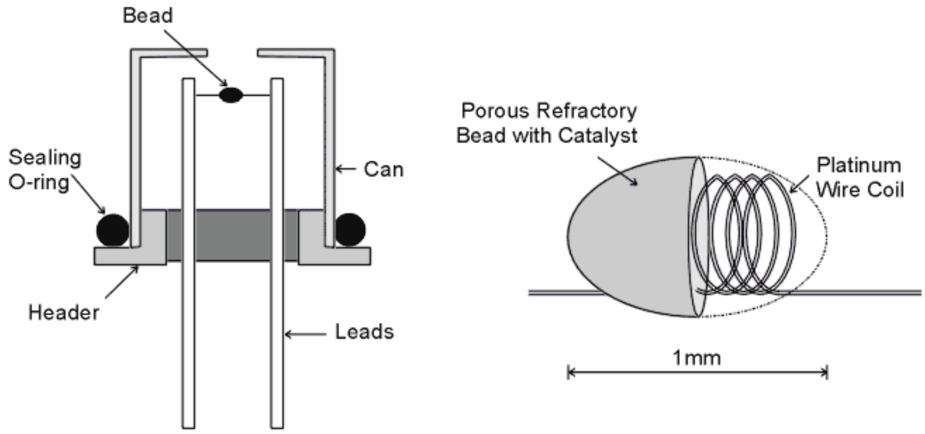


Figure 6.6: Catalytic combustion sensor (City Technology, 2018)

The platinum wire in the bead of the sensor acts as the heater. This platinum wire is heated until the catalytic layer is around a certain temperature, depending on the measurement purpose. The right temperature ensures that the combustible gas will burn on the shell of the catalytic. This causes a heat generation, which results in a change of resistance of the platinum wire. This resistance can be measured by a simple circuit, like a Wheatstone bridge circuit. This Wheatstone circuit compares the unknown resistance with a known resistance, which ensures the output of the amount of gas that is measured (Liu et al., 2012).

The typical specifications of this sensors can be seen in table 6.3. Note that the temperature range relates to the temperature of the environment in which the sensor has to function.

Table 6.3: Typical specifications for a catalytic combustion sensors (Chou, 2000)

Typical specifications	
Temperature range	-40 ° to 60 °C
Response time	10 to 15 sec.
Accuracy	± 5%
Repeatability	2%
Drift	5-10% per year
Life expectancy	Up to 3 years; depending on application

6.2.3. Electrochemical sensor

The first electrochemical sensors were developed in the 1950s and used for the monitoring of oxygen. Ever since, the development of these sensors has gone fast. This has resulted in a wide variety of new and better gas sensors for example in the field of combustible and toxic gas monitoring (Chou, 2000).

The general idea about electrochemical sensors is that they function all similar, however this is not the case. The reason for this thought is the appearance of electrochemical sensors, which is almost always the same (see figure 6.7). Nonetheless, the geometry and the psychical size of the sensor generally depends on its intended usage. Furthermore, there is a great difference in performance between the sensors, especially in terms of: selectivity, response time, sensitivity and operating time.

Figure 6.7: Various electrochemical sensors (Alphasense, 2018)

An electrochemical sensor is actually a small self powered fuel cell. The cell consists of a plastic housing with a small capillary in it. Some electrochemical sensors have an anti-condensation on top of this capillary. The inside of an electrochemical sensor consist of an electrolyte, a sensing electrode (anode) and a counter electrode (cathode) (Delphian, 2018) (see figure 6.8).

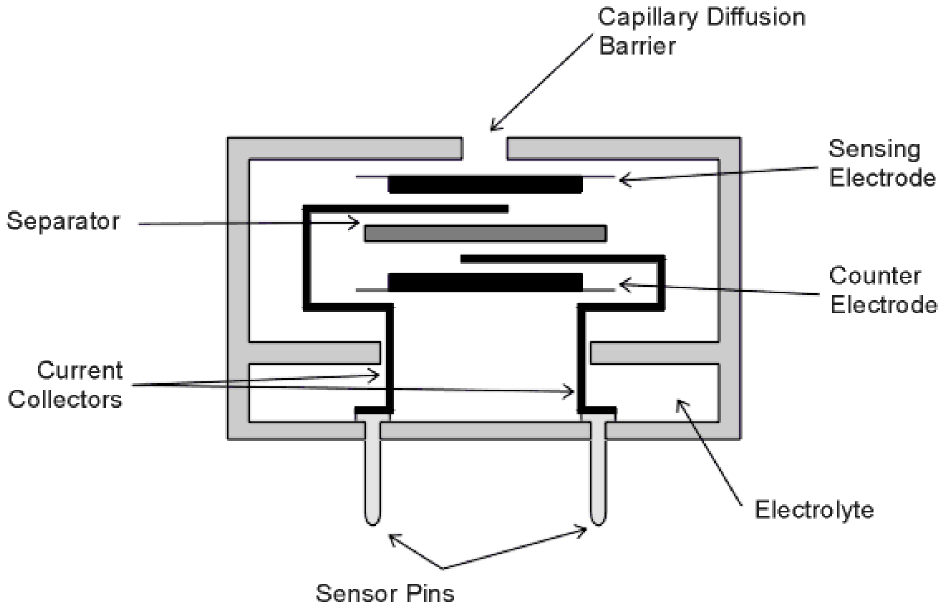


Figure 6.8: Electrochemical sensor (City Technology, 2018)

The target gas that has to be measured enters via the capillary diffusion barrier into the electrochemical sensor. Subsequently, a reaction will take place between the gas and the sensing electrode and the counter electrode. Oxidation will take place at the sensing electrode (anode) and reduction at the counter electrode (cathode). A current will occur due to these reactions, namely a negative flow of ions to the anode and a positive flow of ions to the cathode (Delphian, 2018). This current is measured and used to determine the height of the target gas in ppm.

As described earlier in this section, there are many different ways to manufacture an electrochemical cell. Therefore, it is hard to assess this type of cells in general. Nevertheless, the benefits and downsides which usually apply can be given. The advantages of these type of sensors are: that they can be used to measure a particular gas, their good sensitivity, their excellent accuracy and repeatability. The disadvantages are that they are sensitive to changes in temperature and also that their temperature range is limited. They have a short lifespan, that can be shortened by humidity extremes and very hot or dry areas. Thus, the life expectancy of an electrochemical sensor is very dependent on the environmental conditions to which the sensor is exposed (Chou, 2000).

6.2.4. Nondispersive infrared sensor

The nondispersive infrared (NDIR) sensor belongs to the group of optical methods (see section 6.1). This type of sensor uses infrared light in order to measure the absorption of radiation at a known wavelength, for a particular gas (Gibson and MacGregor, 2013). In other words, the gas molecules only interact with a light beam of infrared light. The advantage of this principle is that there is no direct contact between the gas and the detector inside the sensor. The lifetime of NDIR sensors is, therefore a lot longer than the earlier described sensors.

There are several ways to arrange or manufacture a NDIR sensor. The sensor could be pretty simple or extremely complex, using multiple optical methods depending on the application. This section will describe a basic infrared sensor, as is given in figure 6.9.

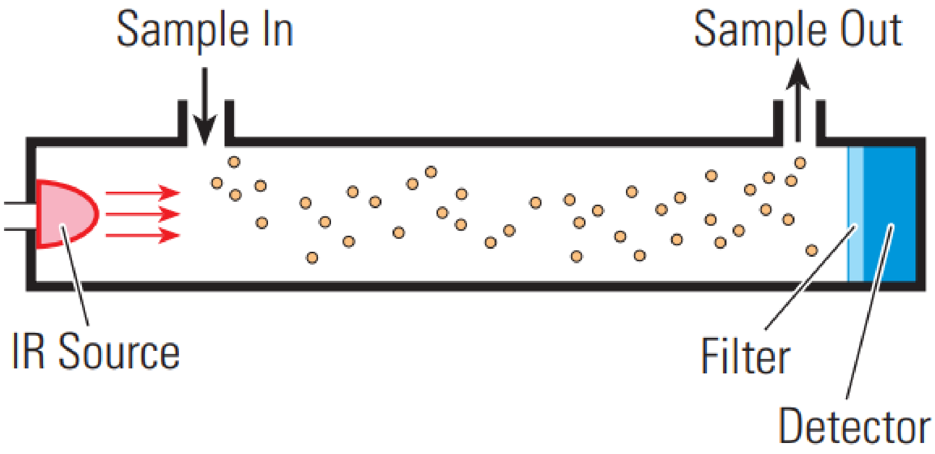


Figure 6.9: A basic infrared gas sensor layout (Chou, 2000)

The sensor as shown in figure 6.9 consists of an infrared source, which emits a beam of infrared light towards a detector. This infrared source is installed in a gas chamber or, for example, in an exhaustpipe. A filter is used in order to select the spectrum absorption range for the gas that has to be measured (Rubio et al., 2007). The amount of infrared light that is absorbed and measured by the detector determines the amount of target gas in ppm.

Another configuration of a NDIR sensor that is often used can be seen in figure 6.10. This sensor makes use of a mirror and two detectors instead of one. The infrared light is emitted by the infrared source in the direction of the mirror, which reflects the infrared light in the direction of the detectors. One detector is called the active detector, which is used to detect the target gas. The other detector is called the reference detector and is used to ignore the target gas. The difference between these two detectors is in the filters. The advantage of this configuration is the ability to provide a base point value, while the active detector determines the signal at the same time. This offers compensation for the sensitivity of the detectors. This makes it possible to overcome a light change over time of the infrared source, also known as drift. Another benefit of the this configuration is double path length, which will lead to a greater signal strength (Chou, 2000).

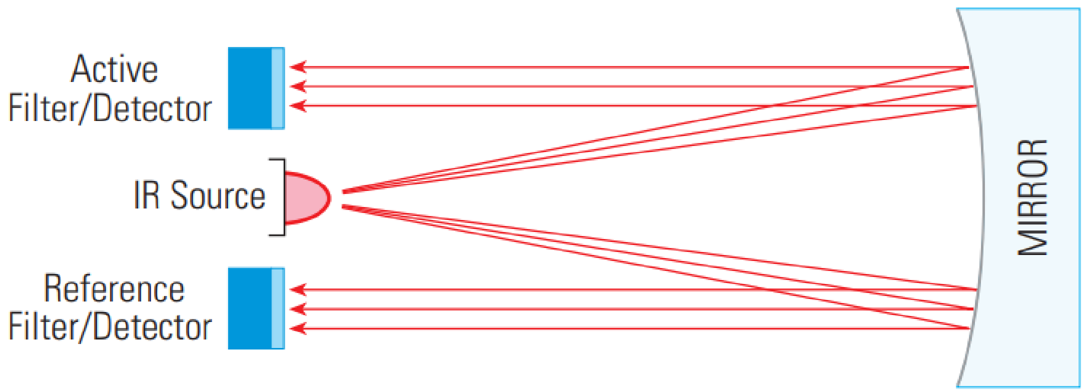


Figure 6.10: A two-detector layout (Chou, 2000)

6.2.5. Nondispersive ultraviolet spectroscopy

The principle nondispersive ultraviolet spectroscopy can be used to measure concentrations and to identify different emissions. A variant of this principle that is widely used, is the differential absorption spectroscopy (DOAS) technique. An example of a sensor that is based on this technique is shown in figure 6.11. This technique is based on the Beer-Lambert absorption law, which states that there is a relationship between the quantity of light that is absorbed and the number of molecules in the light-path (Opsis, 2018b). The working principle of this sensor is almost similar to the infrared technique (see section 6.2.4) and therefore not described in detail.

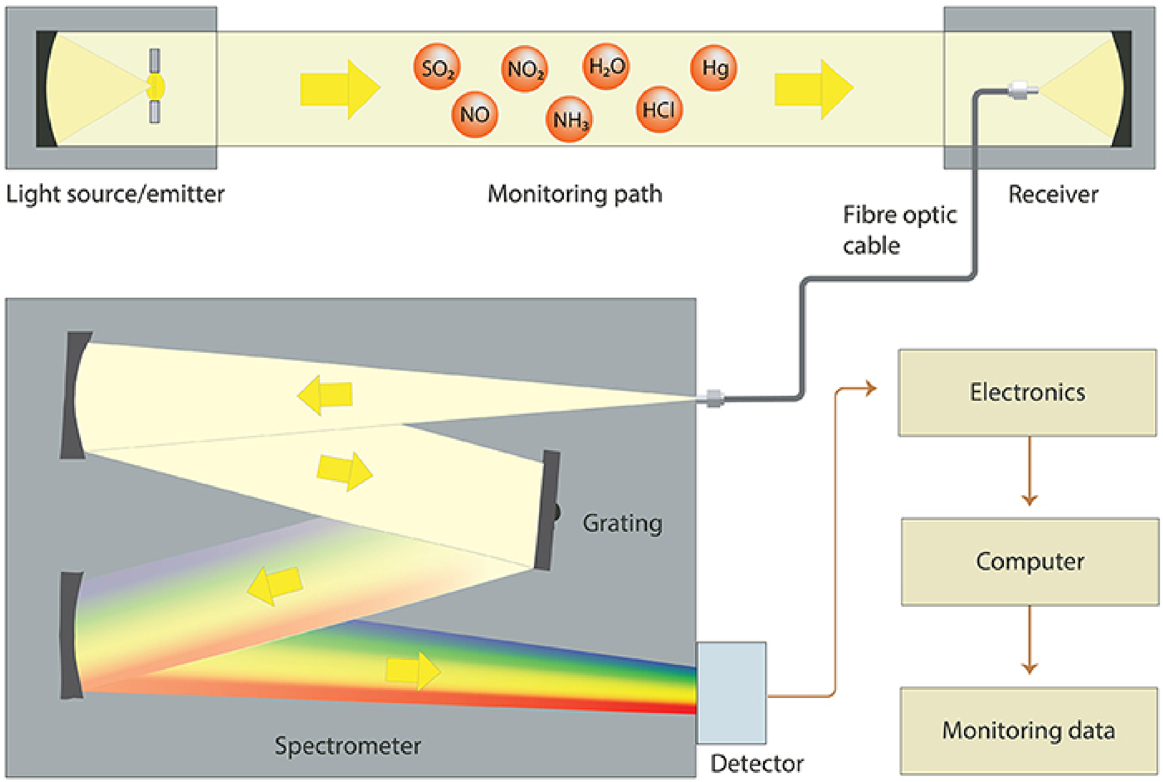


Figure 6.11: UV DOAS technique (Opsis, 2018b)

6.3. Low-end systems

This section will describe the possible low-end systems that are able to meet the requirements. These low-end systems are developed by TNO and successfully used in other applications, but not yet in ships. These low-end systems will have to be adjusted, before they could function on a ship. The expectation from TNO is that these adjustments are certainly achievable and therefore these systems will be taken into account as possible options in the future.

6.3.1. Smart emission measurement system

The smart emission measurement system, SEMS in short, is a system that has been developed by TNO. The system was developed after the Volkswagen emission scandal in 2015, also known as 'dieselgate'. It turned out that the values of an official type approved test significantly differed from the real emission. Since the dieselgate, a real driving test has been added to the type approval test. This real driving test is performed with the use of a portable emission measurement system (PEMS). However, the disadvantage of the PEMS is that it only can be used for a limited time. The system is namely: very costly, voluminous and, besides the driver, an operator is needed to perform the test and to operate the PEMS. TNO developed an emission measurement system, as an alternative for the PEMS what finally became the SEMS. This is a compact sensor-based system that measures emission and can be easily built into a vehicle. Thus, the SEMS is a cost effective alternative for the PEMS and makes large scale emission monitoring possible (TNO, 2018). The large scale emission monitoring is possible, because the SEMS is so compact that a vehicle can be used normally while the measurements are executed.

The SEMS has been developed initially for the measurement of emissions from: light duty vehicles, heavy duty vehicles and non-road mobile machinery. However, it is also intended to measure emissions from other sources with SEMS in the future, like ships (see figure 6.12). There have already been measurements on board of an inland ship. More about this later in this section.

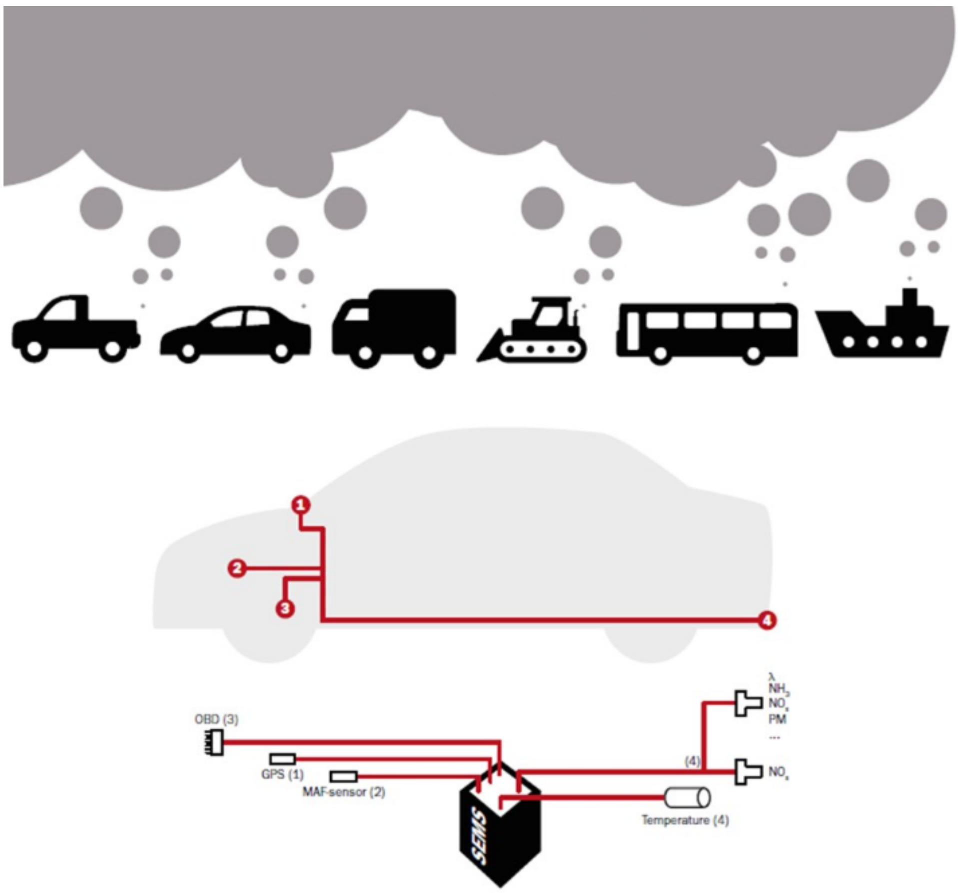


Figure 6.12: Smart emissions measurement system (TNO, 2018)

Important to know is that a SEMS is not equipped with a fixed set of sensors. The SEMS makes it possible to combine measured data of various sensors, with data of the computer of a vehicle. Because, the SEMS is able to combine these different types of data, the SEMS is also called a date acquisition system. An example of the SEMS including the sensors can be seen in figure 6.13.

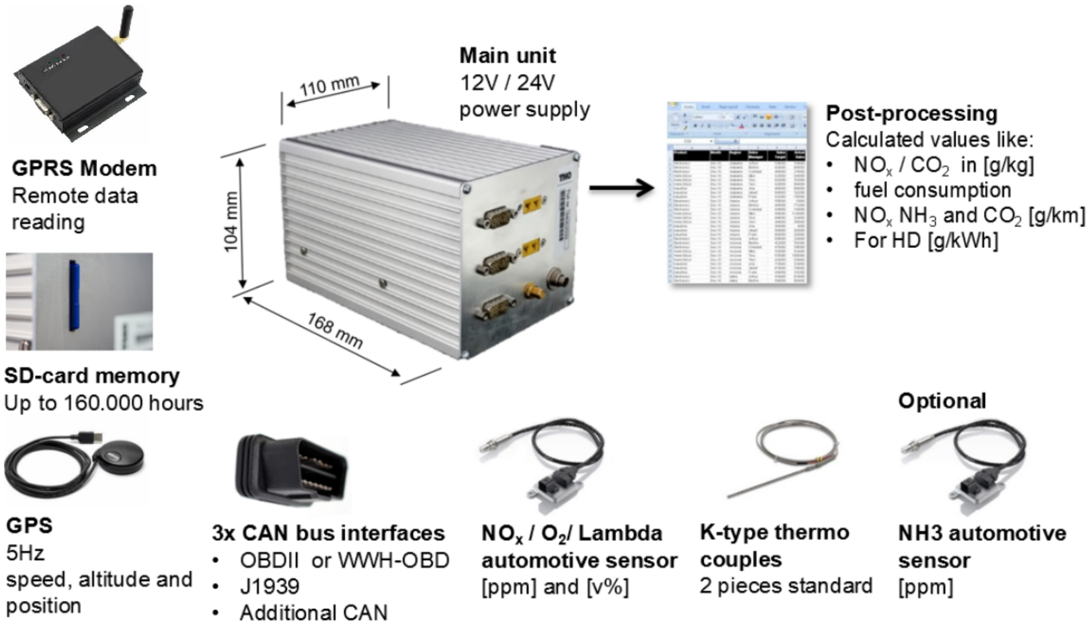


Figure 6.13: Components of a SEMS during an inland ship measurement campaign (van Mensch et al., 2017)

The SEMS of figure 6.13, was used during a measurement campaign of the Prominent project which was funded by the Horizon 2020 program of the European Union (van Mensch et al., 2017). This project focused on the monitoring of NO_x, CO_2, NH_3, energy consumption and the operational profile. To monitor the above mentioned variables, the SEMS was equipped during this project with: a GPRS modem, SD-card memory, a GPS tracker, three CAN bus interfaces, an automotive NO_x sensor, two K-type thermocouples and a main unit. The NO_x sensor was installed in the exhaust pipe of the ship, as shown in the red part of figure 6.14. The main unit of the SEMS is also visible in the blue part of this figure.

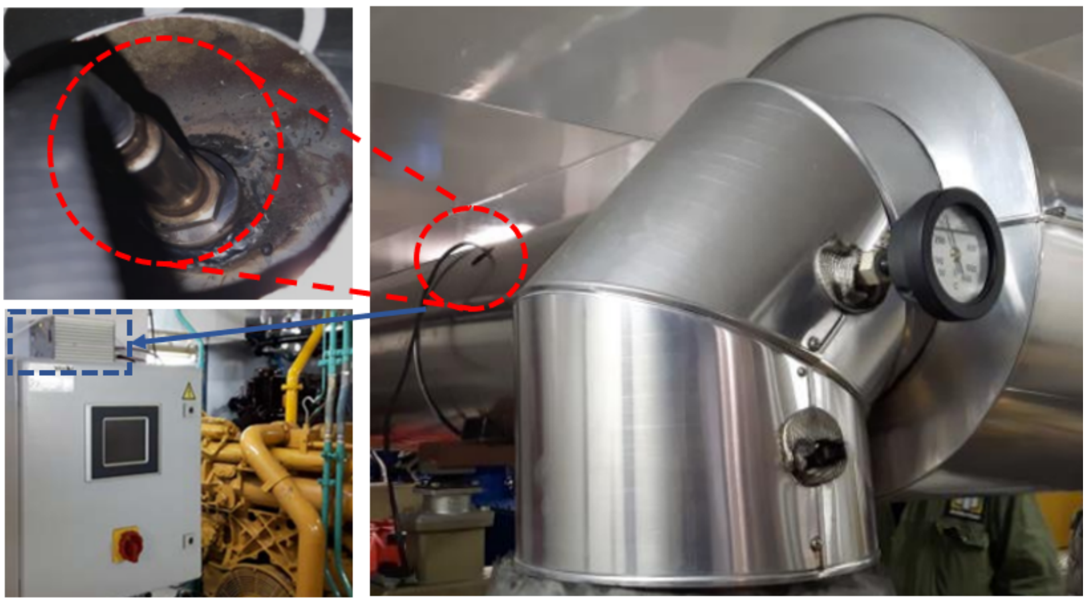


Figure 6.14: SEMS installed on an inland ship including NO_x sensor (own composition, 2018)

The main unit of the SEMS can also be seen in figure 6.15. This main unit contains an Arduino. This is a programmable microcontroller that makes it able to communicate with the various subsystems, like the sensors and ship itself. The Arduino also ensures that the data is written to the memory card of the SEMS. A part of the data enters the SEMS via the CAN bus interfaces. Most SEMS are equipped with three CAN bus interfaces (see 6.15). The CAN messages from the sensors consists of two types of information, the physical signal (voltage differences) and the digital signal (high and low).

Figure 6.15: Smart emission measurement system (own composition, 2018)

It is also possible to connect a GPS receiver directly to the SEMS. The benefit of adding a GPS receiver to the SEMS is that the geographical location can be combined with the other data. This offers the possibility to enforce and monitor emissions when a ship leaves or enters an ECA.

It can be concluded that the SEMS will be an option for emission monitoring on sea going vessels. Certainly for the reason that it has been used successfully on inland ships in the past and frequently in the automotive sector. However, it must be taken into account that the current SEMS will have to be adjusted in order to be able to function successfully on sea going vessels. Thus, SEMS in the current form is not directly applicable on a ship. This is mainly due to the fact that it is uncertain at this moment which sensors can be used and how they will react on the circumstances of a ship. Nevertheless, the developers of the SEMS indicate that it should be possible in the future to measure emissions with the help of a SEMS. The remainder of this section will briefly describe which sensors can be used for this.

According to the measurement of NO_x emissions in combination with a SEMS, multiple sensors can be used with a measurement range of 0-3000ppm. For example: a zirconium oxide sensor (see figure 6.16). The NO_x limits are dependent on the speed of the engine. The rpm should therefore be logged in order to determine the compliance of the ship. The benefit of the SEMS is that this could be done in two different ways. The first option is to connect the SEMS with the engine itself via one of the CAN bus interfaces. The other option is to install a rpm meter that sends the data to the Arduino.

Figure 6.16: NO_x sensor (Mary Brooks, 2018)

A restive electrode sensor is an option for the measurement of PM emissions. TNO already carried out a research to the functioning of this type of sensor in combination with a SEMS (van Heesen, 2018). The resistive PM sensor was installed in an exhaust pipe of multiple vehicles (see figure 6.17). The conclusion of this research was that it is possible to measure PM emissions of vehicles, in combination with the SEMS. Nevertheless, the final report of the PM sensor research also indicates that more research and tests are necessary. These tests will focus on the validation of the sensor, the blow-off phenomena, the calibration factor and measurement of low PM concentrations. The researcher of TNO has expressed the expectation that the resitive PM sensor will probably function well when applied to ships. This has to do with the fact that ships are emitting more PM than for example cars, which makes the sensor function much better. Thus for now it is assumed that the resitive PM sensor will satisfy the requirements for PM measurements on a seagoing vessel, based on the expertise of the TNO expert.

