Background informal technical document on maritime shipping emissions, reduction techniques and determination of their costs

TFTEI background informal technical document

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Prepared by Citepa (TFTEI Techno-Scientific Secretariat)

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List of abbreviations and acronyms

ABS	Ammonium Bisulphate
AGP	Amended Gothenburg Protocol
BC	Black Carbon
CARB	California Air Resources Board
CEIP	Centre on Emission Inventories and Projections
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO	Carbon monoxide
CO_2	Carbon dioxide
DME	Dimethyl Ether
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EB	Executive Body
EC	European Commission
EEA	European Environmental Agency
EGR	Exhaust Gas Recirculation
EMEP	European Monitoring and Evaluation Program
EU	European Union
GDP	Growth Domestic Product
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
HM	Heavy Metals
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
kW/MW	kilowatt/Megawatt
LNG	Liquefied Natural Gas
LRTAP	Long-range Transboundary Air Pollution
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NaOH	Caustic soda
NECA	Nitrogen oxides Emission Control Areas
NFR	Nomenclature For Reporting
NH_3	Ammonia

nm	Nautic Mile
NO_x	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
O_3	Ozone
ODS	Ozone Depleting Substances
PAH	Polyaromatic Hydrocarbons
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SECA	Sulphur oxides Emission Control Areas
SiC	Silicon Carbine
SNAP	Selected Nomenclature for Air Pollution
SO_x	Sulphur Oxides
TEU	Twenty-foot Equivalent Unit
TFTEI	Task Force on Techno-Economic Issues
TSP	Total Suspended Particles
UNECE	United Nations Economic Commission for Europe
U/VLSFO	Ultra/Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compounds
WFE	Water-Fuel Emulsion
wt	weight

Executive Summary

Following the decision 2019/4 initiating the review of the Amended Gothenburg Protocol (AGP, 2012) adopted at the thirty-ninth session of the Executive Body (EB) of the Convention on Long Range Transboundary Air Pollution (CLRTAP) in December 2019 and to satisfy its revised mandate from decision 2018/7 adopted at the thirty-eighth session of the EB in December 2018, TFTEI prepared this report. In a first step, this report provides informal technical background information on maritime shipping emissions and techniques to reduce them. Other shipping emissions will be considered later by TFTEI.

Maritime shipping deals with more than 80% of world global trade volumes, and its activity still grows. Hence, the emissions from maritime shipping, resulting mostly from fuel combustion, globally increase, and its worldwide contribution globally increases as some other sectors such as electricity generation, significantly tackled their emissions. In 2018, maritime shipping represents 2.9% of all anthropogenic CO_2 emissions.

Thus, regulations at international or regional levels have been implemented, such as the MARPOL Annex VI Regulation of the International Maritime Organisation and its amendments. In order to comply with these past and upcoming regulations, reduction techniques must be used to reduce emissions from marine diesel engines.

In this technical document, the different reduction techniques of pollutant emissions available for maritime shipping are presented. The different measures are presented in three different parts:

- Primary techniques, which modify the combustion process, such as water injection, slide valves, slow steaming or new propulsion systems, or switch the fuel, commonly bunker fuel oil, for distillate fuels, LNG or alternative fuels (methanol, biofuels, ammonia, hydrogen, etc.),
- Secondary measures, which are exhaust gas treatment systems such as exhaust gas recirculation, selective catalytic reduction systems, scrubbers or diesel particle filters,
- Measures applicable in ports, such as shore-power supply system or shore-based exhaust cleaning systems.

For each technique, a technical description is provided, as well as the achieved reduction rates per substance and the advantages and drawbacks. In terms of reduction efficiencies, the main findings are as follows:

- Scrubbers and switches to lower sulphur fuels such as marine distillate fuels (diesel or gas oil), LNG or methanol are efficient techniques to tackle SO_2 emissions,
- A switch to LNG