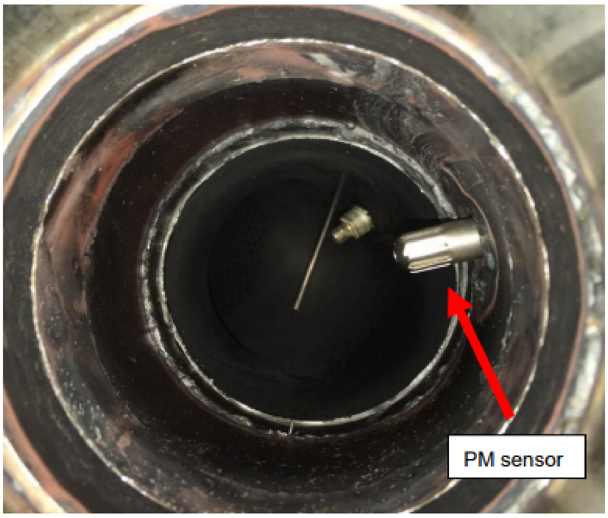


Figure 6.17: A resistive PM sensor installed in an exhaust pipe (van Heesen, 2018)

So the past has proven that a SEMS is able to measure NO_x and PM emissions. Unfortunately, there is no experience with measuring SO_x emissions in combination with the SEMS. That is why it is difficult to determine which sensor of section 6.2 works well together with a SEMS. It is very likely that the SEMS needs to be adjusted for the SO_x sensor. This applies to both software and hardware.

The price of a SEMS including all the sensors is difficult to give exactly. The SEMS experts of TNO estimate the commercial cost price of the SEMS around €5000.

6.3.2. SensA box

Another low end system that is suitable for on board monitoring is the SensA Box. This system is developed by TNO with the objective to measure emissions real-time. The benefit of this system is that it is easy to install and easy to adjust to the emissions that need to be measured. The latter is because the construction of the box, as shown in figure 6.18.

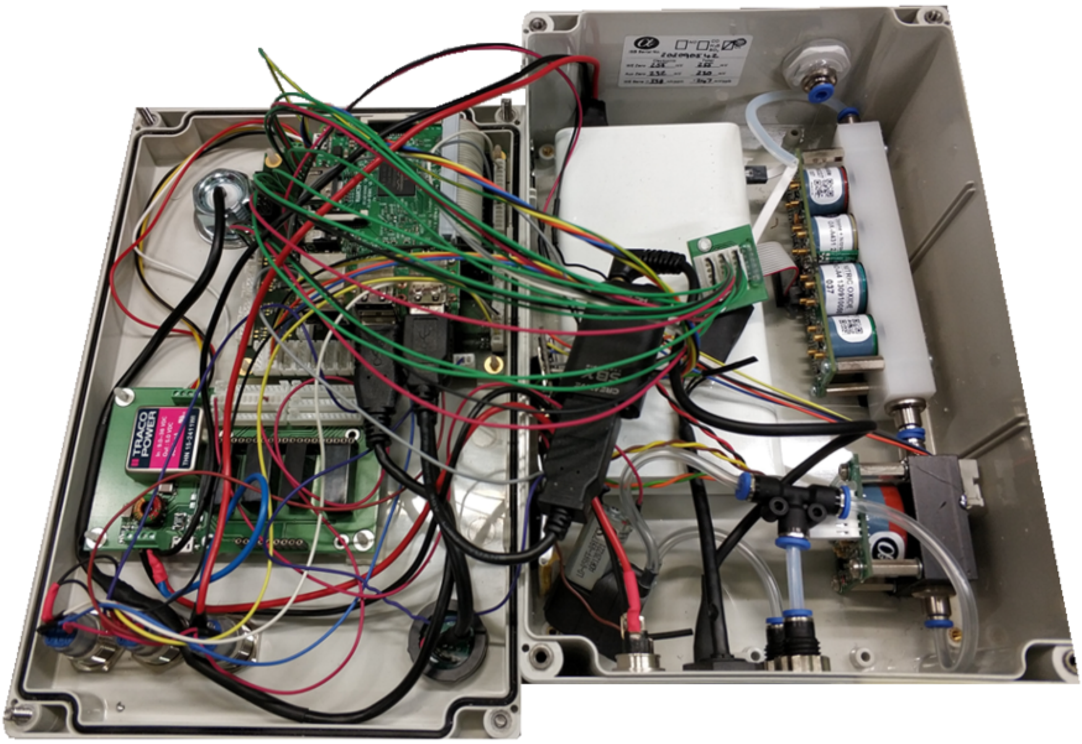


Figure 6.18: SensaBox (own composition, 2018)

The SensA box is constructed in such a way that the sensors can be replaced easily. The sensors can be seen in the top right of figure 6.18 and also enlarged in figure 6.19. The type of sensors that could be installed are: electrochemical, metal oxide, catalytic, NDIR and semiconductor sensors. The sensors in the SensA box are connected with a Rasberry Pi, a single board computer. This Rasberry Pi can be programmed in such a way that the sensors are controlled and read. The data that comes in via the sensors will be written to a hard disk. This process is also controlled by the Rasberry Pi.

Figure 6.19: Sensors of the SensaBox (own composition, 2018)

Another property of the SensA Box is that it is also possible to perform plume measurements outside the ship, as mentioned in section 5.1. When this measurement option is selected, a number of small adjustments must be taken into account. One of the adjustments is that the box has to be made weather proof. Besides the weather, the box must be able to withstand the exposure to salt coming from the sea, because the effects of the salt are unknown to the sensors. Something else that needs attention is the fact that the concentrations of the emissions in open air differs from the emissions in the exhaust pipe. The concentrations that will be measured will be dependent on the distance from the box to the exhaust pipe, as well as the wind direction. Therefore, it is important to calibrate the system when installed, so the difference in concentration of the emissions has to be accounted into the calculation.

The alternative location for the SensA box is inside the ship, near the exhaust pipe. However, it must be taken into account that this system can not be attached directly to the exhaust pipe. This problem can be solved by adding a bypass to the exhaust pipe. The benefit of this bypass is that a number of variables can be controlled like for example: the amount of exhaust gas that is offered to the sensors and the temperature of the exhaust gas. This bypass provides the possibility to protect the sensors, so they can last longer. This is due to the fact that the bypass is controllable and this offers the possibility to expose the sensors less long to the exhaust stream. The exhaust gas could be guided into the bypass in various ways, for example with an aspirator, also known as an ejector-jet pump.

The SensA box in the current form is equipped with sensors of Alphasense (see figure 6.19). The available Alphasense sensors that meet the requirements for measuring NO_x, SO_x, PM and CO_2 are looked up, because the experiences are good with these sensors. These sensors, including the most important technical specifications, are shown in table 6.4. The response time is specified as T_{90}. This is the time it takes for the sensor to measure 90% of the maximum of the applied concentration. The overgas limit is the maximum amount of ppm the sensor can measure when exposed to a gas pulse of 10 minutes. The other specifications speak for themselves and require no further explanation.

Table 6.4: Overview of possible sensors for the SensA box (own composition, 2018)

		Technical specifications						
Emission	**Sensor name**	**Range [ppm] or [%vol]**	**Response time [s]**	**Temperature range [°C]**	**Overgas limit [ppm]**	**Life expectancy [months]**	**Weight [g]**	**Brand**
NO_x	NO-AE	0-5000 ppm	<75 from 0 to 250 ppm	-30 to 50	10000	>24	6	Alphasense
	NO2-AE	0-200 ppm	<40 from 0 to 10 ppm	-20 to 50	1000	>24	6	Alphasense
SO_x	SO2-BF	0-100 ppm	<40 from 0 to 20 ppm	-30 to 50	1000	>24	13	Alphasense
	SO2-AE	0-2000 ppm	<33 from 0 to 400 ppm	-30 to 50	10000	>24	6	Alphasense
	SO2-BE	0-2000 ppm	<30 from 0 to 20 ppm	-30 to 50	10000	>24	13	Alphasense
CO_2	IRC-AT	0-2000 ppm 0-20 %vol	<40 at 20 °C	-20 to 50	2500	>120	15	Alphasense
	IRC-A1	0-500 ppm 0-20% vol	<40 at 20 °C	-20 to 55	2500	>120	15	Alphasense

What stands out in table 6.4 is the temperature range of these sensors. This temperature range is actually a lot lower than the exhaust gas temperature, which should be taken into account. Thus, the temperature of the exhaust gas should be lowered in some cases. This can be done by cooling the exhaust gas in the bypass before it is delivered to the sensors of the SensA box. The cooling does not necessarily have to take place when a ship is equipped with a wet scrubber. This is because the contact with the relative cold washwater in the scrubber. This causes an estimated temperature drop of 85% of the original exhaust gas temperature (EGCSA, 2018b). Table 6.4 shows also that the CO_2 sensors last five times longer in comparison with the other sensors. One of the benefits of these sensors are the low weight and the size. Figure 6.20 gives an indication of the size of these type of sensors and also shows the simplicity. These specifications ensure that it is easy to replace the sensors.

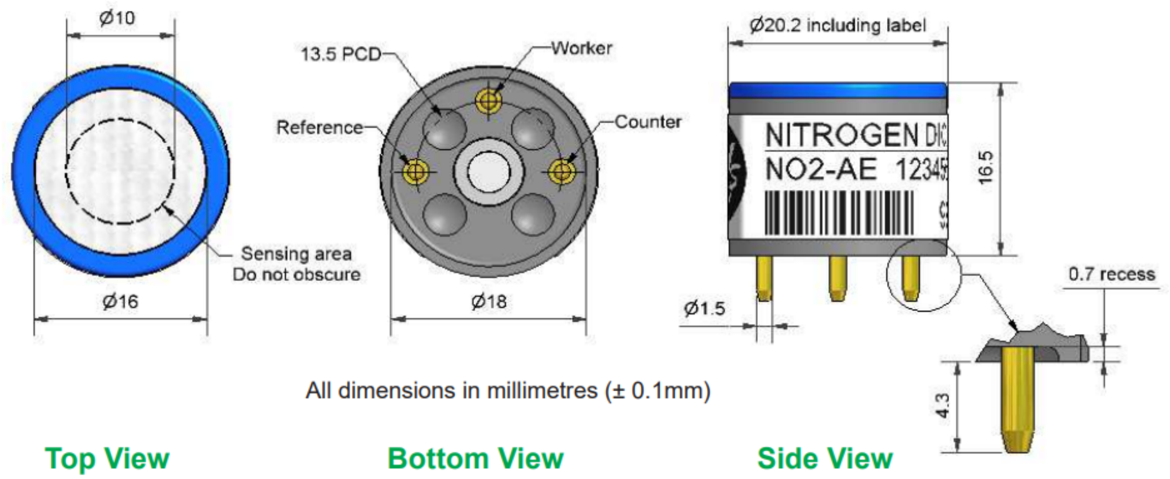


Figure 6.20: Dimensions of a nitrogen sensor of Alphasense (Alphasense, 2018)

It is also possible to equip the SensA box with a PM sensor besides the above mentioned sensors. An example of a sensor that is suitable for the measurement of PM, can be seen in figure 6.21. This sensor provides digital output for PM_{10}, $PM_{2.5}$ and PM_1 every second.

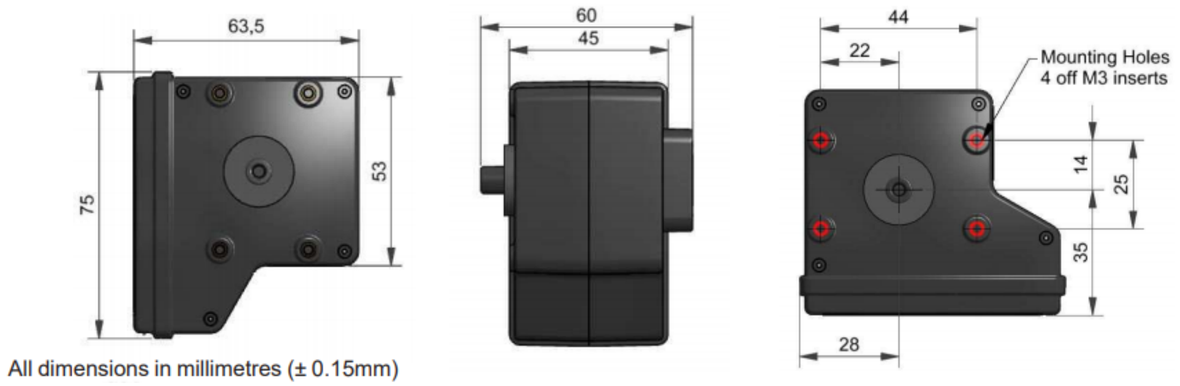


Figure 6.21: Dimensions of a PM sensor (Alphasense, 2018)

The SensA box is not yet available on the market, because it is still under development at TNO, as mentioned earlier. This makes it difficult to give an estimation of the commercial price in the future. Nevertheless, based on the costs of the hardware it is possible to give a rough estimation. The costs of the hardware of the SensA Box are around €2500. This price is based on the components that can be seen in figure 6.18. Important to know according the price, is the share of the sensors in the total price. This because the fact that these sensors are the most vulnerable part of the SensA box and have to be replaced at least every two years. The price of one particular sensor is around €60. This means that the sensors account for 10% of the total costs of the SensA box. The additional costs will come from the adjustments that have to be made in order to make the system maritime proof. The production costs should also be added at the price. Besides the costs of the box itself, costs of additional components have to be also taken into account. Examples of these components are: a bypass for the system, a cooler, a transmission system and a pump. The total costs of this system are estimated between €5000 and €15000. This price depends on the location of the system, the configuration of the exhaust system and the engines on board the ship.

6.4. High-end systems

This section will describe the high-end systems that are available on the market. The systems that will be described are already used on ships to measure the emissions. Most systems are used for the measurement of SO_x emissions after a scrubber (see section 4.2). The systems that will be described are based on the available information. This means that systems without the necessary information will not be described in this chapter, because this information is essential to compare and asses them in chapter 7.

6.4.1. ABB - GAA630-M

The GAA330-M is a continuous emission monitoring system designed by ABB for the following gases: CO_2, SO_2, O_2 NO, NO_2 and NO_x (ABB, 2015). The system is based on a modular system, the analyser system, the sampling system and the heated sampling probe (see figure 6.22). The system is able to measure the emissions downstream or upstream of the scrubber. This offers the possibility to prove and document compliance according to the scrubber regulations. The O_2 and CO emissions can be measured in order to optimize the combustion of the engine.

Figure 6.22: ABB - GAA630-M (ABB, 2015)

The heated sampling probe should be installed directly into the stack, a device that extracts the gases. These gases are then transferred to the sampling unit via the heated sample lines. The probe and sample lines are heated to avoid condensation. The sampling unit has thereafter the task to cool the gases and to remove the moisture. The analyzer receives the gases after they are treated in the sampling unit. This analyzer system makes use of a number of sensors that are able to measure certain emissions. The SO_2 and CO_2 emissions are measured by NDIR technology (see section 6.2.4). An electrochemical sensor (see section 6.2.3) is used to measure O_2 concentrations and the NO_x emissions are measured based NDUV technology (see section 6.2.5) (ABB, 2015).

The specifications of this system are collected and shown in table 6.5. What stands out in the specifications is the size of the system and the weight of the system in comparison with the other systems in this chapter. Unfortunately, ABB tells nothing about the amount of maintenance that is required for this, so this can not be indicated with certainty. The expectation is that quite some maintenance is needed, because the system is in direct contact with the emissions and there are also some filters present in the system that need to be replaced regularly. An advantage of the system is that it is equipped with gas filled cells, which makes it possible to calibrate the system automatically.

Table 6.5: Specifications ABB - GAA630-M (ABB, 2015)

General

Application	Ship emission measuring device
Technology	NDIR spectroscopy NDUV spectroscopy Elctrochemical cell
Maximum number of measurands	4

Measuring ranges

SO_2	0 - 250 ppm / 0 - 500 ppm
CO_2	0 - 20 Vol. %
NO	0 - 1000 ppm
NO_2	0 - 400 ppm
NO_x	0 - 1400 ppm
O_2	0 - 25 Vol. %

Performance

Linearity deviation	<1% of span
Sensitivity drift	<1% measuring value per week
Zero drift SO2, CO2 NOx	<1% of span per week <2% of span per week
Response time	<3 seconds

Environmental

Operating ambient temperature (sensor)	max. 500 °C
Ambient temperature	5 - 55 °C
Storage temperature	-20 - 70 °C
Ingress protection	IP65

Inputs and outputs

Ethernet	TCP/IP
Analog signals	8 x AO 4 x AI
Digital signals	8 x DO 8 x DI

Power

Power supply	115 V / 230 VAC 50 / 60 Hz
Power consumption	Analyzer: 400 W Sample line: 54 W/m Sampling probe: 400 W Sample conditioning: 800 W

Dimensions (W x H x D)

Sample conditioning	800 x 1150 x 550 mm
Analyzer	750 x 850 x 850mm

Weight

Sample conditioning	260 kg
Analyzer	300 kg

Conformities

MARPOL Annex VI and NTC 2008 – MEPC.177(58)
Guidelines for exhaust gas cleaning systems MEPC.259(68)

6.4.2. Afriso/(ABB) - Maritime emission measurement 3000 / 3300

The MEA 3000 and MEA 3300 systems are developed by Afriso (in collaboration with ABB) with the purpose to measure continuously SO_2, CO_2 emissions and also with the option to measure NO_x emissions (Bsachaden, 2017). Afriso offers two different versions, namely the maritime emission measurement (MEA) 3000 system and the maritime emission (MEA) 3300 system. The MEA 3000 is also offered by ABB under the name GA330-M (ABB, 2016) and therefore not separately described once again in another section.

The small difference between the MEA 3000 and the MEA 3300 is the number of sample points. Namely, the MEA 3300 is able to measure SO_2 and CO_2 emissions upstream the scrubber (at the location of the inlet) and also downstream the scrubber in multiple stacks. The MEA 3000 is only able to measure downstream of the scrubber. So the MEA 3300 has the advantage that an insight can be obtained over the performance of the scrubber.

These systems are especially designed to be applied on ships that are equipped with a scrubber installation. These systems are therefore based on the MARPOL regulations that are described in chapter 3. Both system are tested by DNV-GL and approved with a conformation of compliance according the IMO regulations (Osterkamp and Kurok, 2015). These systems are measuring the limit values of the above mentioned emissions to then transfer the data to the main control system. The measurement technology which is used in the probes of these systems are non-dispersive infrared sensors (NDIR) (see section 6.2.4).

Afriso claims that both systems require very little maintenance, due to: the innovative high filter capacity technology, a self cleaning probe, a dual-stage backflush-system and a practical calibration system. Another advantage of this system is that there is no need for test gas storage on board. Afriso also indicated that due to the modular concept the system will be future proof, which means that additional modules can be added at any time, for example a module that measures PM.

The specifications of the systems are the same and summarized in table form in table 6.6. Besides the technologies of Afriso, the system also uses an analyser from the brand ABB (see top part figure 6.23). The dimensions of the systems are included in appendix F.1, also MEA 3300 is included in the same appendix.

Table 6.6: Specifications MEA

Measuring specifications	
Exhaust gas temperature range	0 - 500 °C
SO_2 range	0 - 250 ppm 0 - 500 ppm
CO_2 range	0 - 12 Vol.%
Measuring principle	NDIR
Operating temperature range	
Operating	5 - 35 °C, with fan 5 - 45 °C, with air conditioning system
Storage	2 - 60 °C
Power	
Supply voltage	AC 100-240 V (±15%) 50-60 Hz (± 3Hz)
Input	Approx. 1200 VA without heated line Additionally 100 W/m for the heated line
Output	2 x 4 - 20 mA
Dimensions	
Size (H x W x D)	1100 x 750 x 640 mm
Weight	110 kg

Figure 6.23: Afriso MEA 3000 (Afriso, 2018)

6.4.3. Consilium - Opsis M800

The Opsis M800 system (see figure 6.24) is used for exhaust gas monitoring of scrubbers on board a ship (Consilium, 2018). The basic version of the system is able to measure the following gases: CO, CO_2, NO, NO_2, SO_2, CH_4 and NH_3. Consilium indicates that the basic system could be easily updated, so additional gases could be measured and monitored. The update consists of a simple software update and the addition of an analyser for the desired gas. Such an update makes it also possible to measure PM.

The Opsis M800 is certified by DNV-GL for continuous emission monitoring. Based on the guidelines of the IMO. The measurement system is based on a method where no direct contact is made between the sensor and the emissions. The system makes use of an optical measurement path that is installed in the stack (see figure 6.24). This optical path consists of a light beam that is sent by the emitter through the exhaust stack. The receiver catches the light and transfers it to an analyser in the analyser cabinet. This is done via an optic fibre cable. The analysis is performed using UV/IR Differential Optical Absorption Spectroscopy (DOAS). The analyser of the Opsis M800 could be connected to an optical multiplexer, which offers the possibility to make use of 12 measuring points.

The advantage of this system is that there is no need for filters, heated lines or pumps. This means that the system does not has to deal with difficulties, such as drying the gas and cooling. Another positive point of this system is the very fast response time (even faster than the requirements of the IMO), which enables to measure accurate within seconds.

Consilium claims that that the system operates with minimum maintenance, because of the non-sampling method and the optical technique. Besides this they indicate that the system is self operating, with a high reliability, ensuring low lifetime costs. In addition they claim that many systems are operating for more than 15 years without troubles, which means that this system is the most cost efficient and reliable system on the market (Consilium, 2018).

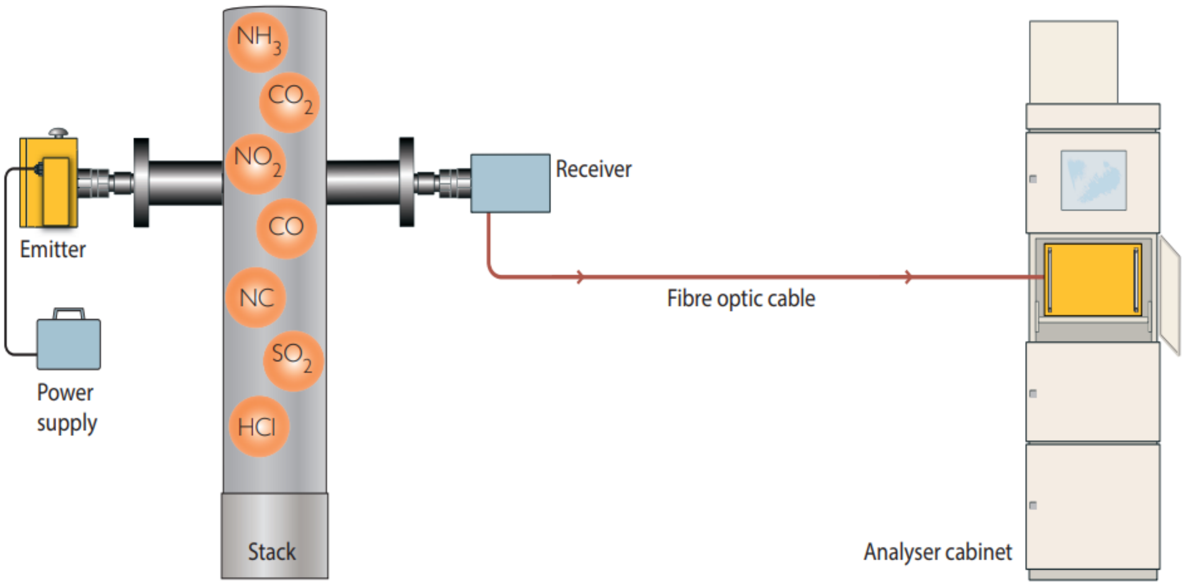


Figure 6.24: Consilium Opsis M800 (Consilium, 2018)

6.4.4. Danfoss - MES 1001

The Marine Emission Sensor (MES) 1001 is designed by Danfoss to measure NO_x, SO_2 and NH_3 emissions that are emitted by ships (see figure 6.25). The system should be mounted directly on the exhaust stack. The measurement probe will than be the only part that sticks into the exhaust stack. This measurement probe is equipped with a sensor that operates according the DOAS principle (see section 6.2.5).

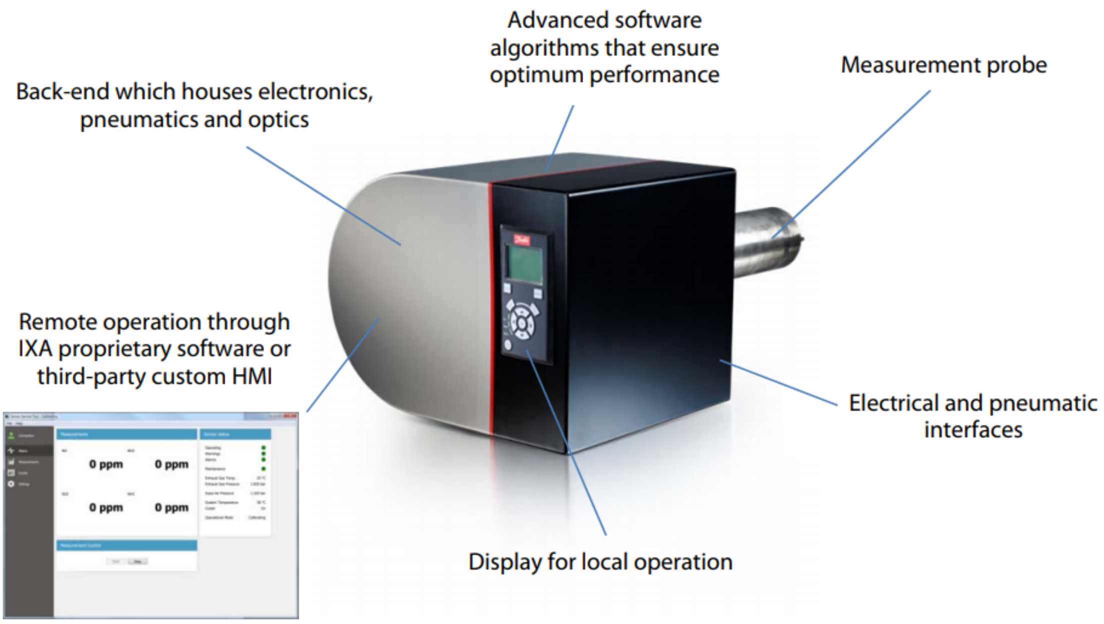


Figure 6.25: Danfoss MES 1001 (Skouboe, 2016)

The detector inside the measurement probe of the system collects the UV light that is emitted by the light source. The collected UV light will than be converted into an electrical signal. This signal is than sampled and delivered to the computer inside the sensor (Skouboe, 2016). The computer of the system makes use of a proprietary gas reference library in combination with a state-of-the-art algorithm that calculates the concentrations of the emissions. The results of a measurement could then be showed on a monitor (see figure 6.26).

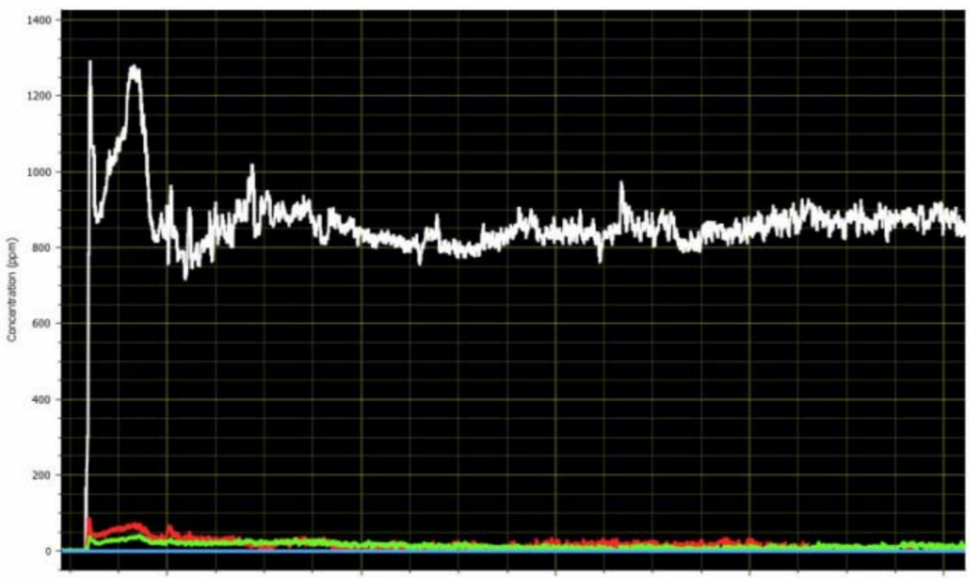


Figure 6.26: Example of Measurement of NO (white), NO_2 (red) and SO_2 (green) over a 2-hour Period (Skouboe, 2016)

One of the advantages of this system is that it can be easily connected to the infrastructure of the ship itself (see figure 6.27). The reason for this is that the MES 1001 offers multiple physical interfaces. The various interfaces could be find in table 6.7 under the heading inputs and outputs. Figure 6.27 shows that is possible to connect with the GPS network of the ship. This offers the possibility to tag the measured emission data with the position of the ship. This is a big advantage in the field of enforcement.

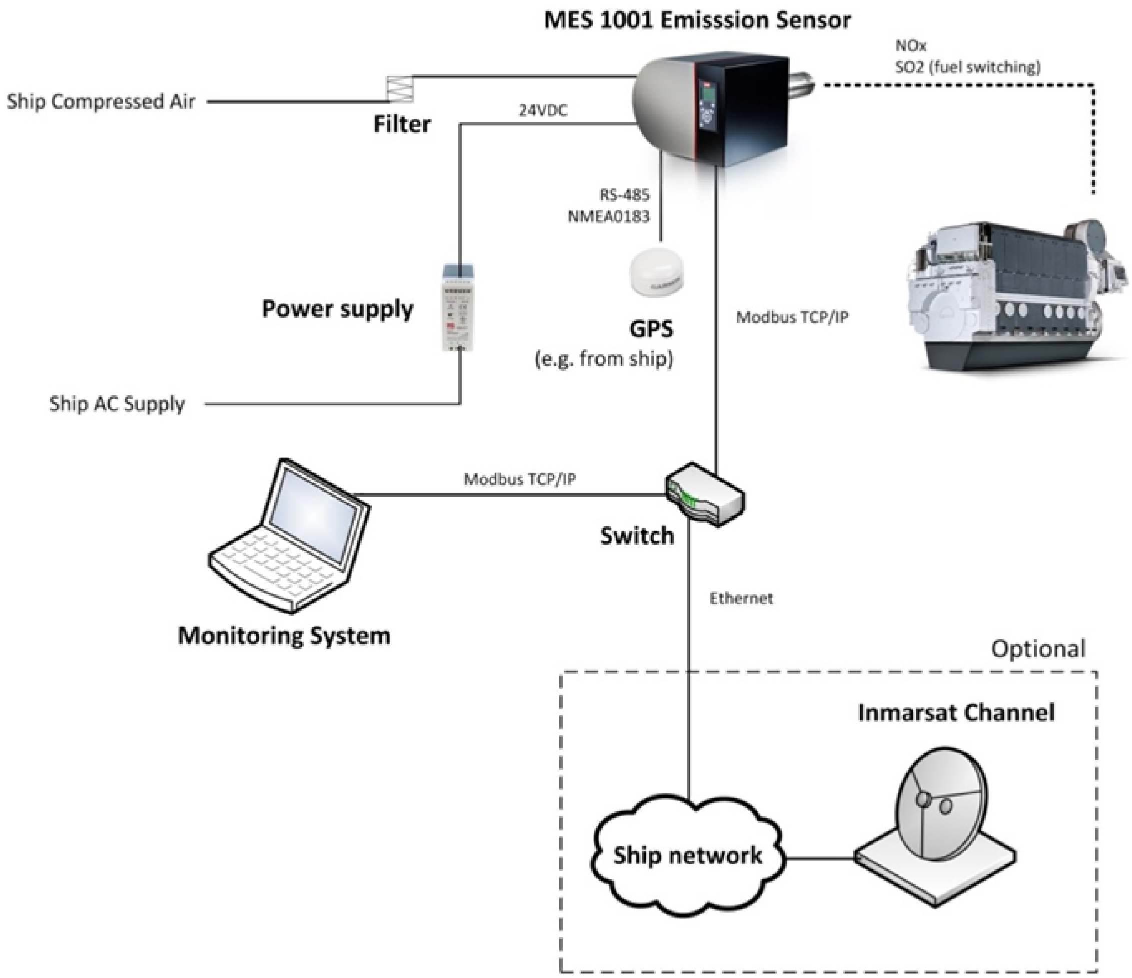


Figure 6.27: Danfoss MES 1001, example with engine control or fuel switching applications (Skouboe, 2016)

Danfoss indicates that the system could operate without a lot of maintenance. The maintenance prediction for this system is that the UV lamp should be replaced every 12-14 months. The system is also able to calibrate automatically using compressed air of the ship. The calibration is done by the purge air system. This calibration system ensures also that the optics inside the probe will not be fouled with particles or soot during operation. A disadvantage of the system is that it can not be extended with the measurement of other gases.

All the available specifications of the MES 1001 are shown in table 6.7. What stands out is that the dimensions of this system are small compared to other systems (figure 6.28).

Table 6.7: Specifications Danfoss MES 1001 (Skouboe, 2016)

General

Application	In situ emission sensor
Technology	UV absorption spectroscopy
Mounting flange	Circular bolted connection
Location	Low pressure side -after turbo charger or after SCR

Inputs and outputs

Ethernet	10 BASE-T 100 BASE-TX
RS-422	Yes, for ships GPS supported protocol: NMEA 0183
Analog output	4 x 4 - 20 mA
Digital inputs	2 (relay controlled)
Digital outputs	2 (relay controlled)

Measurement ranges

SO_2	0 - 1000 ppm
NO_x*	0 - 2000 ppm
NH_3	0 - 100 ppm

Power

Power supply	24 VDC ± 25%
Power consumption	< 75 W

Performance

Data update rate	1 second
Output resolution	1 ppm digital
Response time	<10 seconds (T_{90})

Dimensions

Size (H x W x D)	275 x 375 x 395 mm
Weight	33 kg

Environmental

Operating ambient temperature (sensor)	0 - 55 °C
Exhaust gas temperature (probe)	Max. 500 °C
Storage temperature	Min. 25 - 85 °C
Ingress protection	IP65
Humidity	95% RH

Approvals

CE marking	EMC Directive-2014/30/EU EN61000-6-3:2011
Marine type approval	DNV-GL, cert. no. 422238-15 HH
Certificates	MARPOL Annex VI expected 2018

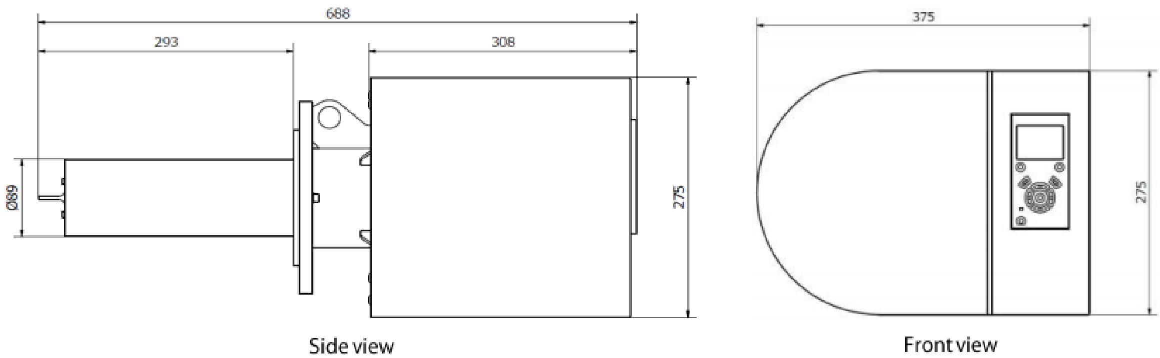


Figure 6.28: Dimensions of the MES 1001 system in mm (Skouboe, 2016)

6.4.5. Green Instruments - G7000

The G7000 is designed by Green Instruments (see figure 6.29) in order to monitor the SO_2 and CO_2 exhaust gas emissions. The gas analyser of this system is based on the NDIR measurement principle (see section 6.2.4), for more explanation about this principle. The gas analyser measures the SO_2 emissions in ppm and the CO_2 emissions in percent as well as the SO_2/CO_2 ratio (Green Instruments, 2018b).

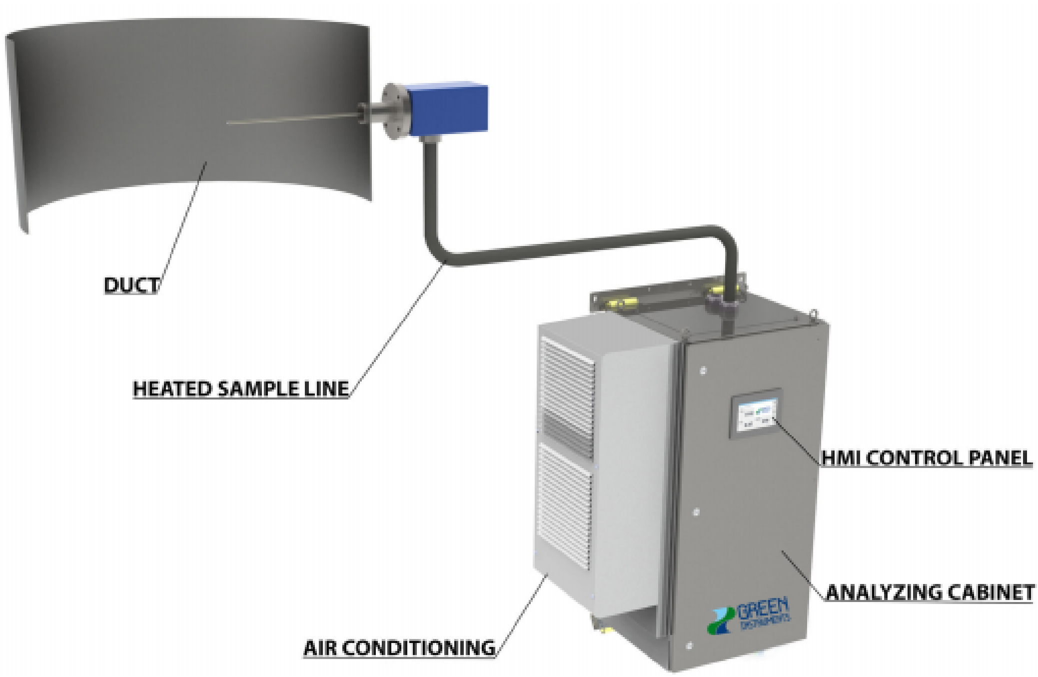


Figure 6.29: Green Instruments - G7000 (Green Instruments, 2018b)

The system is equipped with a double sample conditioning unit. The advantage of this feature is that it gives the ability to sample up and analyze up to 5 different sample points at the same time without influencing the response time. The system consists of two main components, namely the monitoring cabinet ,the probes and the heated sample lines (see figure 6.29). The specifications of these two main components are given in table 6.8.

An advantage of this system is that the system automatic calibrates itself daily, which means that there is no need for special calibration gases. Green Instruments payed also attention to the harsh maritime condition, which resulted in a robust design. As a result, Green Instruments claims that little maintenance is required. The drawback of this system is that it only monitors the above mentioned emission. The system is, for example, not expandable with NO_x monitoring. Green Instruments offers another system for NO_x, the G4130 (see section 6.4.6).

Table 6.8: Specifications Green Instruments G7000 (Green Instruments, 2018b)

Monitoring cabinet

Measurement principle	NDIR
SO_2 range	standard: 0 - 200 ppm optional: 0 - 1000 ppm
CO_2 range	standard: 0 - 10 Vol.% optional: 0 - 25 Vol.%
Linearity	<±2% of reading or <±0.3% of full scale
Repeatability	<±1% of full scale above 100 ppm or <±2% of full scale below 100 ppm
Calibration	Zero calibration: using compressed air Span calibration: using optical filters
Power	230 V AC - 50/60 Hz. 16 A dependent configuration
External communication	Modbus TCP/IP (RJ45)
Material/ Enclosure	Painted mild steel RAL 7035 / IP 55
Ambient temperature	Tested from 5 to 55 °C
Dimensions (H x W x D)	1265 x 1005 x 540 mm
Weight	225 kg

Probes and heated sample lines

Power supply	Supplied from monitoring cabinet
Material	316TI, or Hastelloy
Flange dimension	DN65/PN6
Probe insert length	500 mm
Sample line length	4 - 25 m; optional lengths
Exhaust gas pressure	Min. 50 - 500 mm WC dependent on material
Exhaust gas temperature	0 - 500 °C

6.4.6. Green instruments - G4130

The G4130 is especially designed by Green Instruments (see figure 6.30) in compliance with the NO_x technical code of the IMO (Green Instruments, 2018a). The system measures NO_x and O_2 emissions on a wet basis at high temperatures. The benefit of this is that there is no need for sampling lines and multiplexing systems (converters and coolers), which are systems with disadvantages.

The system is equipped with a zirconium oxide sensor with multiple diffusion cells (Green Instruments, 2018a). The probe of the sensor should be installed directly on the stack. The probe measures the NO_x emissions in ppm and the O_2 emissions in percent. The exact ranges and specifications of this system could be find in table 6.9.

The system is suitable to analyze and optimize the use of emission control technologies. For example, in combination with an exhaust gas re-circulation system or a selective catalytic reduction system (see chapter 4).

The design of the system is kept simple by Green Instruments, which results in less and easy maintenance. The probe is also equipped with an automatic back flushing system, which also ensures less maintenance, according to Green Instruments.

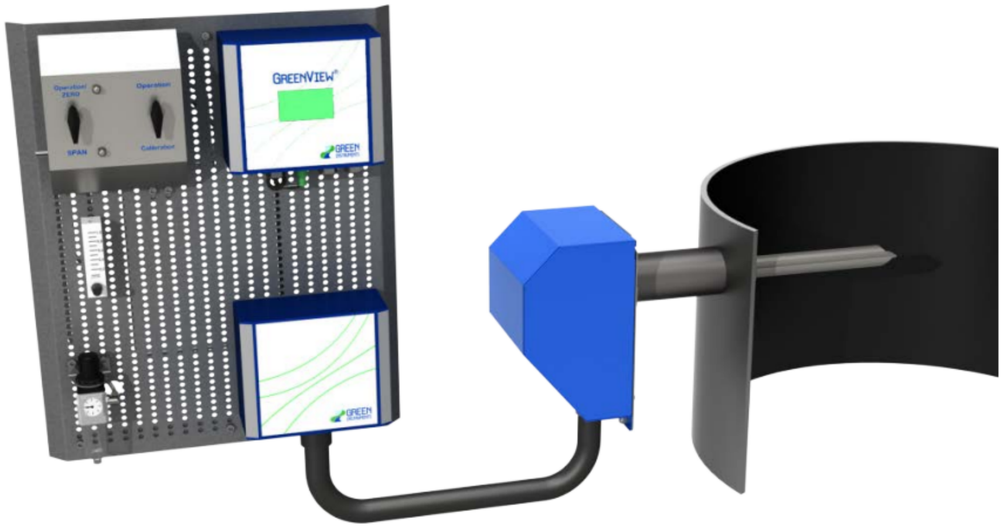


Figure 6.30: Green Instruments - G4130 (Green Instruments, 2018a)

Table 6.9: Specifications Green Instruments - G4130 (Green Instruments, 2018a)

Analyzer

NO_x range	0 - 1500 ppm (F.S.)
O_2 range	0 - 21 % (F.S.)
Power supply	100-230 VAC - 50/60 Hz or 24 VDC.
Output signal	2×4 - 20 mA range selectable: O_2: 0 - 25.0 % NO_x: 0 - 2000 ppm
Max. load signal	600 Ω / 24 VDC
Alarm relays	Volt free 24 VAC/DC 5 A
Display	Touch screen 71×39 mm with trend graph display
Ambient temperature	0 - 55 °C
Size (H x W x D)	170 x 200 x 90 mm
Enclosure	Aluminum casing IP67

Analyzing Board

Size (H x W x D)	600 x 500 x 140
Weight	10 kg
Span NO_x gas connection	6/4 mm tubing max. 1 bar
Air supply filter regulator	r 1/8" BSP connection max. 1 bar
Air supply quality	Instrument air quality according to ISO 8573-1

Diffusion probe

Sensor technology	Heated zirconia sensor
Sample temperature	0 - 500 °C
Probe insert length	Approx. 208 - 338 mm for duct diameters: 235 - 2800 mm
Mounting type	Welding socket size: OD: 70 mm L: 190 mm
Air supply connection for back-flushing & calibration	6/4 mm tubing
Calibration gas flow	Approx. 0.5 - 1.0 l/min
Dimensions short/long (H x W x D)	S: 285 x 180 x 475 mm L: 285 x 180 x 600 mm
Weight	Approx. 6.0 kg without packaging

Umbilical cord

Length	3.0 m
Tubing	28 mm nylon conduit

6.4.7. Sick - Marsic200 & Marsic300

Sick developed two different ship emissions measuring devices, the Marsic200 and the Marsic300 (see figure 6.31). These systems are type-approved by DNV-GL according the MARPOL Annex VI regulations. The main differences between both systems are shown in table 6.31.

(a) Marsic200 (b) Marsic300

Figure 6.31: Marsic emissions measuring devices (Sick, 2018)

The Marsic200 is based on a modular housing concept (see figure 6.31a), a distribution unit, a sample conditioning unit, an analyzer unit and a probe. The distribution unit is the central power supply for the complete system and also contains the sample gas pump. The sample conditioning unit ensures that the gas is cooled down and dried in a sample gas cooler. The analyzer unit consist out of a number of sensors, namely an electrochemical cell for the measurement of O_2 emissions, a NDIR sensor for the measurement of CO_2 and a NDUV sensor for the measurement of SO_2, NO and NO_2. The probe is directly installed in the exhaust duct and extracts the sample gas (Sick, 2016). All detailed specifications from the Marsic200 can be read in table 6.11.

The Marsic300 is a compact complete system (see figure 6.31b) that is able to measure the following emissions: SO_2, CO_2, CO, NO, NO_2, NH_3, CH_4, H_2O, O_2. This number of emissions that can be measured is an important difference with respect to the Marsic200. The system is therefore, equipped with an extra zirconium dioxide sensor. All detailed specifications from the Marsic200 can be read in table 6.12.

Table 6.10: Main differences between the Marsic200 and Marsic300 (Sick, 2018)

	Marsic200	**Marsic300**
Measurement technology	Cold extractive, via cooler	Hot extractive, no condensation
Measurement points	Measurement after scrubber and before and/or after SCR	Measurement before and/or after Scrubber, SCR
Number of measurement points	SO_2, CO_2, NO, NO_2, O_2	SO_2, CO_2, CO, NO, NO_2, NH_3, CH_4, H_2O, O_2
Simultaneous measuring components	4	2
Sample gas lines	Maximum length: 50m Short distance with self-regulating, heated sample gas line, long distance with unheated sample gas line	Maximum length: 35 m Controlled heated sample gas line
Response time (T90)	15 ... 30 s	< 140 s, component-specific based on certification
Instrument air	Purge air only (standby 60l/h)	Component-specific via ejector pump, approx. 1,3 m^3/h (1300 l/h)
Power consumption	approx. 1,150 W for 1 measurement point approx. 3,480 W for 4 measurement points	approx. 3,100 W for 1 measurement point approx. 5,200 W for 2 measurement points
Installation	3 small/light housing; long, heated sample gas line	1 housing, heated sample gas line
Operation, Service	Minimal equipment, modular housing concept, predefined modules for easy replacement	Internal adjustment function without test gases, predefined modules for easy replacement

Sick claims that both systems can operate with minimal maintenance requirements. However, Sick indicated that it will be necessary to check the gas sampling system and the filters each month and replace them when necessary. A leak tightness check has to be performed every 6 months. The non-return valve and the sample gas inlet filter have to be replaced preventive every two years. For the drying agent and the IR source applies that they have to be replaced preventive every three years (Sick, 2017).

The advantage of these systems is that they can measure a lot of emissions and are accurate at the same. However, this means at the same time that the system is complicated.

Table 6.11: Specifications Marsic200 (Sick, 2018)

General

Application	Ship emission measuring device
Technology	NDIR spectroscopy NDUV spectroscopy Electrochemical cell
Maximum number of measurands	5
Sample quantity	60 l/h - 100 l/h

Measuring ranges

SO_2	0 - 100 ppm / 0 - 500 ppm
CO_2	0 - 25 Vol. %
NO	0 - 300 ppm / 0 - 1500 ppm
NO_2	0 - 200 ppm / 0 - 500 ppm
O_2	0 - 21 Vol. %

Performance

Accuracy	<1% measuring range full scale
Sensitivity drift	<2% measuring range full scale per week
Detection limit	≤ 0.5 %
Response time	15 s - 30 s

Environmental

Operating ambient temperature (sensor)	10 - 550 °C
Ambient temperature	5 - 45 °C
Storage temperature	-20 - 70 °C
Process pressure	-20 - 200 hPa
Ingress protection	IP54
Humidity	≤ 95% Non-condensing

Inputs and outputs

Ethernet	TCP/IP
Analog outputs	8 x 0 - 24 mA Electrically isolated
Analog inputs	2 x 0 - 20 mA
Digital outputs	16 outputs: changeover switch, 1-pin, 3 connections
Digital inputs	8 x 42V

Power

Power supply	115 V / 230 V 50 / 60 Hz
Current consumption	at 230 V AC: 8 A
Power consumption	Analyzer: 300 W Sample line: 60 W/m Sampling probe: 400 W Sample conditioning: 150 W

Dimensions (W x H x D)

Sample conditioning	275 x 375 x 395 mm
Distribution unit	600 x 660 x 210 mm
Analyzer	550 x 740 x 319 mm

Weight

Sample conditioning	27 kg
Distribution unit	30 kg
Analyzer	37 kg

Conformities

MARPOL Annex VI and NTC 2008 – MEPC.177(58)
Guidelines for exhaust gas cleaning systems – MEPC.184(59)
Guidelines for SCR reduction systems – MEPC.198(62)
DNV GL Rules for Type Approvals (2012)

Table 6.12: Specifications Marsic300 (Sick, 2018)

General

Application	Ship emission measuring device
Technology	NDIR spectroscopy Zirconium dioxide sensor (oxygen measurement)
Maximum number of measurands	9
Spectral range	2000 - 11000 nm
Sample quantity	200 l/h - 300 l/h

Measuring ranges

SO_2	0 - 30 ppm / 0 - 2000 ppm
CO_2	0 - 25 Vol. %
NO	0 - 300 ppm / 0 - 2000 ppm
NO_2	0 - 200 ppm / 0 - 500 ppm
CO	0 - 200 ppm / 0 - 2000 ppm
CH_4	0 - 500 ppm / 0 - 10000 ppm
NH_3	0 - 50 ppm / 0 - 500 ppm
O_2	0 - 21 Vol. %
H_2O	0 - 40 Vol. %

Performance

Accuracy	≤ 2% measuring range full scale
Sensitivity drift	< 2% measuring range full scale per week
Detection limit	< 2% measuring range full scale per week
Response time	≤ 140 s

Environmental

Operating ambient temperature (sensor)	10 - 550 °C
Ambient temperature	0 - 45 °C
Storage temperature	-20 - 70 °C
Process pressure	-20 - 200 hPa
Ingress protection	IP44
Humidity	< 90% Non-condensing

Power

Three-phase current	3-phase:115 V, 50/60 Hz 3-phase:208 V, 50/60 Hz 3-phase:230 V, 50/60 Hz
Current consumption	at 230 V AC: 14 A
Power consumption	Analyzer: 1000 W Sample line: 90 W/m Sampling probe: 750 W

Dimensions

Size (W x H x D)	600 x 1300 x 434 mm
Weight	120 kg

Conformities

MARPOL Annex VI and NTC 2008 – MEPC.177(58)
Guidelines for exhaust gas cleaning systems – MEPC.184(59)
Guidelines for SCR reduction systems – MEPC.198(62)
DNV GL Rules for Type Approvals (2012)

6.4.8. Vimex - ShipCEMS

The ShipsCEMS is a continuous emission monitoring system that is developed by Vimex. The main purpose of this system is to analyze SO_2 and the CO_2 emissions in wet marine exhaust gas. The system could also be extended with the measurement of others emissions, for example with NO_x emissions (Vimex, 2016). The emission monitoring system consists out of multiple systems, like the heated sample probe, the heated transport line, the sample conditioning system and the analyzer cabinet (see figure 6.32). It is also possible to connect the system to the vessel control system.

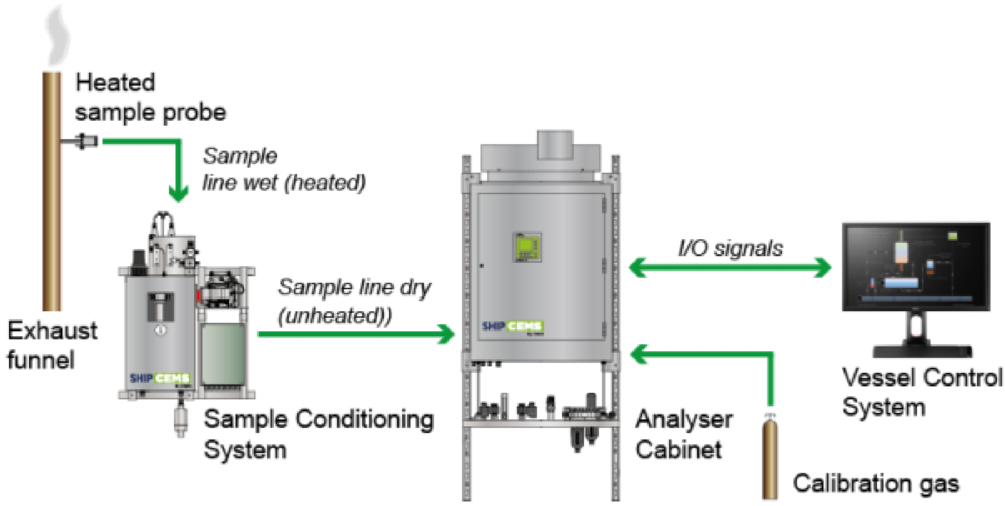


Figure 6.32: ShipCEMS system overview (Vimex, 2016)

The heated sample probe is installed in the exhaust funnel in order to extract a representative sample from the exhaust gas of the ship engine. This probe contains a micron ceramic filter for the separation of dust and other large particles. This filter is kept at a certain temperature to avoid clogging of wet particles and to keep it porous. The heated sample line then takes care for the transportation of the sample to the sample conditioning system. This transport must be heated at all times, otherwise condensation will occur, which causes losses of trace components that has to be measured. The above described components of the ShipCEMS could be seen in figure 6.34.

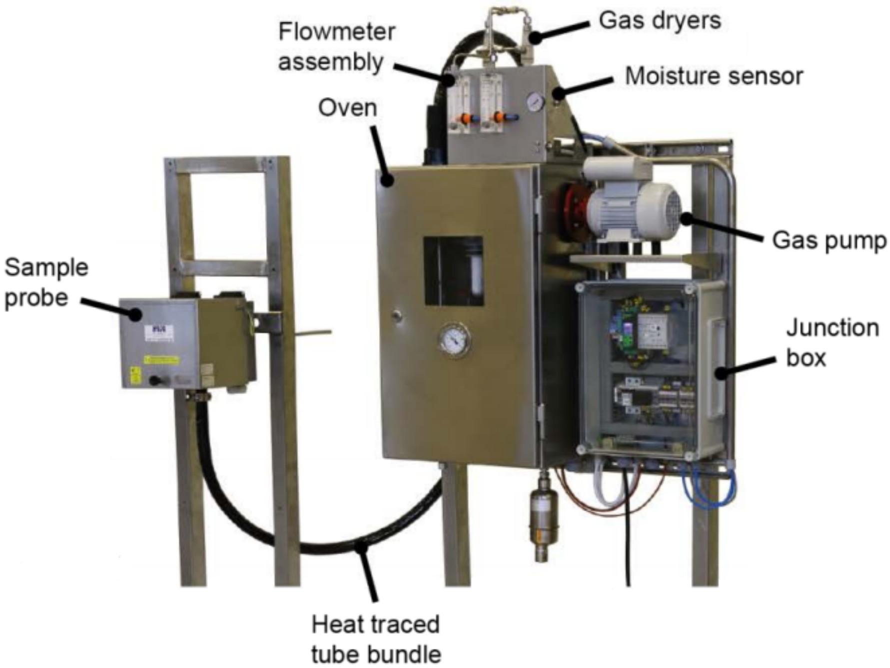


Figure 6.33: Heated probe, heated sample transport line and sample conditioning system of the ShipCEMS (Vimex, 2016)

The sampling conditioning system consists out of the following main components: multiple sensors (temperature, flow and moisture), a heated cabinet, a junction box, a sample gas filter, a sample gas pump and sample gas dryers. The objective of the conditioning system is to treat the sample in a way so it can be transferred to the analyser cabinet. The most important part here is drying the sample. This is done by the permeation dryer tubes, which are connected whit a counter flow stream of dry instrument air.

The analyser cabinet makes use of NDIR technology (see section 6.2.4). This cabinet is also equipped with an cooler on top (see figure 6.34). This cooler will be used if the temperature becomes to high.

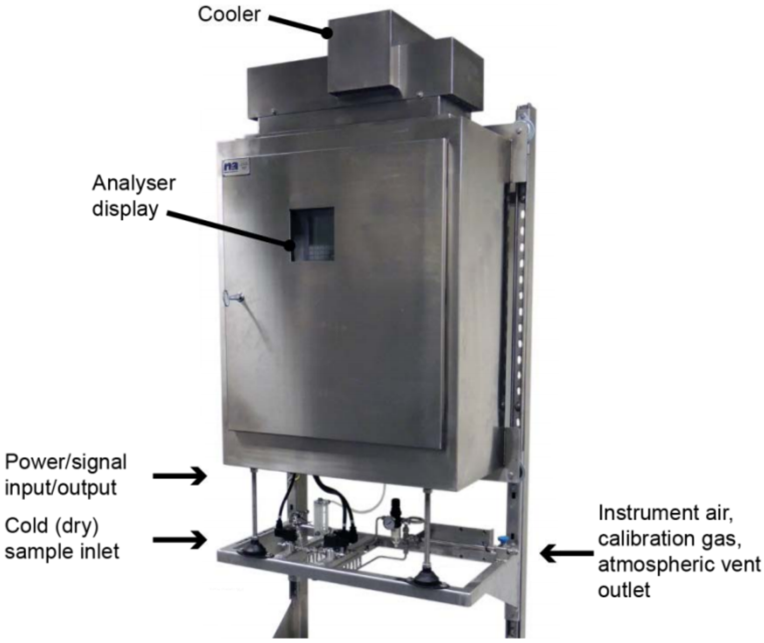


Figure 6.34: Analyser cabinet of the ShipCEMS (Vimex, 2016)

The specifications of the ShipCEMS can be seen in table 6.13. What stands out in the specifications is that this system has multiple type approvals in comparison with the other systems. This is probably due to the fact that this system is supplied as standard in combination with a scrubber of the brand Alfa Laval. The latter is a widely sold scrubber. The specifications also show that the system can deal with four sample points. The configuration of an emission monitoring system with four sample points can be seen in figure 6.35. The figure shows that additional sample conditioning systems, probes and heated sample lines are necessary to achieve this.

Table 6.13: Specifications ShipCEMS (Vimex, 2016)

General

Application	Ship emission measuring device
Technology	NDIR spectroscopy
Maximum number of sample points	4

Measuring ranges

SO_x	Default: 0 - 50 ppm Max: 0 - 1000 ppm
CO_2	Default: 0-10% Max: 0 - 15%

Heated sample probe

Length	254 mm
Flange diameter	160 mm
Weight	10 kg

Type Approvals

DNV-GL
Lloyd's Register
ABS
Bureau Veritas
RINA

Inputs and outputs

Analog output	4-20 mA

Power

Power supply	230 / 110 VAC
Power consumption	Analyzer: 590 W Sample line: 67 W/m Sampling probe: 350 W Sample conditioning: 490 W

Dimensions (W x H x D)

Sample conditioning	400 x 700 x 300 mm
Analyzer	800 x 1000 x 400 mm

Weight

Sample conditioning	52 kg
Analyzer	143 kg

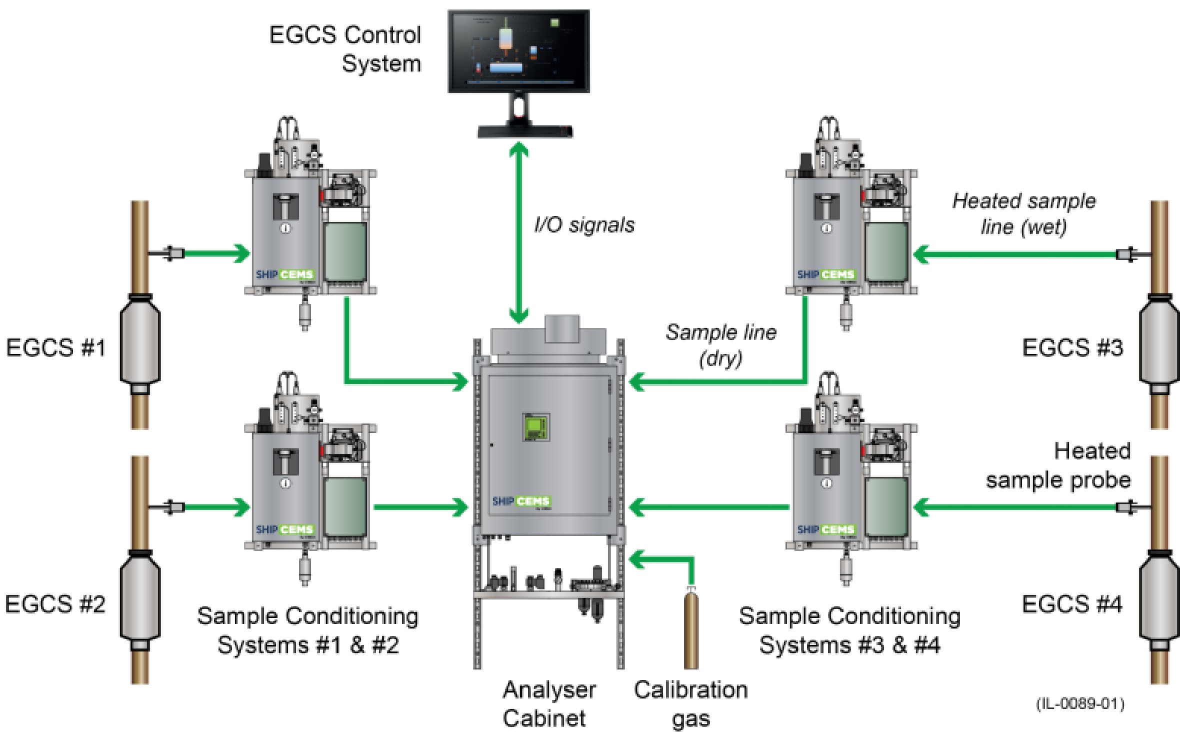


Figure 6.35: Vimex - ShipCEMS (Vimex, 2016)

7

Assessment systems

This chapter will be used to describe the assessment of the possible emissions monitoring systems. The systems that will be assessed and compared are described in chapter 6. However, not all systems of chapter 6 will be assessed in this chapter. It has been decided that the low-end systems (see section 6.3) are not yet sufficiently developed to function as a robust on board emission monitoring system in the near future. The low-end systems certainly have potential, but there are too many uncertainties, which makes it difficult and unfounded to assess them. The low-end system will have to be extensively tested on board of a seagoing ship, more about this in chapter 10.

The high-end systems have already proved to function on board a seagoing vessel and therefore suitable to be recommended. The assessment for the high-end systems will be done based on a multiple-criteria decisions analysis in section 7.1.

7.1. Multiple-criteria decision analysis

This section will show the analysis that is made in order to come up with a recommendation for a certain on board emission monitoring system. The type of analysis that is selected for the assessment is a multiple-criteria decision analysis. This is a scientific evaluation method, with which a rational choice can be made between multiple alternatives. In this case the on board emission monitoring systems.

7.1.1. Criteria

The criteria that are used to compare and assess the high-end systems will be described in this section. It will be indicated per criteria why it is included into the assessment. The weights of the criteria will also be given. The lowest weight that can be assigned to a criteria is 1 point and the highest weight that can be assigned is 5 points. So, this means that a criteria can get 1 (not important) to 5 points (important). The scores for the criteria will be given by the author of this report.

Emissions

One of the criteria that will be assessed, is the capability of a system to measure certain emissions. The systems will be assessed on the following emissions: SO_x, NO_x, PM and CO_2. And the systems can also score points if it is able to measure other emissions besides the above mentioned emissions.

The weights vary per emission type, based on their importance and the scope of this research. The measurement of SO_x and NO_x measurement is highly desirable, because of the IMO legislation and therefore weighted with 5 points. The stakeholders indicated that the PM and CO_2 emissions are also desirable (see chapter 9), because of this they are weighted 3 points. The capability to measure other emission besides the above mentioned emissions is weighted with 1 point.

The height of a score per system on this criteria is based on the measuring ranges per emission type. This means that a system scores better if they are able to measure over a larger range.

Robustness
The robustness of the system is weighted with 4 points, because it is seen as important. The system needs to be able to measure continuously. This means that the system must be able to operate with little downtime. When assessing the systems on robustness, the systems could score points if they demonstrate that they are designed to deal with the hard conditions in an engine room. Examples of this are: vibrations, temperature and movements. Another important component that will be assessed on robustness is the sensor of the system. This is done by looking at the operating principle of the sensor (see chapter 6). A sensor which is not in direct contact with the exhaust gases will score more point on robustness.

Maintenance
The criteria maintenance is, just like the criteria robustness, weighted with 4 points. This is due the fact that they are indirectly related. Namely, if the system is not robust, a lot of maintenance will have to be executed.

The score of the system will be determined on a number of specifications that reduce maintenance. Like the presence of an automated calibration system, an automatic back flushing system, a self cleaning probe and a non sampling method. Besides this, it will also be checked if there are components present at the system, which often have to be replaced. Examples are: multiple filters, valves, drying agent and an IR light source. For the criteria maintenance applies: the higher the score, the less maintenance is required for the system.

Accuracy
One of the objectives of the system will be the enforcement of the emission legislation. The accuracy of the system will play a crucial role in the enforcement. The criteria accuracy is therefore weighted with 5 points. After all, a small difference in measurement results can bring up a penalty for a shipowner.

The assessment per criteria will be based on the specifications: accuracy of the measuring range of the full scale, sensitivity drift, linearity, repeatability and the detection limit. Besides this, it will also be checked if the system certified by a classification society.

Costs
It is evident that the costs will be of great importance. However, it has been found that it is difficult to determine the costs of the systems. The companies of the systems often indicated that they do not want to share the price of the system. However, it was possible to receive price indications from shipping companies for a number of systems. Based on these indications and the working principles of the systems a score could be distributed. A low score for a system means a more expensive system compared to a high score. The range of the prices lies between €20.000 and €80.000.

It has been chosen to give the criteria costs a weight of 2 points. This is done, because of the uncertainties of the prices. This criteria would normally have a higher weight, but this could only have been done if the price was known with certainty.

Dimensions
The dimensions of the system are important, but of secondary importance with respect to the other criteria, which means a weight of 2 points. This criteria is included, because there is often little space around the exhaust system. This means that a compact or light system will score more points, because it will be an advantage with the installation.

Sample points
It is desirable that a system offers the possibility to connect multiple sample points. This criteria is therefore included in the assessment, with a weight of 2 points. A higher score for an individual system means a possibility to connect more sample points.

7.1.2. Results
The results of the assessment in the form of multiple-criteria analysis are given in this section. The scores are awarded per system and based on the above mentioned explanation. The results can be seen in table 7.1 and in figure 7.1.

Table 7.1: Multiple-criteria analysis for on board emission monitoring systems

Criteria		Weight	GAA630-M	MEA 3000 / GA330-M	MEA 3300	Opsis M800	MES 1001
Emissions	SO_x	5	4	4	4	5	5
	NO_x	5	4	2	2	5	5
	PM	3	0	2	2	2	0
	CO_2	3	5	4	4	5	0
	Others	1	3	2	2	4	2
Robustness		4	2	3	3	5	5
Maintenance		4	2	3	3	4	4
Accuracy		5	3	3	3	4	4
Costs		2	3	3	2	1	3
Dimensions		2	1	3	3	2	5
Sample points		3	4	2	3	5	1
Total weighted score			**109**	**107**	**108**	**152**	**127**

Criteria		Weight	G7000	G4130	Marsic200	Marsic300	ShipCEMS
Emissions	SO_x	5	5	0	4	5	5
	NO_x	5	0	4	4	4	2
	PM	3	0	0	0	0	0
	CO_2	3	4	0	5	5	4
	Others	1	2	0	2	5	3
Robustness		4	4	4	3	3	3
Maintenance		4	3	3	3	3	3
Accuracy		5	3	3	3	3	3
Costs		2	3	4	3	2	4
Dimensions		2	3	4	3	4	3
Sample points		3	1	1	4	3	4
Total weighted score			**93**	**82**	**120**	**125**	**115**

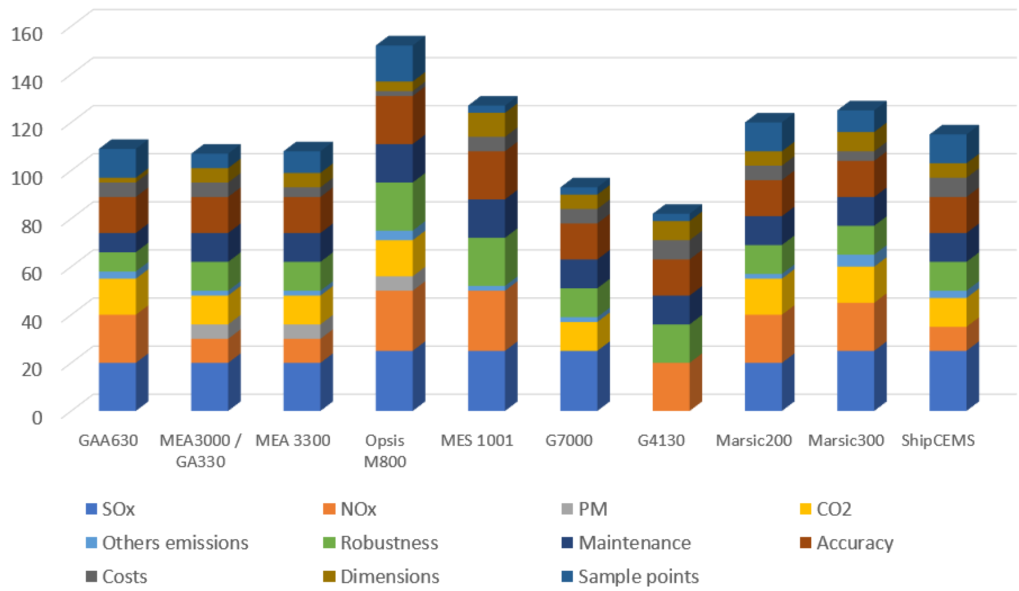


Figure 7.1: Results multiple-criteria analysis for on board emission monitoring systems

From the results of the multiple-criteria analysis can be concluded that one system scores by far the most points, namely the Opsis M800. The score can mainly be explained by the fact that this system operates with the UV/IR Differential Optical Absorption Spectroscopy principle. The big advantage of this principle is that the sensors and the exhaust gas are separated. Another advantage of this system is that this system does not make use of samples, which means that there is no need for a sample conditioning unit. This also means that the system does not have to deal with difficulties, such as drying the gas and cooling. These benefits are directly reflected in the scores for robustness and maintenance.

It is important to know whether this result is not purely based on coincidence. Therefore, a sensitivity analysis is executed in order to verify the result. This sensitivity analysis is executed by changing the weights of criteria. This method is derived from Haddad and Sanders (2018). The sensitivity analysis is done in two ways. Namely, by distributing equal weights and by an inverted distribution of the weights.

The results of the sensitivity analysis with the equivalent weight distribution can be seen in table 7.2 and in figure 7.2. As can be seen in table 7.2, each criteria received a weight of 3 points. What stands out is that the Opsis M800 system still scores the best of all the systems.

Table 7.2: Sensitivity analysis with equivalent weights

Criteria		Weight	Score				
			GAA630-M	**MEA 3000 / GA330-M**	**MEA 3300**	**Opsis M800**	**MES 1001**
Emissions	SO_x	3	4	4	4	5	5
	NO_x	3	4	2	2	5	5
	PM	3	0	2	2	2	0
	CO_2	3	5	4	4	5	0
	Others	3	3	2	2	4	2
Robustness		3	2	3	3	5	5
Maintenance		3	2	3	3	4	4
Accuracy		3	3	3	3	4	4
Costs		3	3	3	2	1	3
Dimensions		3	1	3	3	5	5
Sample points		3	4	2	3	5	1
Total weighted score			**93**	**93**	**93**	**126**	**102**
			G7000	**G4130**	**Marsic200**	**Marsic300**	**ShipCEMS**
Emissions	SO_x	3	5	0	4	5	5
	NO_x	3	0	4	4	4	2
	PM	3	0	0	0	0	0
	CO_2	3	4	0	5	5	4
	Others	3	2	0	2	5	3
Robustness		3	4	4	3	3	3
Maintenance		3	3	3	3	3	3
Accuracy		3	3	3	3	3	3
Costs		3	3	4	3	2	4
Dimensions		3	3	4	3	4	3
Sample points		3	1	1	4	3	4
Total weighted score			**81**	**69**	**102**	**111**	**102**

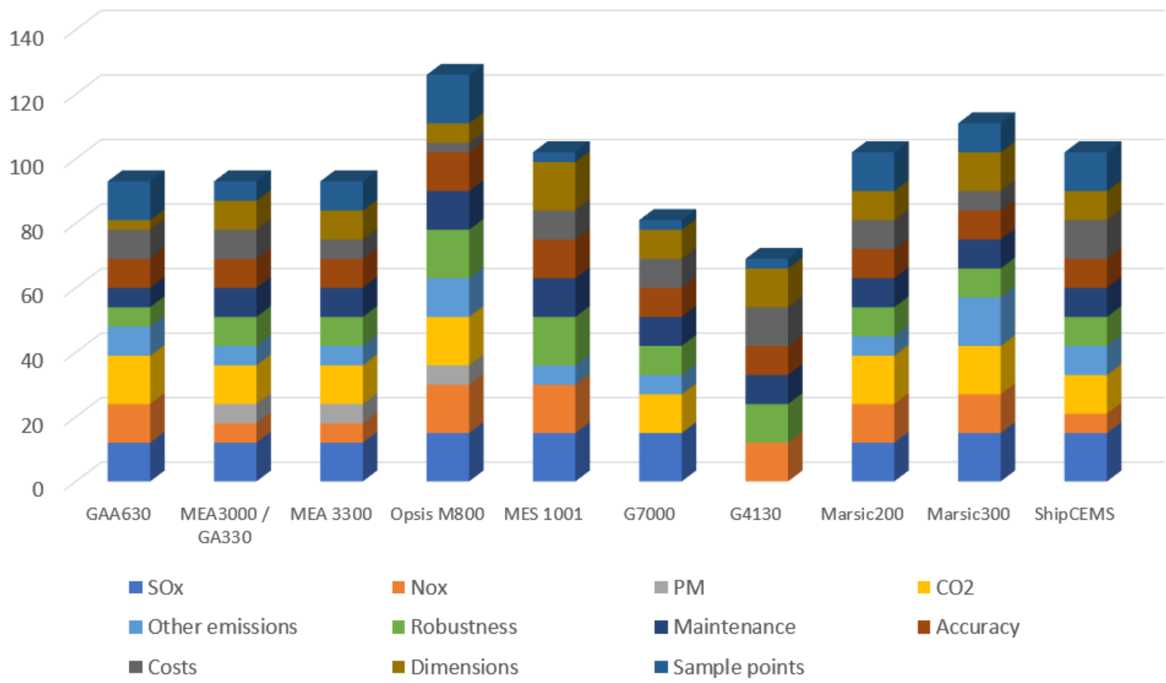


Figure 7.2: Results sensitivity analysis with equivalent weights

The results of the sensitivity analysis with the inverted weights can be seen in figure 7.2 and in table 7.2. It can be seen that the criteria with the highest weight in the original situation is awarded with the lowest weight and vice versa. What turns out again is that the Opsis M800 scores the best. It can be concluded that the result of the multiple-criteria analysis is not based on coincidence. Therefore it can also be concluded that the Opsis M800 is assessed the best, which means that this system will be recommended.

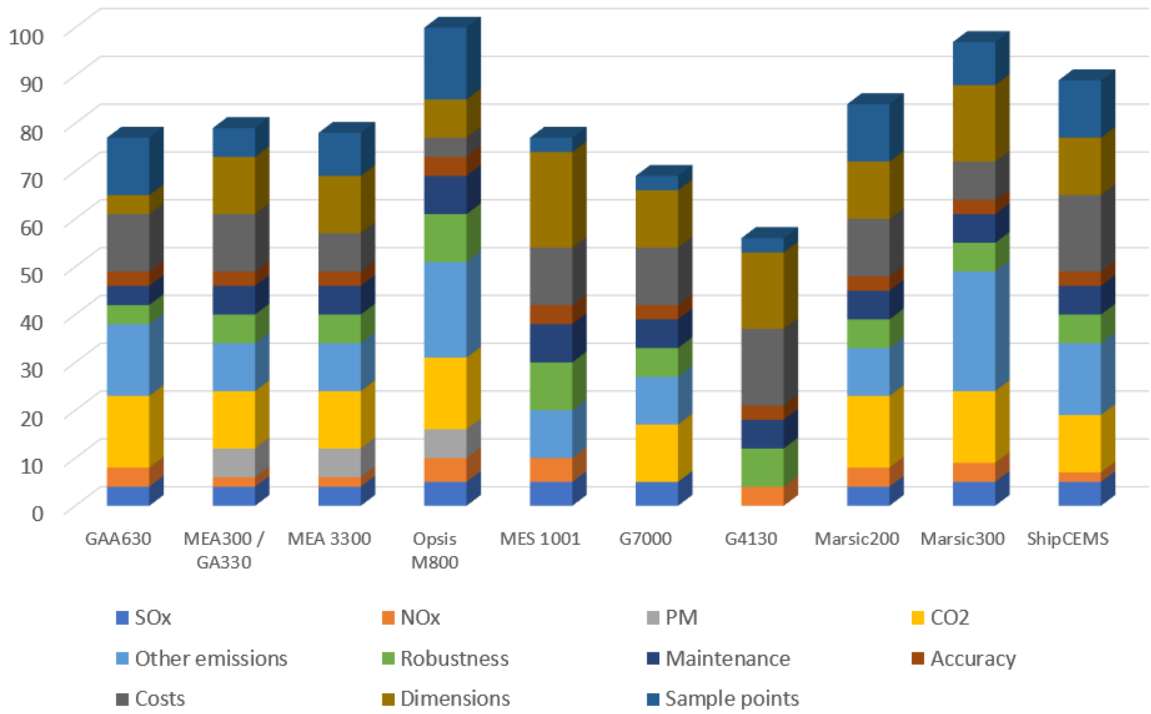


Figure 7.3: Results sensitivity analysis with inverted weights

Table 7.3: Sensitivity analysis with inverted weights

Criteria		Weight	Score				
			GAA630-M	MEA 3000 / GA330-M	MEA 3300	Opsis M800	MES 1001
Emissions	SO_x	1	4	4	4	5	5
	NO_x	1	4	2	2	5	5
	PM	3	0	2	2	2	0
	CO_2	3	5	4	4	5	0
	Others	5	3	2	2	4	2
Robustness		2	2	3	3	5	5
Maintenance		2	2	3	3	4	4
Accuracy		1	3	3	3	4	4
Costs		4	3	3	2	1	3
Dimensions		4	1	3	3	5	5
Sample points		3	4	2	3	5	1
Total weighted score			**77**	**79**	**78**	**100**	**77**
			G7000	**G4130**	**Marsic200**	**Marsic300**	**ShipCems**
Emissions	SO_x	1	5	0	4	5	5
	NO_x	1	0	4	4	4	2
	PM	3	0	0	0	0	0
	CO_x	3	4	0	5	5	4
	Others	5	2	0	2	5	3
Robustness		2	4	4	3	3	3
Maintenance		2	3	3	3	3	3
Accuracy		1	3	3	3	3	3
Costs		4	3	4	3	2	4
Dimensions		2	3	4	3	4	3
Sample points		3	1	1	4	3	4
Total weighted score			**69**	**56**	**84**	**97**	**89**

8

Data transmission and storage

This chapter will describe the possibilities that can be used to transfer the emission data from the monitoring system to the shore. This description will not be too detailed, because of the objective of this chapter. The objective of this chapter is to give an impression of the possibilities with the most potential in terms of feasibility. This chapter will also use information from the stakeholders (see chapter 9).

It appears from conversations with various stakeholders that the data transmission and storage will be of great importance for them. That is why the data transmission part will co-determine the success of the monitoring system. An opinion from the inspection is that the data transmission must be safe and robust, so that fraud is impossible. For the shipping companies it is however important that the data will not be made public, because of the competition and the public opinion. A solution for both causes is to send the data encrypted (see figure 8.1). Data encryption is namely a conversion of data into a code (scrambled data) for confidentiality or security or compression. This technique is developed with the primary purpose to protect the data transmitted via internet or other networks. The benefit of encrypted data is that it can only be understood by authorized parties. Thus, in this case the authorized parties should be the shipping companies and the inspection.

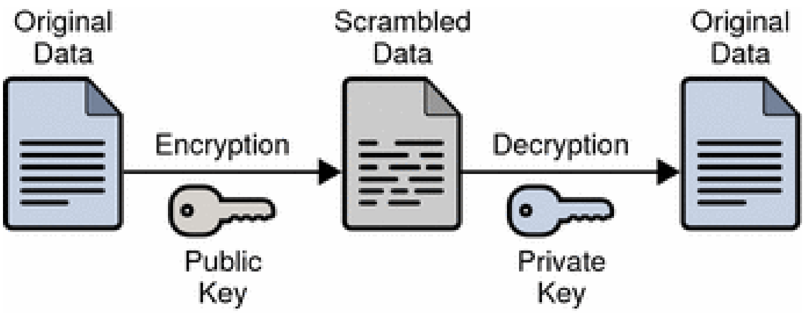


Figure 8.1: Encrypted data transmission (Chaintanya, 2016)

According to the moment of sending the data, a number of options will be available. These options are: continuously, with a time interval, random or dependent on location. A critical parameter that will determine the moment of data transmission is the capacity of the network that will be used. It is for example more difficult to send the data when a ship sails in the middle of the ocean. Essential is that a procedure is drawn up, by which the inspection is able to enforce the emission regulation. Nevertheless, the cots will also play an important role in this consideration.

The interviews with the inspection have indicated that they do not need to have all the data, but that the data, when an offence is committed, will be sufficient to enforce. On the contrary, the shipping companies indicated that they want to have the data continuously in order to optimize their engines from shore. The wish of both stakeholders can be met by sending the data double in different versions. The next paragraph will describe how this can be achieved.

The configuration of the data transmission and storage part of the system is shown in figure 8.2. The measuring module (in this case the emission monitoring system (see chapter 6) will ensure that the height of the emissions are known. This data will then be processed by a computer and thereafter be stored on a hard disk. It is important that the computer is separated from the control systems of the ships network to prevent the possibility to edit the data before it is sent to the inspection. This computer also has the task to determine if a violation has been committed. The computer will therefore also have to make use of the GPS coordinates. The latest in order to determine if a ship sails in or outside an ECA. The computer also ensures that the data is sent to the inspection (when a violation is made) and to the office of the shipping company. This data will be transmitted in an encrypted form, as described above. All the emission data will be stored on the hard disk, so that it can serve as backup, when for example the transmissions of the data fails. The hard disk makes it also possible to send the data with time intervals, if there is no connection at a certain moment. In the end the data will be sent by the transmitter. The communication systems of the ship itself are used for this job. This option is chosen, because this saves costs of an addition transmitter and the shipping companies indicated that this will be easily possible. This option is also not a problem according the data confidentiality and security, because the data is encrypted when it is sent.

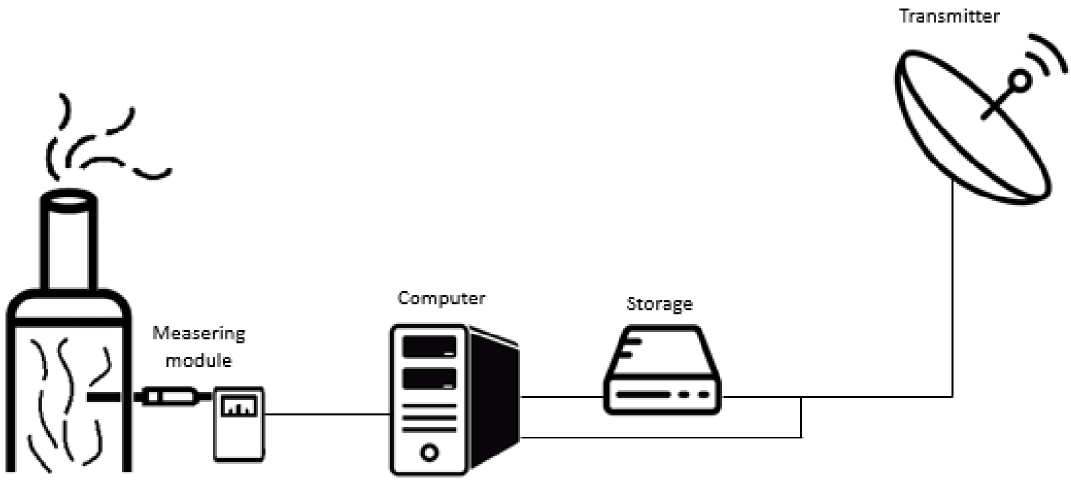


Figure 8.2: Data transmission overview on board the ship (own composition, 2018)

There are two options to transmit the data from the ship to the shore. The first option is shown in figure 8.3. This option makes use of satellites to transfer the data from the ship to shore. This option has multiple benefits. Namely, the data could be sent from any location and sending in this way is safe. A disadvantage of this option is the possible high costs of sending data via the satellite. However, the expectation is that the costs will decline in the future. Another disadvantage could be the capacity of the data that can be sent by the route of for example a satellite. This because the fact that the satellite coverage is not the same everywhere in the world. The latter can make it difficult to send data continuously.

Note, figure 8.3 shows a GPS satellite and the inspection office. This GPS satellite is necessary to label the emission data with the coordinates of the ship. The inspection office is an example in this figure and could also be replaced by the office of a shipping company, because the data is sent to both.

Another option for the data transmission is shown in figure 8.4. This option makes use of data transmission via a land-based fixed network. It is intended with this option that a ship connects to this network when it is in the port to then send the data via the land-based network. The benefit of this system that it is cheaper than the satellite option. However, the drawbacks of this option are that continuously receiving data is no longer possible and and that this network is less safe. The preference will therefore go to option 1. For both options applies that if the data transmission fails for whatever reason, the inspection still can go on board of the ship to secure the hard disk with data.

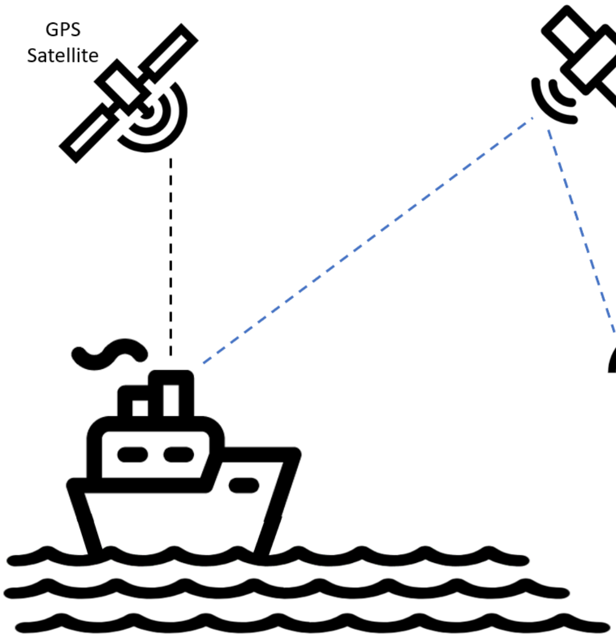


Figure 8.3: Data transmission option 1 (own composition, 2018)

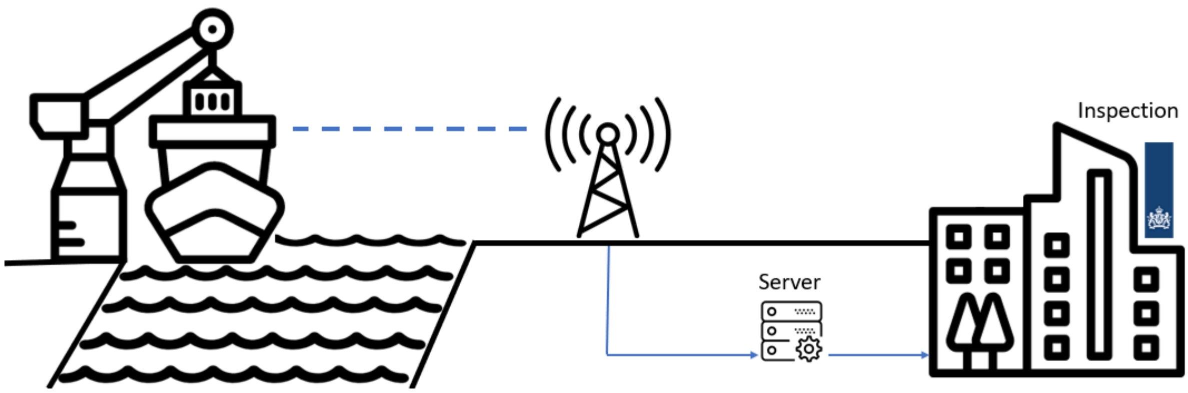


Figure 8.4: Data transmission option 2 (own composition, 2018

9
Stakeholders

This chapter reflects on the conversations and discussions with the various stakeholders. The objective of the conversations was obtaining insights on different topics, according to the on board emission monitoring system. The conversations were held with eight different stakeholders. The co-operation of these eight stakeholders have resulted in a lot of new insights.

It had been agreed with most of the stakeholders that their information or opinions will not be mentioned in this report in combination with their name. This has to do with the fact that their opinions are competition sensitive. Therefore, it has been chosen to describe the gathered information from the stakeholder who want to remain anonymous in a general form.

The stakeholders that indicated that they could be mentioned with their name in the report are two Dutch government institutions. Namely, the ministry of Infrastructure and Water management and the Inspectie Leefomgeving en Transport. The ministry is responsible for the policy in the field of shipping for the Netherlands and was therefore useful as stakeholder. Especially because they participate in the international rules (IMO). The Inspectie Leefomgeving en Transport is responsible for the enforcement of the regulations.

Ministry of Infrastructure and Water management

Important to know is that the ministry of Infrastructure and Water management could not give their opinion according to an on board emission monitoring system. This is because of strategic reasons. Nevertheless, the ministry was allowed to explain how an on board emission monitoring system can be successful on a political level. The ministry indicated that the system could be successful if it will be regulated internationally in the form of regulations. The main benefit of arranging it internationally, is that a level playing field can be guaranteed. However, arranging it internationally means that a broad support is necessary, which can make it difficult. The ministry indicated that the primary route to arrange this internationally will be via the IMO. This is however often a slow process and could take years. Another option to accelerate this process is to arrange it at European level first, like it is done with for example MRV (see section 3.6). An option for this is the composition of a new European convention.

The monitoring system could also be successful according to the ministry when it will be used for scientific purposes. Especially with the objective to make good assumptions for the amount of emissions per ship type when operational. The system could then be used for the validation of the emissions factors, what is rarely done at the moment. Another option which could help to make the system successful, is to focus on certain niche markets. Examples of niche markets that could be interesting are the cruise industry and the yacht industry, because these ships are often in populated areas. A positive side effect of the system is that more knowledge will be obtained, which makes it possible for the ministry to estimate the consequences for the public health.

Important to know according the ministry is that an on board emission monitoring system that functions well can also lead to regulations. Namely, the step to choose for such a system could become smaller, when the on board monitoring system shows their capabilities to enforce the limits.

Inspectie Leefomgeving en Transport

The Inspectie Leefomgeving en Transport (Human Environment and Transport Inspectorate) has the task to enforce the regulations, (IMO and the Dutch legislation). The inspectorate is an important stakeholder, because they are involved in the enforcement on a daily basis. Besides this, the inspectorate will be one of the users, in particular with the final product, the emission data.

The inspectorate was able to speak freely according this subject, because they do not have any strategic importance or influence according to, for instance, the regulations. They could especially speak about the current enforcement procedure and the possible benefits or disadvantages of the emissions monitoring system. They also indicated whats important for them and what could be improved.

This research focuses on a number of emission, however the inspectorate indicated that they mainly focus on the SO_x emission limit. They enforce the SO_x emission limit according guidelines from the IMO and the European commission. The inspectorate takes physical samples of the marine diesel fuels that are being used on ships. These samples are thereafter used to verify the sulphur content. This check can be performed in three ways: by analysing the sealed bunker sample from the fuel supplier, by obtaining and analysing a fuel spot sample drawn from the fuel system in the ship or by a representative sample according the bunker delivery note.

The inspectorate is obliged to check a certain quantity of ships on the sulphur content. This quantity is primarily based on the annual number of individual ships that are calling for a member state. The minimum quantity of inspections that all state members have to carry out is fixed at 10% of the individual ships that are calling for their port. The inspectorate processes the results of the inspections in a system called Thetis-EU. This is an 'Union information system' for exchanging and recording the details and findings of on board inspections, including the results of the fuel sampling. This system is developed by the EMSA and was used in 2015 for the first time. The inspection indicated that the use of this system is voluntary. Therefore, it isn't used by every inspectorate.

The inspectorate indicated that they are allowed to use other technologies to check SO_x compliance in support of the physical sample check. The goal of using these technologies is to obtain a quick indication, whether a ship appears to be complaint to the SO_x regulations, or whether there is a reasonable doubt. It triggers the inspection for a normal inspection when there is doubt about the compliance. The alternative technologies that are used for a compliance check are, for example remote sensing technologies, sniffers and portable sample devices. Sniffers are often installed at: port entry points, onto bridges, patrol vessels and planes. The inspectorate told that these techniques are expensive and that the success of the measurements depends on variables, such as the wind direction.

The disadvantage of the current inspection procedure is that there is little insight into what happens at the open oceans. Especially, at the important point when a ship enters or leaves an ECA (see section 3.2). The inspectorate therefore indicated that they see potential for an on board monitoring system. The inspectorates thinks that the system could help to make the control procedure more robust, which is important for the level playing field. They were also in favor for the system, because it offers the opportunity for them to monitor the emission whenever and everywhere they want. This advantage creates the opportunity to offer exemptions to shipowners concerning the checks. On the condition that the system will work properly and robust. Thus, it can be concluded that the Dutch inspectorate sees potential in the on board monitoring system, because they recognize the advantages.

Shipping companies

This part will describe the opinions and thoughts of the shipping companies, concerning the on board emission monitoring system. It is chosen to generalize the obtained information, in order to ensure their anonymity. This means that a distinction is made between two groups. The first group contains shipping companies who are primarily engaged in the transportation of goods. For instance, companies with general cargo vessels, container ships, dry bulk carriers or product tankers. The second group consists of shipping companies that are not engaged in transporting goods. Like companies that operate in the offshore wind, offshore oil & gas or dredging business. It should be noted that the opinions per company within the above mentioned groups may differ from each other at detail level. However, it has been noticed that the companies are having comparable opinions on a higher level.

Group 1

This section describes the generalized opinion of shipping companies that are primarily engaged in the transportation of goods. The stakeholders indicated that they see advantages in an on board emission monitoring system. The main advantage of the system according to them is the possibility to enforce properly, especially in the field of SO_x emissions. They indicated that proper enforcement of the emission regulations will create a level playing field. This level playing field is of great importance for them, because it is of direct economic importance. The stakeholders pointed out that the competition in this sector is often that immense that a shipowner could have economic gain if they break the rules. The stakeholders indicated that they have their doubts about the enforcement with the associated level playing field after 2020 (new global sulphur limit, see section 3.4). Therefore, they certainly see the system as an option when it comes to proper enforcement. However, they also see some difficulties to implement the system.

One of the difficulties is that the success of the system in terms of creating a level playing field strongly depends on international regulations. Even if the system is mandatory in the future they foresee possible obstacles. For instance, the robustness of the system in combination with the consequences. For example, what happens if the monitoring systems does not function for a certain period of time? It will therefore be important for the shipping companies that all uncertainties will be taken away. This is important because multiple stakeholders indicated that new regulations often lead to frustrations. This is due to the fact that regulations are often elevated to a requirement and when they are implemented, no longer reviewed according to the stakeholders. These frustrations and possible extra costs can be so high that it outweighs the advantages of the system. That is why it will be important to guarantee the robustness of the system and to take away the uncertainties when the system operates. Heard uncertainties are for instance: who is responsible for the maintenance or calibration of the system? Is there an immediate intervention by the inspection when the system malfunctions?

The conversations with the stakeholders from this group have also revealed that they are interested in the monitoring and enforcement of particular type of emissions. They are interested in SO_x emissions, from the emissions that are included in the scope of this research. This has again to do with economic motifs. Namely, the SO_x emissions are directly related to the use of the fuel type and the emissions control technologies. These two are one of the biggest cost items for the companies and therefore of great importance for them. This does not apply for NO_x, PM and especially BC emissions. The companies indicated that it is not desirable to monitor BC, due to the lack of regulations for this type of emission. This also implies indirectly for the measurement of PM. The opinion for NO_x monitoring is again based on economic considerations. They indicated that the consequences of the NO_x limits are quite low in comparison to the SO_x limits and are therefore not interested in the monitoring of NO_x emissions. However, it was indicated by the stakeholders that CO_2 monitoring has potential besides the above mentioned emissions. The monitoring system including CO_2 could then play a role in the MRV regulations, which ensures that crew is much less burdened.

Another topic that has been discussed with the stakeholders is the data transmission. This discussion was mainly focused on the openness of the data. What turned out was, that the opinions of the various stakeholders from group 1 were more divided. What could be concluded is, that none of the stakeholders wants that the data becomes public. A frequently heard opinion is that they do not want that a person who has no knowledge of the shipping sector will form an opinion according to their emissions.

Thus, it can be concluded that the shipping companies of this group are focused on the regulations in combination with their economical interest. This also explains the fact that the stakeholders within this group have indicated that they are not willing to invest in the system if it is not mandatory. This is immediately the most important difference with group 2 (see next section).

Group 2

This groups contains shipping companies that are not engaged in transporting goods. Like companies that operate in the offshore wind, offshore oil & gas or dredging business. What immediately was noticeable at these companies was that they had other ideas for the emission monitoring system. They indicated that they are not interested in the enforcement task/option of the system, in order to create a level playing field. This can be explained by the fact that the companies within this group impose themselves stricter requirements, because it is expected from their customers. For example, assume a random dredging company that gets a contract for maintaining the sailing routes in the port. The principal, in this example the port authority, then demands requirements, also regarding the emissions. Thus, it means that these companies do not have any work, when they cannot meet the requirements. Violating the rules for this group is therefore very undesirable. Often also because of their public function. Therefore, it can be concluded that creating a level playing field by using an on board emission monitoring system will not be necessary according to this group.

Nevertheless, the shipping companies see a lot of potential in the system when it comes to other applications. For example for optimization purposes, like lubricating oil consumption. By obtaining data of the emissions it should be possible to keep the lubricating oil consumption low. They also indicated that if the data will be sent directly to the office, remote assistance will be a possibility.

Another possibility that could make the system successful, is by using the system for emission calculations for their clients. The shipping companies are often obligated by their client to calculate the pollutants or the CO_2 footprint for a particular assignment. This is done nowadays with an estimation based on emission factors. A considerable advantage of the on board emission monitoring system is that the pollutants or CO_2 footprint could be determined with a high accuracy. The latest is in favor of the shipping companies and their clients.

In general it can be concluded that this group pays a lot attention for a better environment. That is why they are more willing to make investments in such a system in comparison with group 1. However, the companies will only invest if the system will lead to benefits or more insight in their emissions.

10

Conclusion and recommendation

The research presented in this report has given an insight in the possibilities and the potential of an on board emission monitoring system. The knowledge that has been gained is used to formulate a conclusion. This conclusion will answer the research sub-questions that are formulated in chapter 1 and also indicate if the objective of this research has been achieved. The objective of this research was formulated as follows:

Recommend an on board monitoring system that is able to monitor pollutant emissions of seagoing vessels, in relation with costs and benefits, robustness, accuracy, maintenance and future legislation for NO_x*,* SO_x *and particulate matter/black carbon.*

The research sub-questions that are used in order to achieve the above mentioned objective were:

- What is the impact and contribution of SO_x, NO_x, PM and BC emissions from seagoing ships?
- What is the current legislation and what will be the future legislation regarding the emissions?
- What are the options for the shipowners to comply with the legislation?
- Which sensors are available for the measurement of emissions?
- Which low-end and high-end systems are available for the measurement of emissions?
- What are the options to send the data to the inspection?
- Which system is most suitable as an on board emission monitoring system?
- What is the opinion of the stakeholders according to an on board emission monitoring system?

It can be concluded that the impact of the SO_x, NO_x, PM and BC emissions are quite large for the human health and environment. Namely, the air pollution from international shipping accounts for circa 50,000 premature deaths per year in Europe. It has also been shown that there is still much to be gained in reducing the emissions in sea shipping. This is why the IMO has drawn up regulations in order to reduce these emissions. However, it has been found that there is only legislation for the NO_x and the SO_x emissions, in the form of emission limits and fuel regulations. For BC and PM emissions applies that there are no direct limits. The PM emissions are indirectly regulated via the above mentioned SO_x regulations. The literature study revealed that the absence of BC regulations probably originates from the lack of knowledge toward BC emissions from shipping. The IMO is currently executing a measurement program in order to verify the BC definition of Bond et al. (2013) and to test the measurement equipment. Because the uncertainties towards the definition of BC, it has been concluded that the research on BC measurement was no longer desirable and therefore excluded from measurement scope of this research.

It has been demonstrated by a literature study that the above mentioned emission limits for NO_x and SO_x were effective, in particular the Tier II limits for NO_x emissions and the SO_x limits within an Emission Control Area. However, these regulations are not yet strict enough, due to the increased requirements on land and the awareness of the consequences nowadays. Therefore, the IMO decided that new regulations must be introduced, such as the global 0.5% sulphur limit and the Tier III NO_x limit. These new regulations are reviewed in this report and it can be concluded that the global sulphur limit of 2020 will have the biggest impact on the maritime sector. This is also confirmed by the stakeholders. This means that the focus of the shipping companies will be on the global 2020 SO_x regulation, because this regulation applies to all ships and not only to new build ships, which is the case for the NO_x Tier III limit. These new regulations provides opportunities for the emission monitoring system.

According to the possibilities of the shipowners to comply with the future regulations, it can be concluded that they have basically two main options. One of these options is to use a fuel type with a low sulphur content. The other option is to use emission control technologies in combination with a fuel type with a higher sulphur content. It has been concluded that both options had to be taken into account for the monitoring system, because it is hard to predict which of the two options will be chosen.

The sensors of the on board emission monitoring system are largely responsible for the success of the system. That is why it was important to know which gas sensing principles are available and how the sensors operate. The investigation of these sensors has shown that multiple options can be used. It was found out that there were five different sensor types for an on board monitoring system. Namely, a semiconducter metal oxide sensor, a catalytic combustion sensor, an electrochemical sensor, a nondispersive infrared sensor and a nondispersive ultraviolet senor.

The search that was executed into the available monitoring systems was focused on low-end systems and high-end systems. An important conclusion that was made after the search, was that the low-end systems are not sufficient developed yet to function in marine environments as an on board emission monitoring system in the near future. This meant that only the high-end systems were compared and assessed in a multiple-criteria decision analysis. The following criteria were used in this analysis: robustness, maintenance, accuracy, type of emissions, dimensions and number of sample points.

The high-end system that scored the best during the assessment was the **Consilum M800** and is therefore recommended as an on board emission monitoring system. The main advantage of this system is that it operates with the UV/IR Differential Optical Absorption Spectroscopy principle. The big advantage of this principle is that the sensors and the exhaust gas are separated, which means that much less maintenance is required. An additional benefit of this principle is that there is no need for a sample conditioning unit that ensures cooling and drying of the exhaust gas. Besides this the system is able to use 12 measuring points by the use of an optical multiplexer. This is a large benefit relative to the other systems.

This indicates that the objective of this research has been achieved, except from the BC monitoring. Figure 10.1 shows how the on board emission monitoring is situated in the ship.

According to the data transmission options can be concluded that the best option will be to send the data via a satellite. The security of the emission data will be important with this option. This can be guaranteed by encrypting the data.

Another important conclusion that can be made is about the opinion of the stakeholders. Namely, they indicated during the interviews that they see potential for an on board monitoring system, especially with the goal to create and maintain a level playing field. At the same time, they indicated that they will purchase the system only if it is mandatory or when they can earn money with it.

Recommendations

The objective of this research has been met in the form of a recommendation of an on board monitoring system that is able to measure multiple emissions. However, black carbon emission was not included in this recommendation. The measurement of black carbon was desirable in the beginning of this research, but it turned out that it was not feasible to achieve this. The reason for this is the lack of knowledge according black carbon measurement in sea shipping at the moment. The results of the IMO measurement campaign are necessary to complete the research for black carbon monitoring. This could also be done by TNO. The following measurement techniques must then be tested: Filter Smoke Number, Laser Induced Incandescence, Photo-Acoustic Spectroscopy, Multi Angle Absorption Photometry and Thermal Optical Analysis.

It was concluded that the low-end systems still need further development in order to be used as an on board monitoring system. However, these systems do have a lot of potential, because their low price and simple operating principle. Therefore, it will be desirable to review the assessment again in the future, when the low-end systems are adjusted to maritime environments. It is important for the low-end systems that they will be tested on board a ship. To find out how these systems, and in particular the sensors, will react to the maritime environment including exhaust gases of a marine diesel engine. This investigation should determine at least the following aspects: the cross-sensitivity of the sensor, the operating life time, the amount of maintenance and the contamination of the sensors due to the exhaust gas.

It was difficult to get an insight in the costs of the high-end systems. Therefore, it will be desirable to do more research into this subject. This helps to improve the assessment of the high-end systems. This also applies for the other criteria of the assessment. Therefore, it will be desirable and recommended to test all the high-end systems in practice in order to determine and compare their performance.

The data transmission and storage part in this report is described in a conceptual way. It is therefore desirable that the mentioned options will be tested and reviewed by experts, especially according the security of the transmission, because it is important that the security of data is guaranteed.

This research mainly focused on the enforcement task of the emission monitoring system, seen from the legislation and inspection. However, the shipping companies indicated that they see more options for the emission monitoring system. Like: engine optimization purposes and emission footprint calculations for principles. It is therefore desirable that these possibilities of the system are examined further.

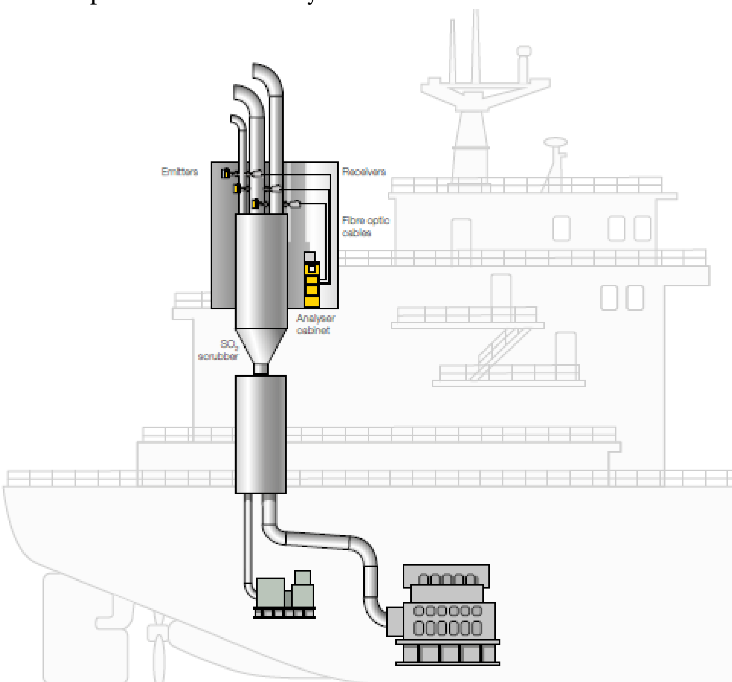


Figure 10.1: Example of a high end solution (Opsis, 2018a)

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Appendices

A

Emission control areas

Figure A.1: Baltic and North Sea/English Channel ECA (American Bureau of Shipping, 2018)

Figure A.2: The North American ECA 200 nautical miles offshore US and Canada, including Hawaii, St. Lawrence Waterway and the Great Lakes (American Bureau of Shipping, 2018)

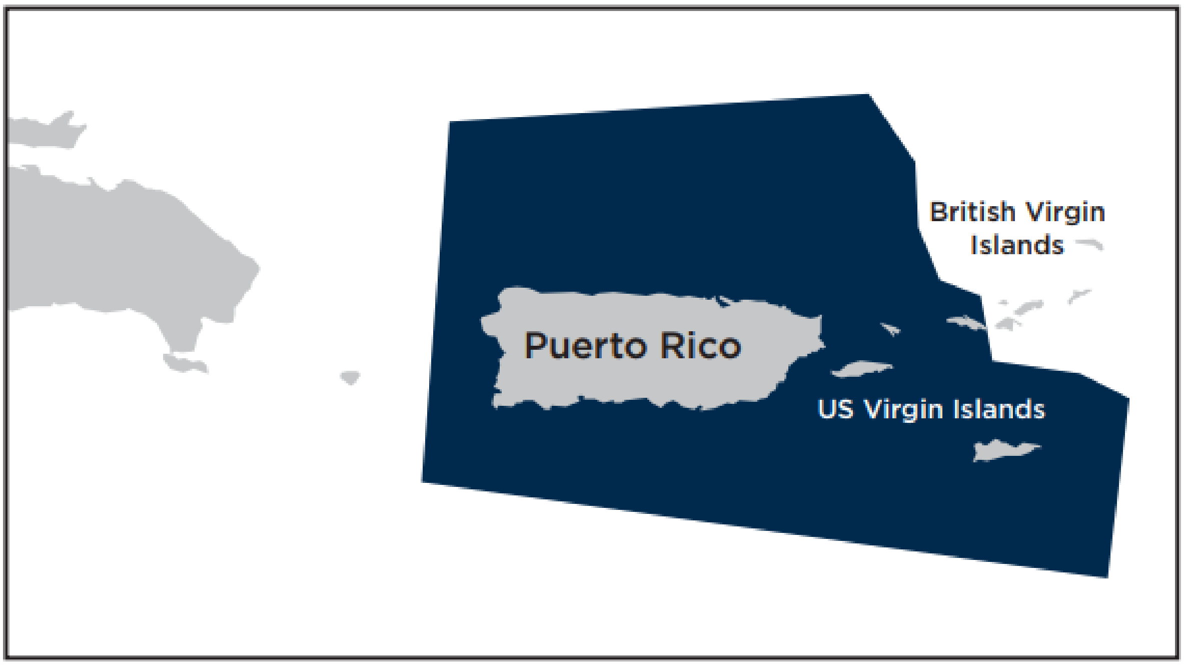

Figure A.3: The United States Caribbean Sea ECA (American Bureau of Shipping, 2018)

B

MARPOL Annex VI

Regulations for the prevention of air pollution from ships

B.1. Regulation 13

Nitrogen oxides (NO_x)

Application

1.1 This regulation shall apply to:

.1 each marine diesel engine with a power output of more than 130 kW installed on a ship; and

.2 each marine diesel engine with a power output of more than 130 kW that undergoes a major conversion on or after 1 January 2000 except when demonstrated to the satisfaction of the Administration that such engine is an identical replacement to the engine that it is replacing and is otherwise not covered under paragraph 1.1.1 of this regulation.

1.2 This regulation does not apply to:

.1 a marine diesel engine intended to be used solely for emergencies, or solely to power any device or equipment intended to be used solely for emergencies on the ship on which it is installed, or a marine diesel engine installed in lifeboats intended to be used solely for emergencies; and

.2 a marine diesel engine installed on a ship solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly, provided that such engine is subject to an alternative NO_x control measure established by the Administration.

1.3 Notwithstanding the provisions of paragraph 1.1 of this regulation, the Administration may provide an exclusion from the application of this regulation for any marine diesel engine that is installed on a ship constructed, or for any marine diesel engine that undergoes a major conversion, before 19 May 2005, provided that the ship on which the engine is installed is solely engaged in voyages to ports or offshore terminals within the State the flag of which the ship is entitled to fly.

Major conversion

2.1 For the purpose of this regulation, major conversion means a modification on or after 1 January 2000 of a marine diesel engine that has not already been certified to the standards set forth in paragraph 3, 4, or 5.1.1 of this regulation where:

.1 the engine is replaced by a marine diesel engine or an additional marine diesel engine is installed, or

.2 any substantial modification, as defined in the revised NO_x, Technical Code 2008, is made to the engine, or

.3 the maximum continuous rating of the engine is increased by mere than 10% compared to the maximum continuous rating of the original certification of the engine.

2.2 For a major conversion involving the replacement of a marine diesel engine with a non-identical marine diesel engine or the installation of an additional marine diesel engine, the standards in this regulation in force at the time of the replacement or addition of the engine shall apply. On or after 1 January 2016, in the case of replacement engines only, if it is not possible for such a replacement engine to meet the standards set forth in paragraph 5.1.1 of this regulation (Tier III), then that replacement engine shall meet the standards set forth in paragraph 4 of this regulation (Tier II). Guidelines are to be developed by the Organization to Set forth the criteria of when it is not possible for a replacement engine to meet the standards in paragraph 5.1.1 of this regulation.

2.3 A marine diesel engine referred to in paragraph 2.1.2 or 2.1.3 of this regulation shall meet the following standards:

.1 for ships constructed prior to 1 January 2000, the standards set forth in paragraph 3 of this regulation shall apply; and

.2 for ships constructed on or after 1 January 2000, the standards in force at the time the ship was constructed shall apply.

Tier I

3 Subject to regulation 3 of this Annex, the operation of a marine diesel engine that is installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

.1 17.0 g/kWh when n is less than 130 rpm;

.2 $45 \cdot n^{-0.2}$ g/kWh when n is 130 or more but less than 2,000 rpm;

.3 9.8 g/kWh when n is 2,000 rpm or more.

Tier II

4 Subject to regulation 3 of this Annex, the operation of a marine diesel engine that is installed on a ship constructed on or after 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

.1 14.4 g/kWh when n is less than 130 rpm;

.2 $44 \cdot n^{-0.2}$ g/kWh when n is 130 or more but less than 2,000 rpm;

.3 7.7 g/kWh when n is 2,000 rpm or more.

Tier III

5.1 Subject to regulation 3 of this Annex, the operation of a marine diesel engine that is installed on a ship constructed on or after 1 January 2016:

.1 is prohibited except when the emission of nitrogen Oxides (calculated as the total weighted emission of $N0_2$) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

.1.1 3.4 g/kWh when n is less than 130 rpm;

.1.2 $9 \cdot n^{-0.2}$ g/kWh when n is 130 or more but less than 2,000 rpm;

.1.3 2.0 g/kWh when n is 2,000 rpm or more.

.2 is subject to the standards set forth in paragraph 5.1.1 of this regulation when the ship is operating in an emission control area designated under paragraph 6 of this regulation: and

.3 is subject to the standards set forth in paragraph 4 of this regulation when the ship is operating outside of an emission control area designated under paragraph 6 of this regulation.

5.2 Subject to the review set forth in paragraph 10 of this regulation, the standards set forth in paragraph 5.1.1 of this regulation shall not apply to:

.1 a marine diesel engine installed on a ship with a length (L), as defined in regulation 1.19 of Annex I to the present Convention, less than 24 metres when it has been specifically designed, and is used solely, for recreational purposes; or

.2 a marine diesel engine installed on a ship with a combined nameplate diesel engine propulsion power of less than 750 kW if it is demonstrated, to the satisfaction of the Administration, that the ship cannot comply with the standards set mm in paragraph 5.1.1 of this regulation because of design or construction limitations of the ship.

Emission control area

6 For the purposes of this regulation, emission control areas shall be:

.1 the North American area, which means the area described by the coordinates provided in appendix VII to this Annex; and

.2 any other sea area, including any port area, designated by the Organization in accordance with the criteria and procedures set forth in appendix III to this Annex.

Marine diesel engines installed on a ship constructed prior to 1 January 2000

7.1 Notwithstanding paragraph 1.1.1 of this regulation, a marine diesel engine with a power output of more than 5,000 kW and a per cylinder displacement at or above 90l installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000 shall comply with the emission limits set forth in paragraph 7.4 of this regulation, provided that an approved method for that engine has been certified by an Administration of a Party and notification of such certification has been submitted to the Organization by the certifying Administration. Compliance with this paragraph shall be demonstrated through one of the following:

.1 installation of the certified approved method, as confirmed by a survey using the verification procedure specified in the approved method file, including appropriate notation on the ship's international Air Pollution Prevention Certificate of the presence of the approved method; or

.2 certification of the engine confirming that it operates within the limits set forth in paragraph 3,4, or 5.1.1 of this regulation and an appropriate notation of the engine certification on the ship's International Air Pollution Prevention Certificate.

7.2 Paragraph 7.1 of this regulation shall apply no later than the first renewal survey that occurs 12 months or more after deposit of the notification in paragraph 7.1. If a shipowner of a ship on which an approved method is to be installed can demonstrate to the satisfaction of the Administration that the approved method was not commercially available despite best efforts to obtain it, then that approved method shall be installed on the ship no later than the next annual survey of that ship that falls after the approved method is commercially available.

7.3 With regard to a ship with a marine diesel engine with a power output of more than 5,000 kW and a per cylinder displacement at or above 90l installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000, the International Air Pollution Prevention Certificate shall, for a marine diesel engine to which paragraph 7.1 of this regulation applies, indicate that either an approved method has been applied pursuant to paragraph 7.1.1 of this regulation or the engine has been certified pursuant to paragraph 7.1.2 of this regulation or that an approved method does not yet exist or is not yet commercially available as described in paragraph 7.2 of this regulation.

7.4 Subject to regulation 3 of this Annex, the operation of a marine diesel engine described in paragraph 7.1 of this regulation is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of N02) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

.1 17.0 g/kWh when n is less than 130 rpm;

.2 $45 \cdot n^{-0.2}$ g/kWh when n is 130 or more but less than 2,000 rpm;

.3 9.8 g/kWh when n is 2,000 rpm or more.

7.5 Certification of an approved method shall be in accordance with chapter 7 of the revised NO_x Technical Code 2008 and shall include verification:

.1 by the designer of the base marine diesel engine to which the approved method applies that the calculated effect of the approved method will not decrease engine rating by more than 1.0%, increase fuel consumption by more than 2.0% as measured according to the appropriate test cycle Set forth in the revised NOx Technical Code 2008, or adversely affect engine durability or reliability; and

.2 any other sea area, including any port area, designated by the Organization in accordance with the criteria and procedures set forth in appendix III to this Annex

Certification

8 The revised NO_x Technical Code 2008 shall be applied in the certification, testing and measurement procedures for the standards set forth in this regulation.

9 The procedures for determining NO_x emissions set out in the revised NO, Technical Code 2008 are intended to be representative of the normal operation of the engine. Defeat devices and irrational emission control strategies undermine this intention and shall not be allowed. This regulation shall not prevent the use of auxiliary control devices that are used to protect the engine and/or its ancillary equipment against operating conditions that could result in damage or failure or that are used to facilitate the starting of the engine.

Review

10 Beginning in 2012 and completed no later than 2013, the Organization shall review the status of the technological developments to implement the standards set forth in paragraph 5.1.1 of this regulation and shall, if proven necessary, adjust the time periods (effective date) set forth in that paragraph.

B.2. Regulation 14

Sulphur oxides (SO_x) and particulate matter

General requirements

1 The sulphur content of any fuel oil used on board ships shall not exceed the following limits:

.1 4.50% m/m prior to 1 January 2012;

.2 3.50% m/m on and after 1 January 2012; and

.3 0.50% m/m on and after 1 January 2020.

2 The worldwide average sulphur content of residual fuel oil supplied for use on board ships shall be monitored taking into account guidelines developed by the Organization.

Requirements within emission control areas

3 For the purpose of this regulation, emission control areas shall include:

.1 the Baltic Sea area as defined in regulation 1.11.2 of Annex I and the North Sea as defined in regulation 5.1 (f) of Annex V;

.2 the North American area as described by the coordinates provided in appendix W to this Annex; and

.3 any other sea area, including any port area, designated by the Organization in accordance with the criteria and procedures set forth in appendix III to this Annex

4 While ships are operating within an emission control area, the sulphur content of fuel oil used on board ships shall not exceed the following limits:

.1 1.50% m/m prior to 1 July 2010;

.2 1.00% m/m on and after 1 July 2010; and

.3 0.10% m/m on and after 1 January 2015.

5 The sulphur content of fuel oil referred to in paragraph 1 and paragraph 4 of this regulation shall be documented by its supplier as required by regulation 18 of this Annex.

6 Those ships using separate fuel oils to comply with paragraph 4 of this regulation and entering or leaving an emission control area set forth in paragraph 3 of this regulation shall carry a written procedure showing how the fuel oil changeover is to be done, allowing sufficient time for the fuel oil service system to be fully flushed of all fuel oils exceeding the applicable sulphur content specified in paragraph 4 of this regulation prior to entry into an emission control area. The volume of low sulphur fuel oils in each tank as well as the date, time and position of the ship when any fuel oil changeover operation is completed prior to the entry into an emission control area or commenced after exit from such an area shall be recorded in such logbook as prescribed by the Administration.

7 During the first twelve months immediately following an amendment designating a specific emission control area under paragraph 3 of this regulation, ships operating in that emission control area are exempt from the requirements in paragraphs 4 and 6 of this regulation and from the requirements of paragraph 5 of this regulation insofar as they relate to paragraph 4 of this regulation.

Review provision

8 A review of the standard set forth in paragraph 1.3 of this regulation shall be completed by 2018 to determine the availability of fuel oil to comply with the fuel oil standard set forth in that paragraph and shall take into account the following elements:

.1 the global market supply and demand for fuel oil to comply with paragraph 1.3 of this regulation that exist at the time that the review is conducted;

.2 an analysis of the trends in fuel oil markets: and

.3 any other relevant issue.

9 The Organization shall establish a group of experts, comprising representatives with the appropriate expertise in the fuel oil market and appropriate maritime, environmental, scientific and legal expertise, to conduct the review referred to in paragraph 8 of this regulation. The group of experts shall develop the appropriate information to inform the decision to be taken by the Parties.

10 The Parties, based on the information developed by the group of experts, may decide whether it is possible for ships to comply with the date in paragraph 1.3 of this regulation. If a decision is taken that it is not possible for ships to comply, then the standard in that paragraph shall become effective on 1 January 2025.

C

Engine control technologies configurations

C.1. Exhaust gas recirculation

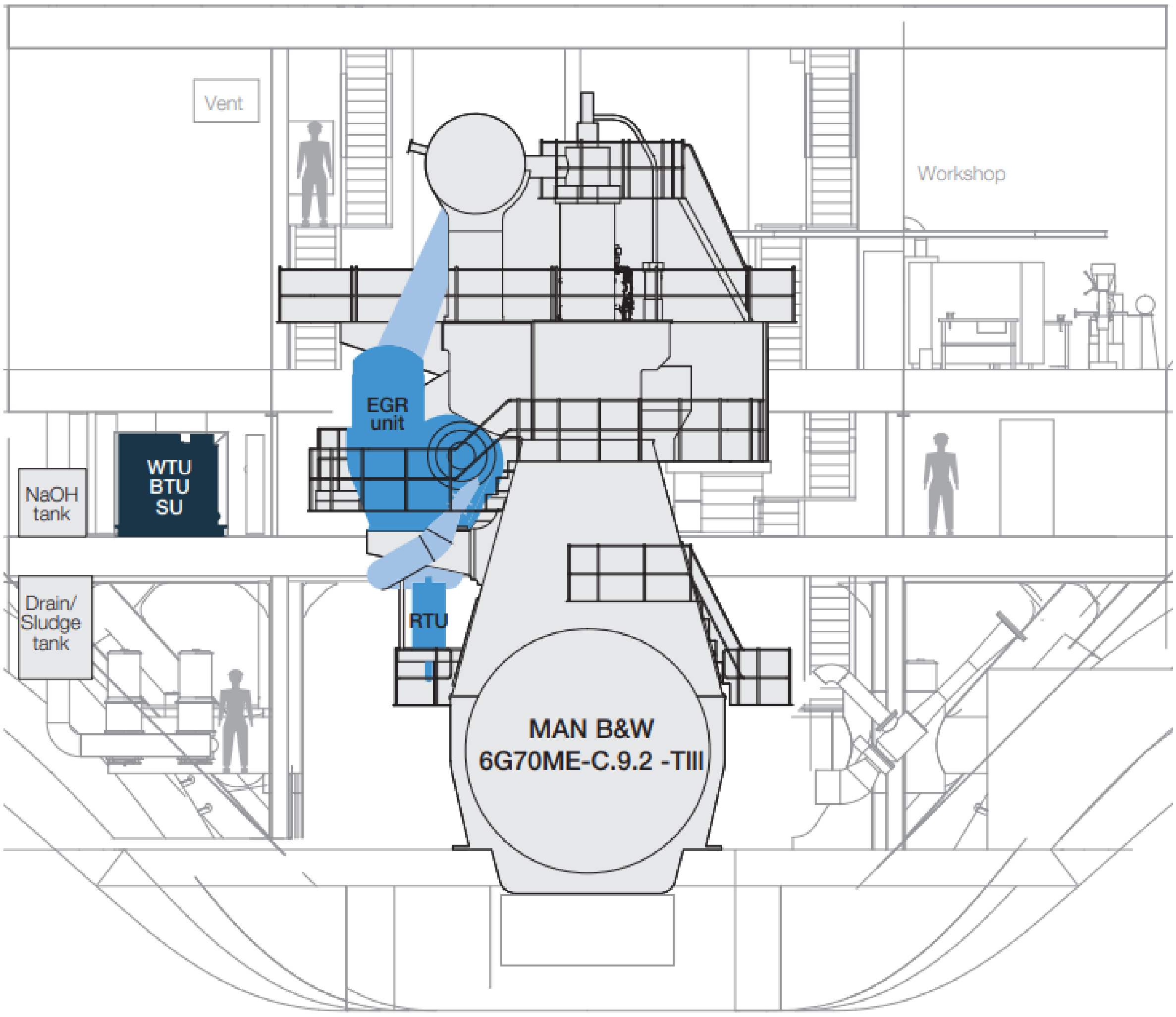

Figure C.1: Example of EGR System on a 182,000 DWT Bulk carrier (MAN, 2017)

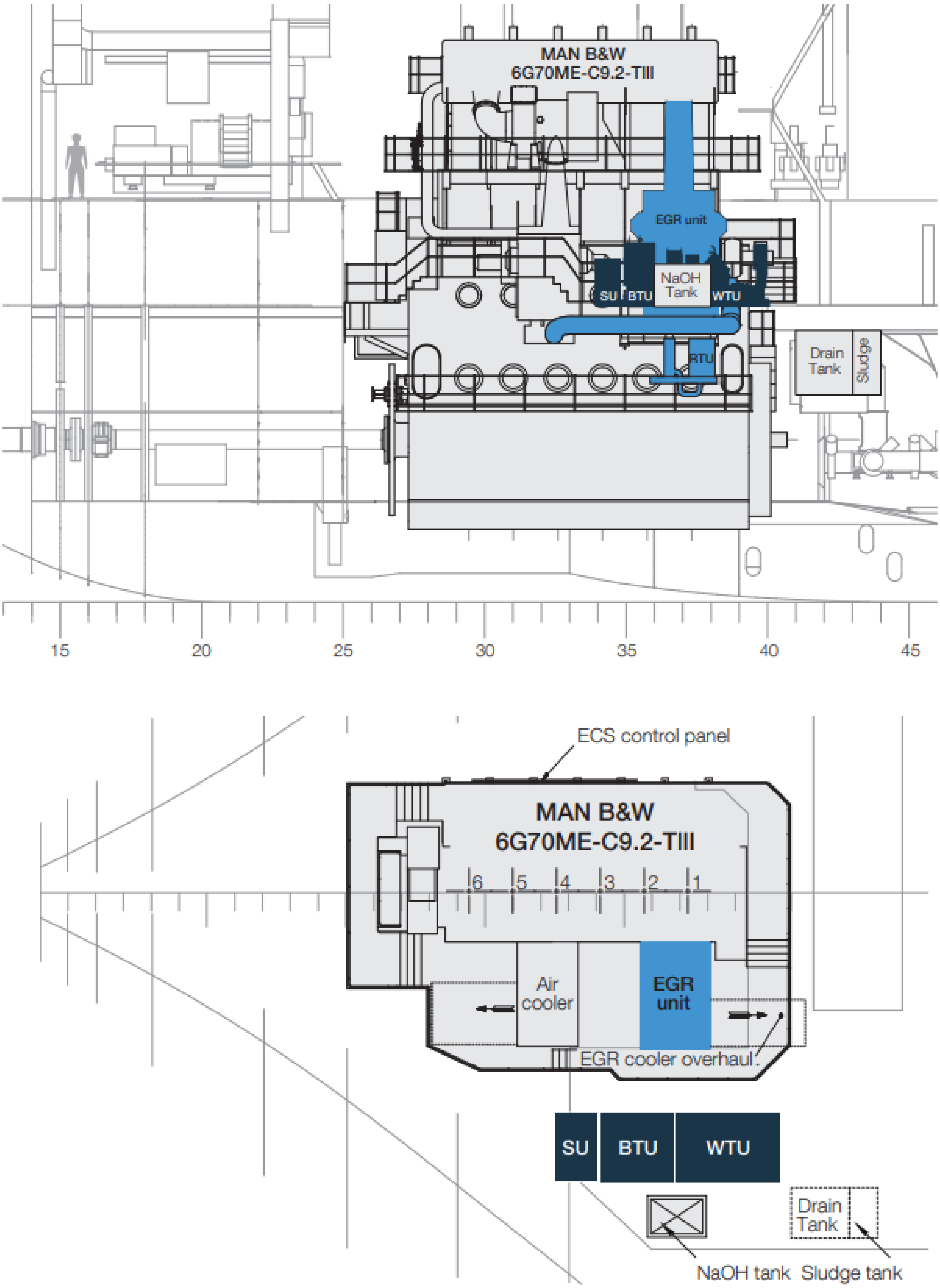

Figure C.2: Example of EGR System on a 182,000 DWT Bulk carrier (MAN, 2017)

D

After-treatment configurations

D.1. Selective catalytic reduction

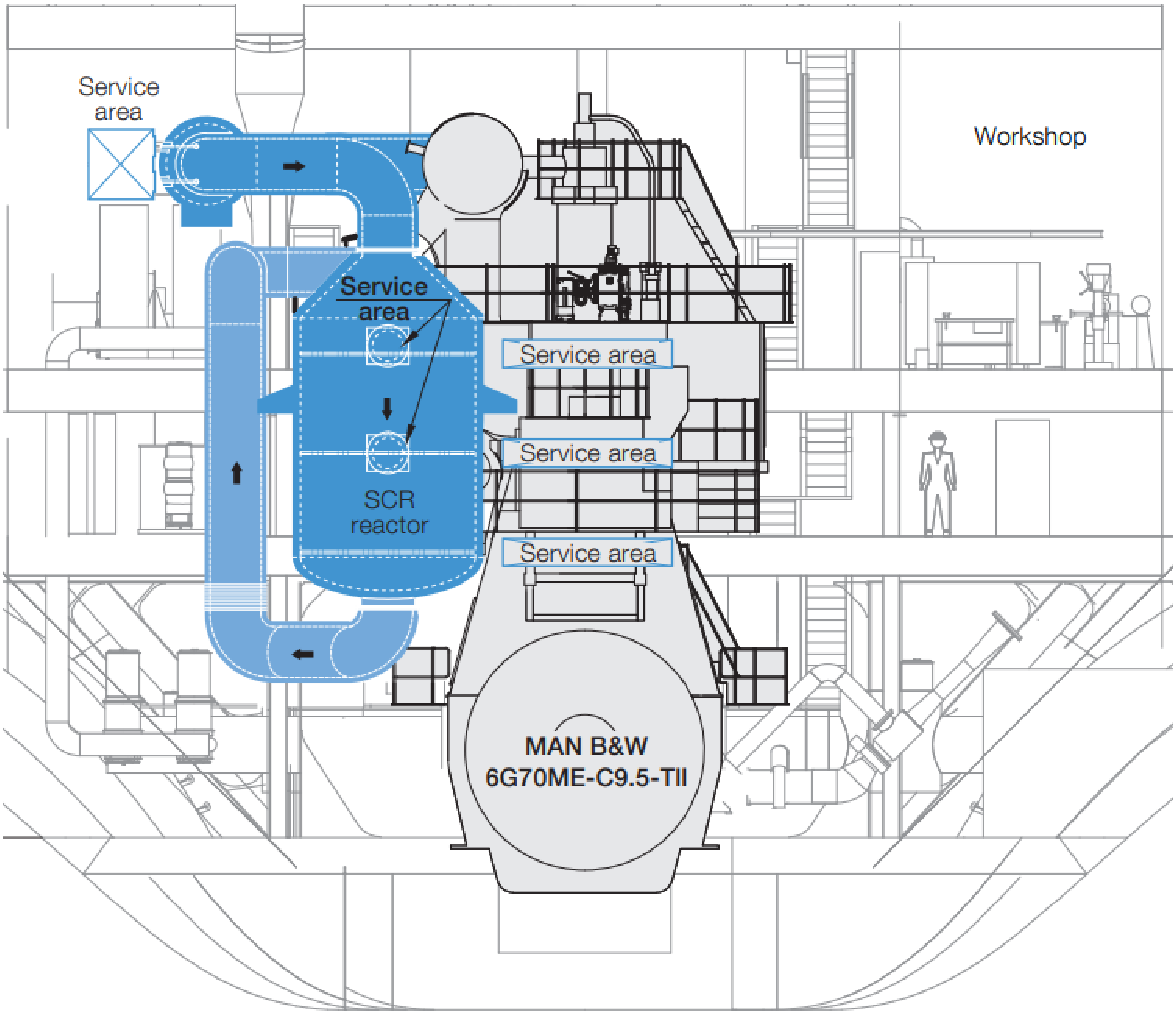

Figure D.1: Example of SCR System on a 182,000 DWT Bulk carrier (MAN, 2017)

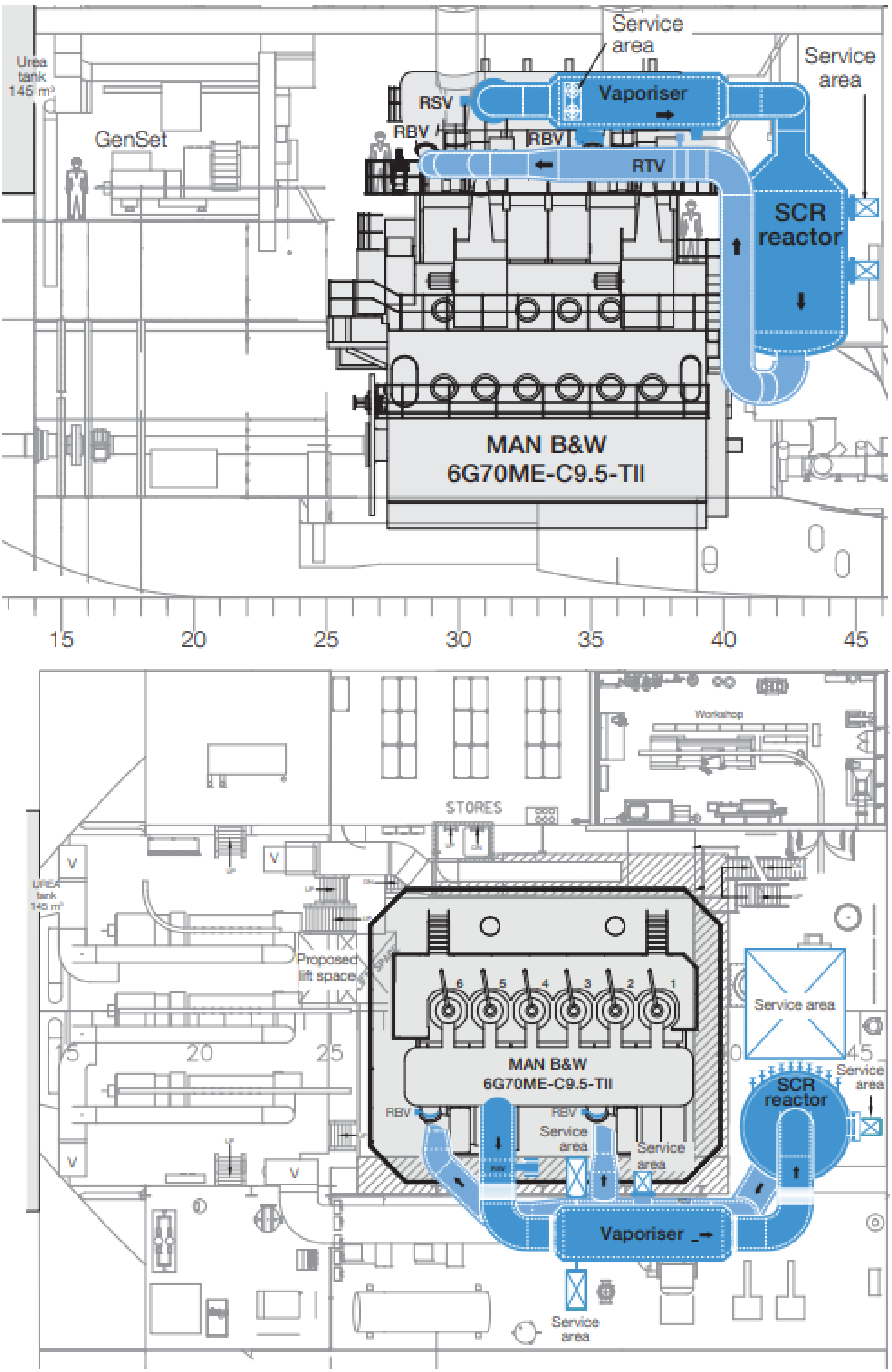

Figure D.2: Example of SCR System on a 182,000 DWT Bulk carrier (MAN, 2017)

D.2. Wet scrubber

D.2.1. Open loop

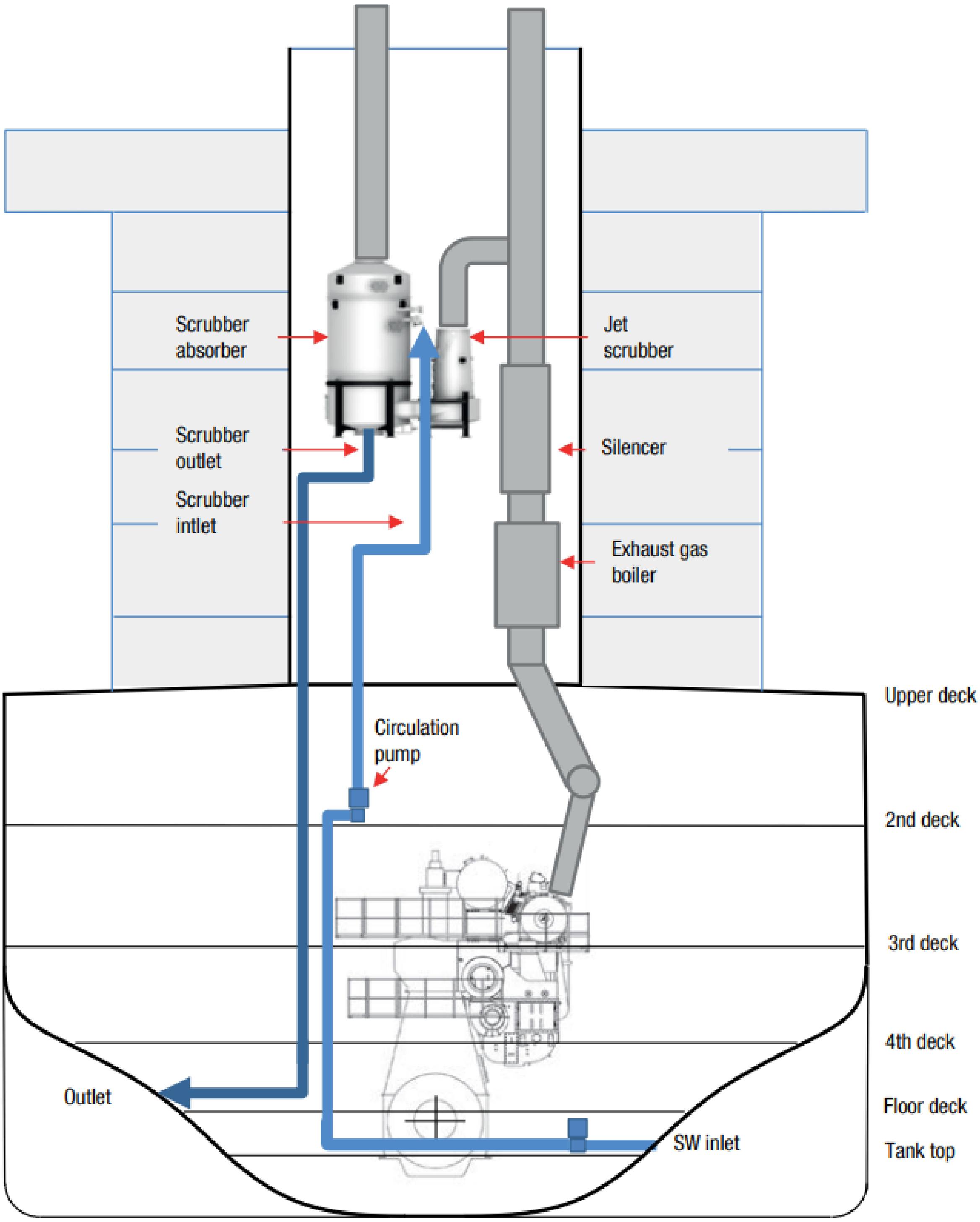

Figure D.3: Schematic arrangement of an open loop scrubber system (MAN, 2017)

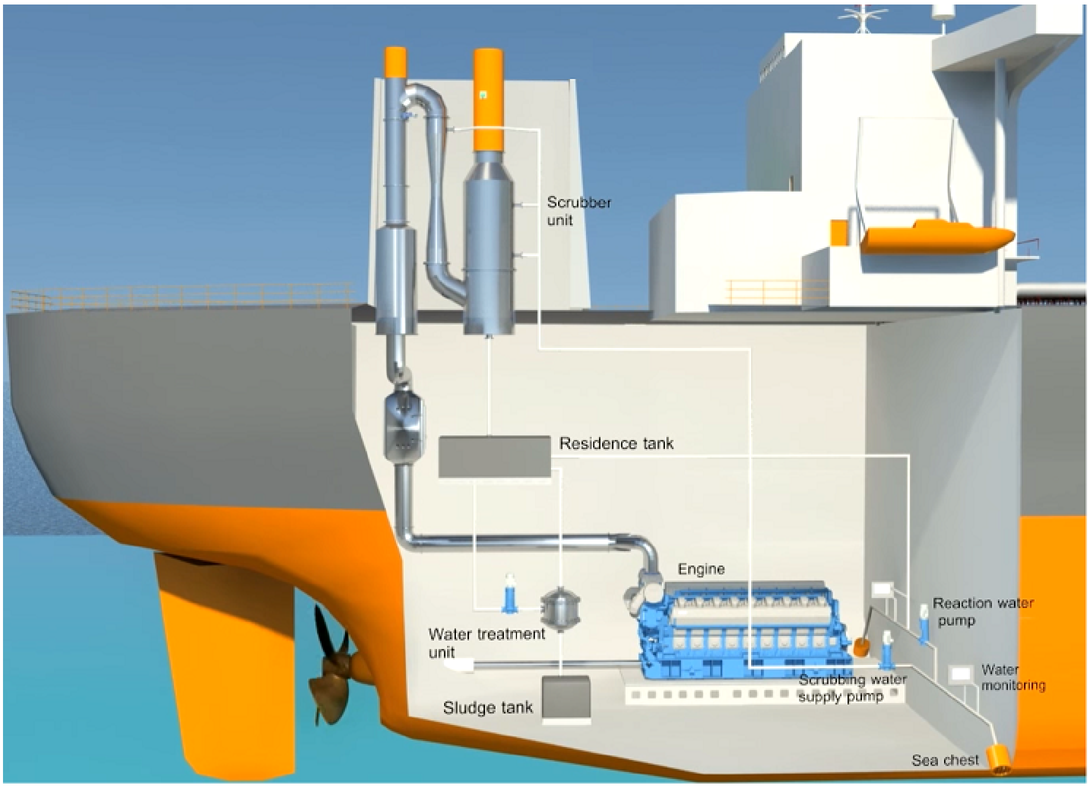

Figure D.4: Schematic arrangement of an open loop scrubber system (Wärtsilä, 2018b)

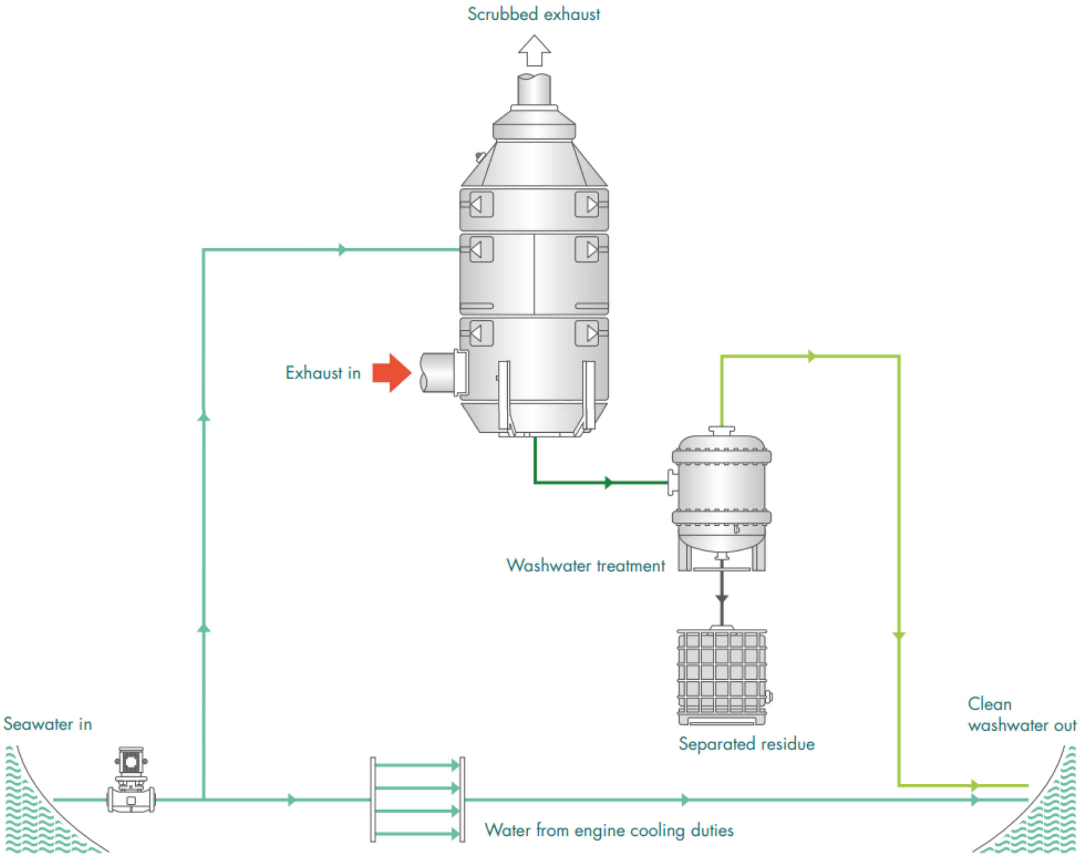

Figure D.5: Schematic arrangement of an open loop scrubber system (Gregory and Confuorto, 2012)

D.2.2. Closed loop

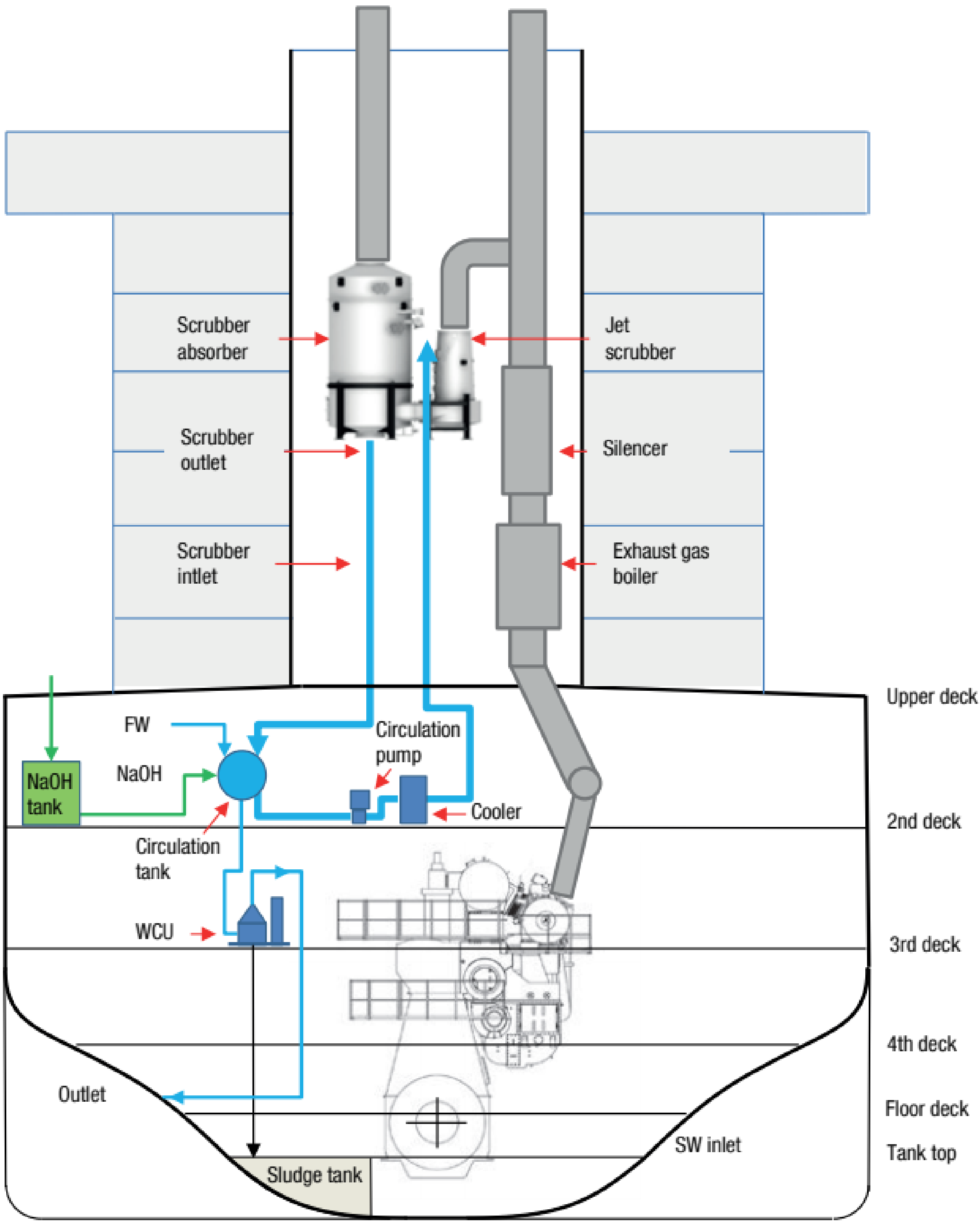

Figure D.6: Schematic arrangement of a closed loop scrubber system (MAN, 2017)

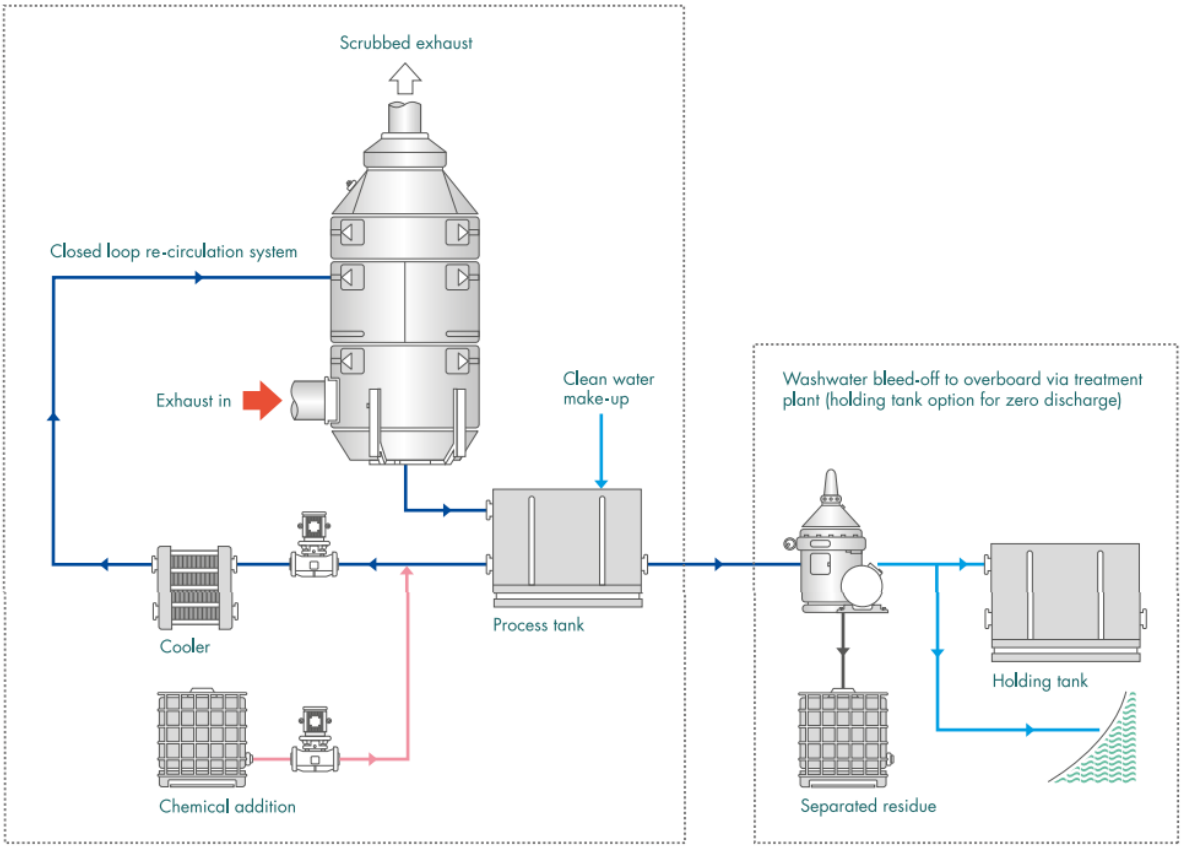

Figure D.7: Schematic arrangement of a closed loop scrubber system (Gregory and Confuorto, 2012)

D.2.3. Hybrid system

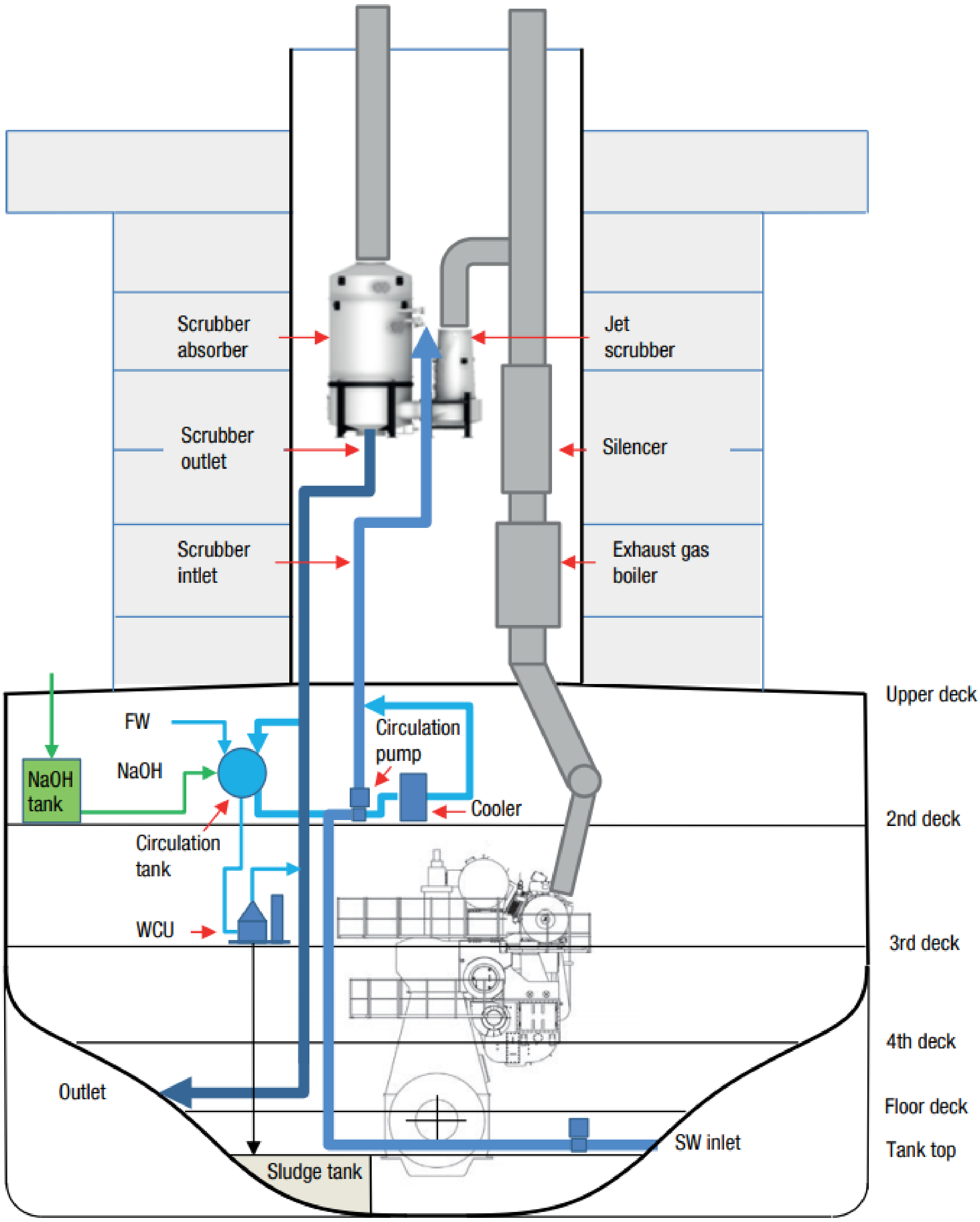

Figure D.8: Schematic arrangement of a hybrid scrubber system (MAN, 2017)

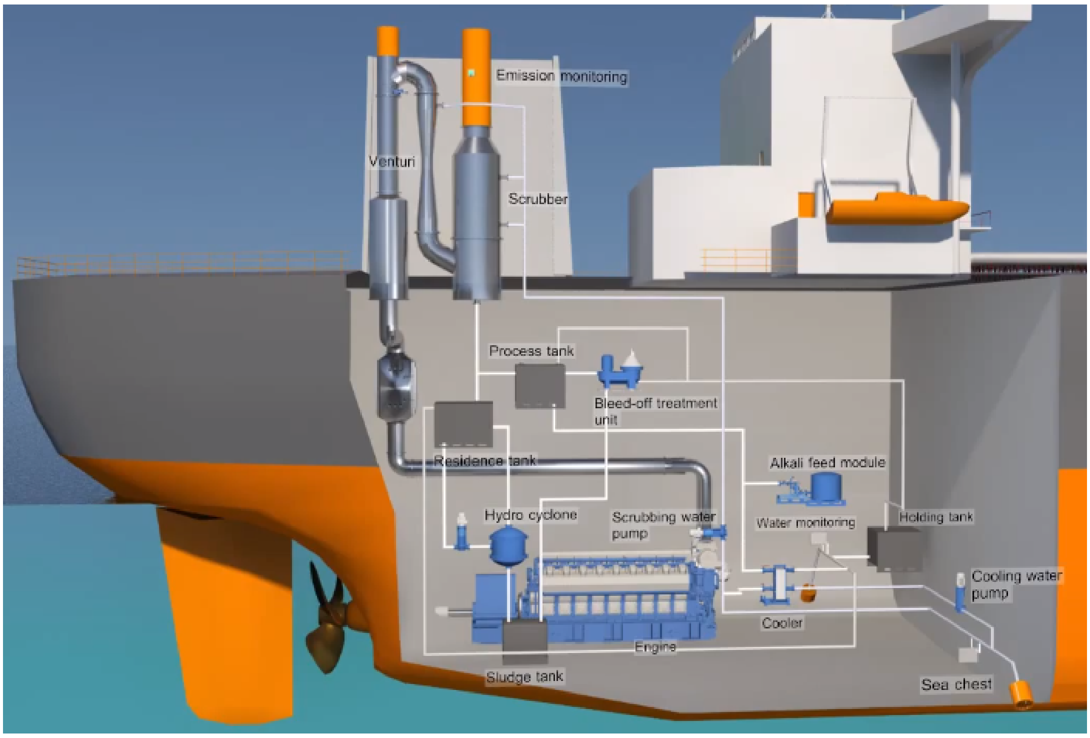

Figure D.9: Schematic arrangement of a hybrid scrubber system (Wärtsilä, 2018a)

D.3. Dry scrubber

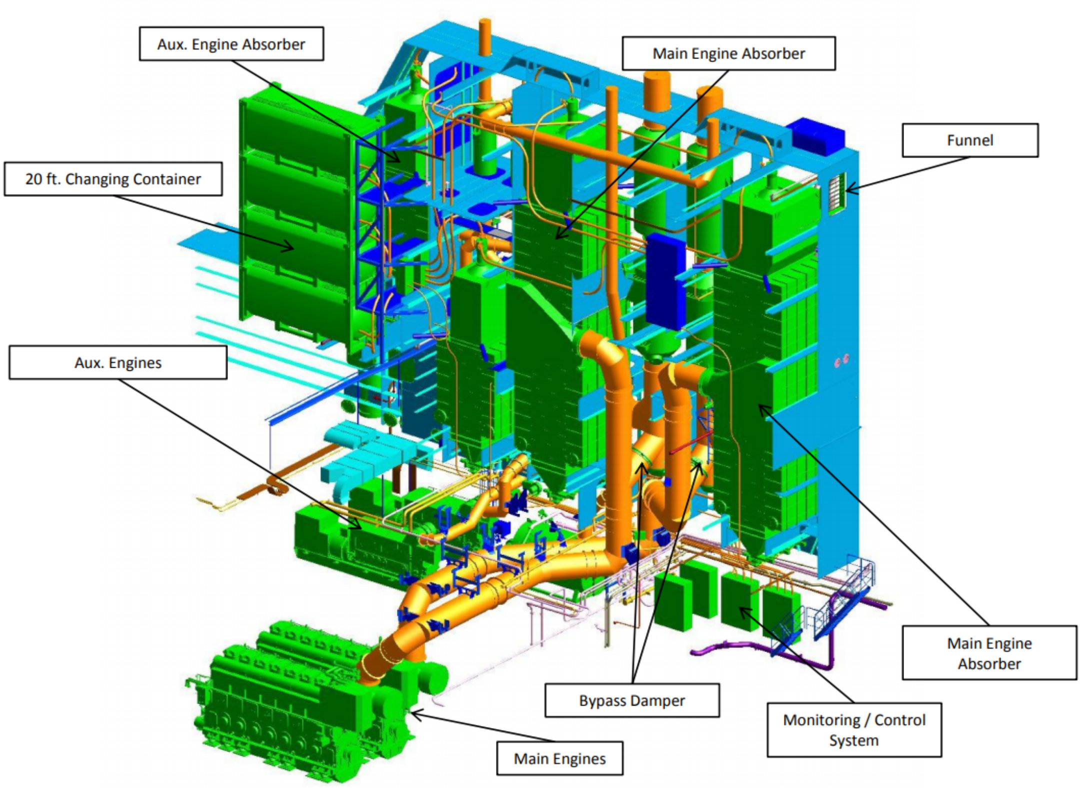

Figure D.10: Schematic arrangement of a dry scrubber system (Couple Systems GmbH, 2010)

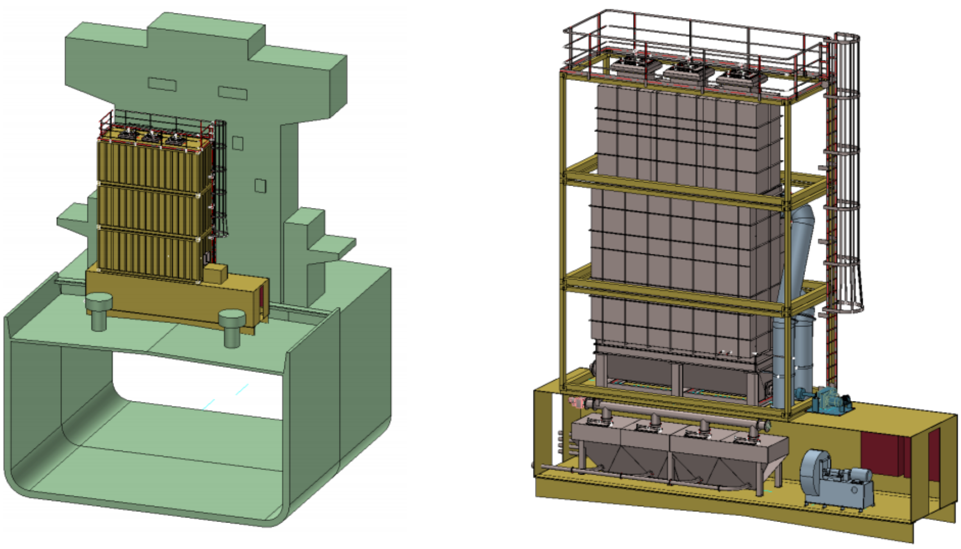

Figure D.11: Example of a dry scrubber onboard the MV Timbus (Couple Systems GmbH, 2010)

E

Fuel

E.1. 0.10% Heavy Fuel Oil (ECA Fuel)

Table E.1: Different Heavy Fuel Oils with 0.10% sulphur content (American Bureau of Shipping, 2018)

	Shell ULSFO	**ExxonMobil HDME 50**	**ExxonMobil AFME 200**	**LUKOIL**	**CEP SA**	**BP**	**Phillips 66**
Denstiy [kg/m^3]	790 - 910	900 - 915	917	886	868	854.4	855.2
Viscosity [cSt]	10 - 60	30 - 45	67	16	8.8	8.8	8.6
Micro carbon (MCR) [mass %]	2	<0.30	<10	0.1	0.1	0.1	0.04
Sulphur [mass %]	<0.1	<0.10	<0.10	0.07	0.05	0.03	0.06
Pour point [C°]	18	6 - 12	6 - 15	18	-12	21	-12
Flash point [C°]	>60	<70	<70	165	72	>70	79
Water [vol. %]	0.05	0.05	<0.5	0.05	0.004	0.01	0
Acid number [mg KOH/g]	<0.5	<0.1	<0.1	0.5	0.27	0.04	NA
Vanadium [mg/kg]	2	<1	1	1	<1	<1	<0.10
Al + Si [mg/kg]	12 - 20	<5	<10	2	NA	<1	2
Lubricity [microns]	NA	<320	NA	270	410	326	NA
CCAI	800	795 - 810	799	793	NA	765	NA

E.2. Fuel prices

Figure E.1: Global 20 ports average bunker price of MGO (Ship & Bunker, 2018)

Figure E.2: Global 20 ports average bunker prices of IFO380 (Ship & Bunker, 2018)

E.3. Fuel change over record book

LOW SULFUR FUEL OIL CHANGE OVER RECORD FOR REGULATED AREA (ENTERING REGULATED AREA)								
Begin FO Change Over to LSFO					Complete FO Change Over to LSFO			
Date:		Time:			Date:	Time:		
Location:	Lat:		Long:		Location:	Lat:	Long:	
Volum of LSFO in each tank on completion of Change Over					Regulated Area (ECA) Entry			
Tank	Capacity (m^3)	Current Vol^m (m^3)	Type of LSFO	Grade (% S) of LSFO	Date:	Time:		
					Location:	Lat:	Long:	
					Hourly FO Consumptions by Engines and Boilers (m^3):			
					Main Engine:			
					Auxiliary Engines:			
					Auxiliary Boilers:			
					Required for California Regulated Water (24 nm offshore of CA)			
					Vessel Name:			
					IMO No.:			
					Port/s Visited:			
					Port Call Date/s:			
					Regulated California Water Entry			
					Date:	Time:		
					Location:	Lat:	Long:	
					Auxiliary Engines: Type of Marine Fuel (e.g. IFO 380, IFO 180, MDO (DMB), MGO (DMA))			
					FO switched from	Type:	% S:	
					FO switched to	Type:	% S:	
Sign by Duty Engr.	Name	Sign	Date	Sign by Chief Engr.	Nme	Sign		Date

LOW SULFUR FUEL OIL CHANGE OVER RECORD FOR REGULATED AREA (LEAVING REGULATED AREA)								
Regulated Area (ECA) Exit								
Date:		Time:						
Location:	Lat:		Long:					
Begin FO Change Over to HSFO					Complete FO Change Over to HSFO			
Date:		Time:			Date:	Time:		
Location:	Lat:		Long:		Location:	Lat:	Long:	
Volum of LSFO in each tank on completion of Change Over					Required for California Regulated Water (24 nm offshore of CA)			
Tank	Capacity (m^3)	Current Vol^m (m^3)	Type of LSFO	Grade (% S) of LSFO	Leaving Regulated California Water			
					Date:	Time:		
					Location:	Lat:	Long:	
Sign by Duty Engr.	Name	Sign	Date	Sign by Chief Engr.	Nme	Sign	Date	

Figure E.3: Low sulfur fuel oil change over record for regulated areas

E.4. Fuel tank configuration

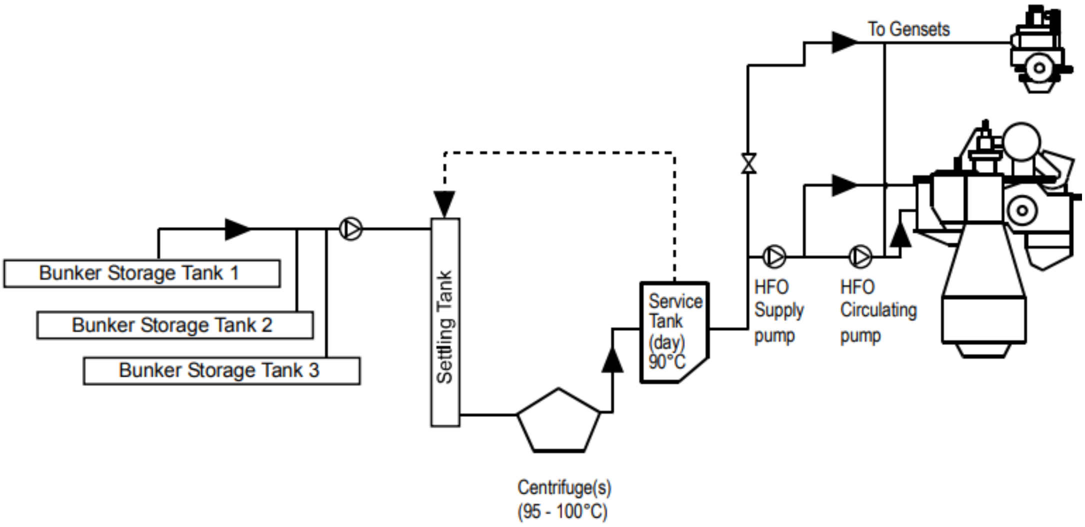

Figure E.4: Fuel system of a one fuel ship

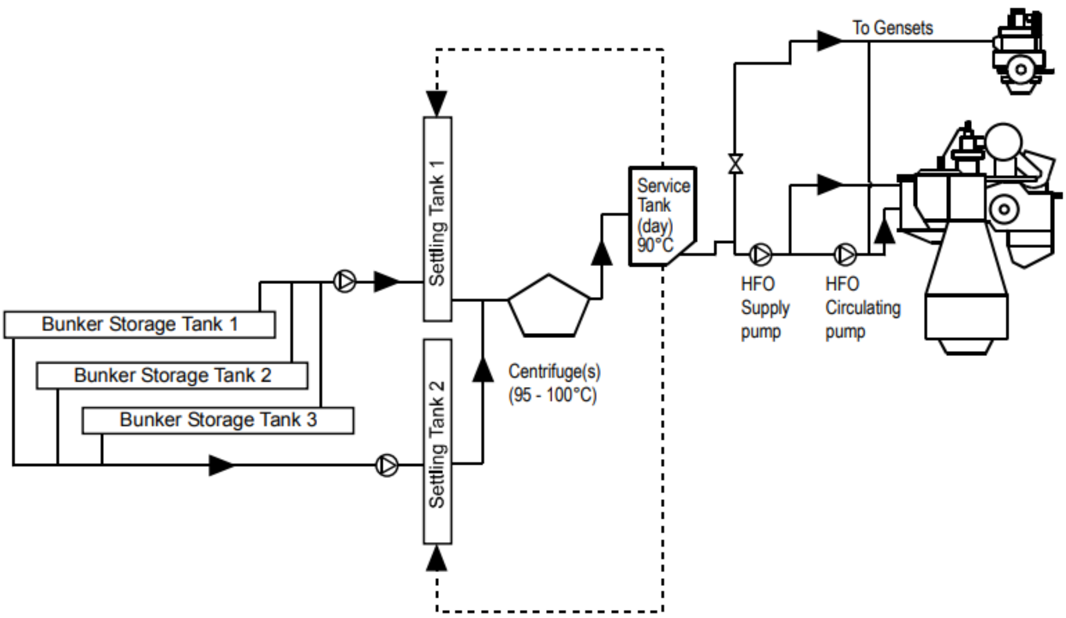

Figure E.5: Fuel system with 2 settling tanks

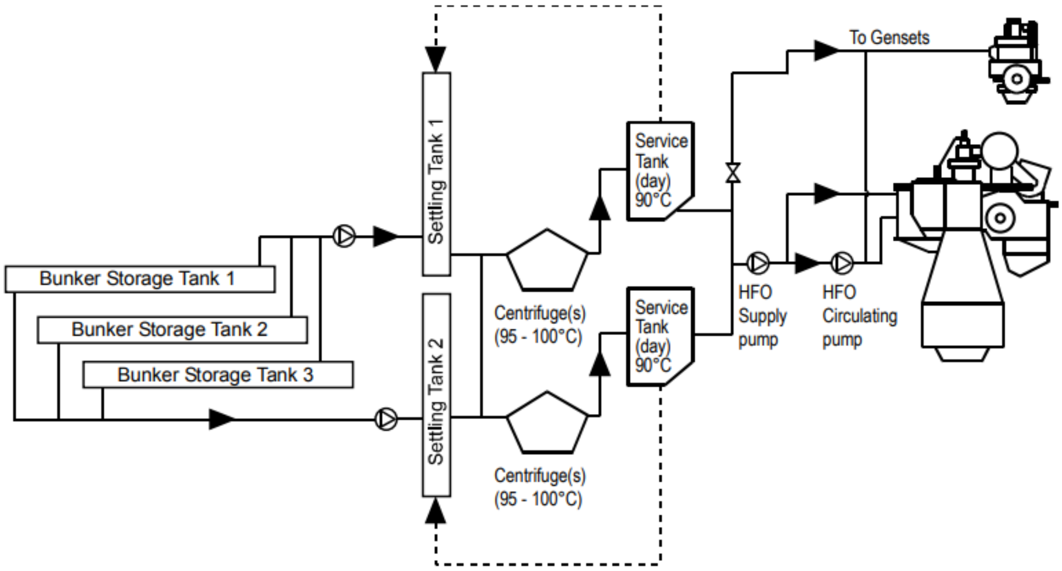

Figure E.6: Fuel system with 2 settling and 2 service tanks

F

Systems

F.1. Afriso MEA 3000 / 3300

Figure F.1: Afriso MEA 3300

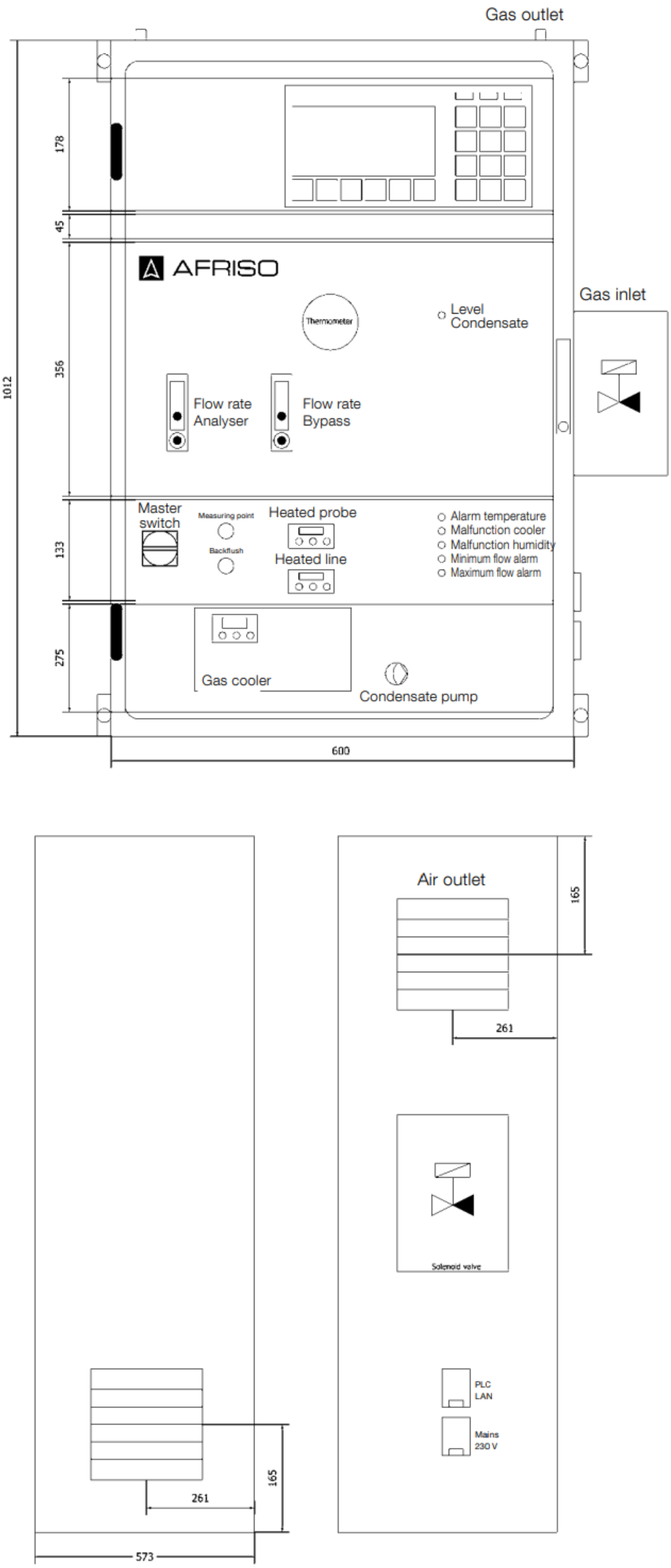

Figure F.2: Afriso MEA dimensions in mm

F.2. Consilium Opsis M800

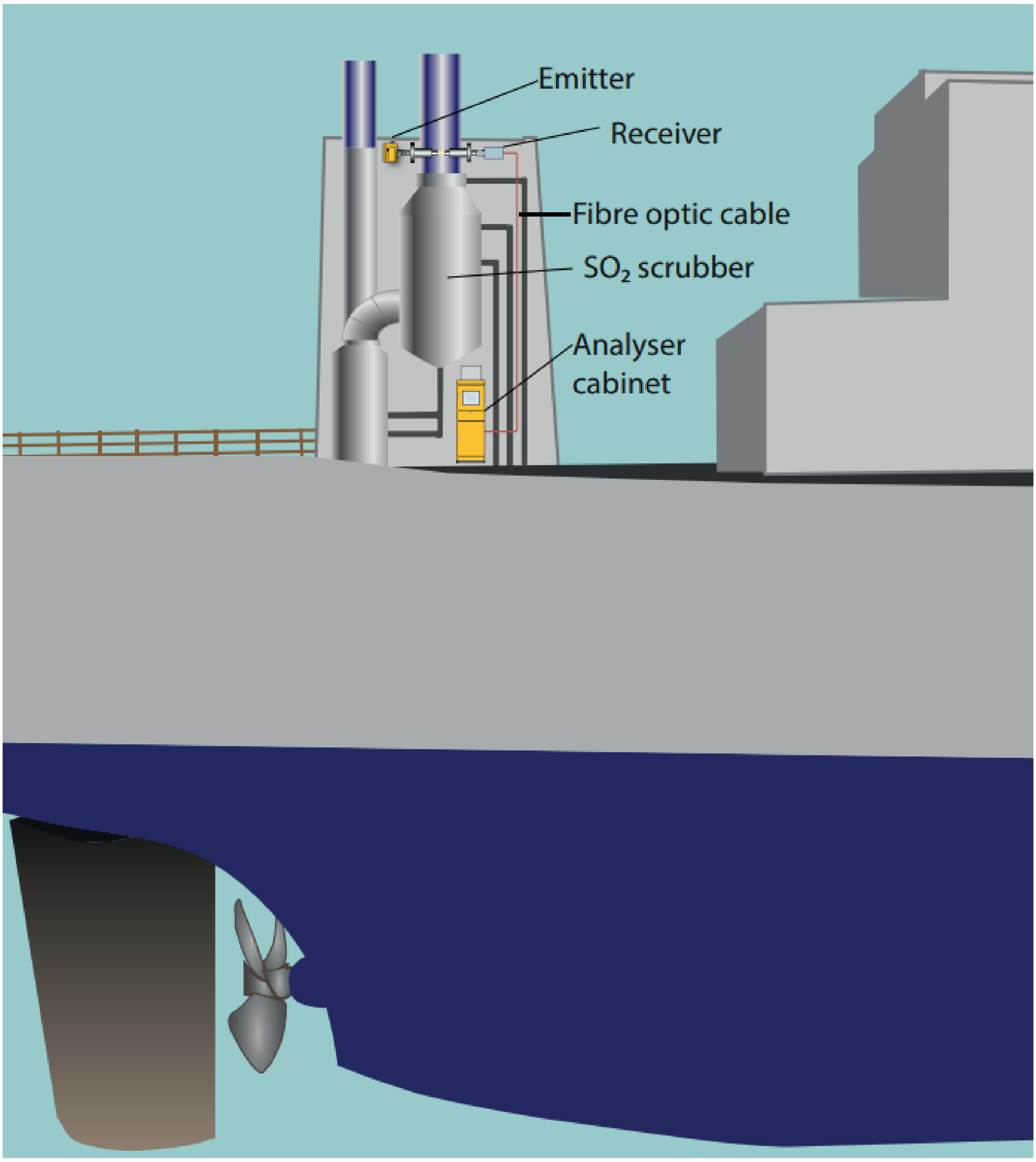

Figure F.3: Consilium Opsis M800 installed on ship

G

Semiconducting oxides

Table G.1: Operating parameters of solid-state gas sensors on the base of metal oxides and technological peculiarities of their fabrication (Korotcenkov, 2007)

Metal oxide	Gas optimal for detection	Operating temperature (°C)	Stability	Compatibility with standard IC fabrication	Fabrication complexity	Sensitivity to air humidity	Stability in reducing atmosphere technologies	Readiness of synthesis and deposition
$Sn0_2$	Reducing gases (CO, H_2, CH_4, etc)	200-400	Excellent	Imperfect	Acceptable	High	Good	High
WO_3	O_3, NO_x, H_2S, SO_2	300-500	Excellent	Low	Moderate	Reduced	Good	Medium
Ga_2O_3	O_2, CO	600-900	High	Good	Acceptable	Low	Moderate	Medium
In_2O_3	O_3, NO_x	200-400	Moderate	Good	Acceptable	Reduced	Moderate	High
MoO_3	NH_3, NO_2	200-450	Moderate	Moderate	Moderate	-	Good	-
$Ti0_2$	O_2,CO, SO_2	350-800	Enhanced	Moderate	Moderate	Low	Excellent	Medium
ZnO	CH_4,C_4H_10,O_3, NO_x	250-350	Satisfactory	Good	Acceptable	Excellent	High	-
CTO	H_2S, NH_3, CO, voc's	300-450	High	Imperfect	Moderate	Low	Moderate	Medium
Fe_2O_3	Alcohol, CH_4, NO_2	250-450	Low	Moderate	Acceptable	High	Low	Medium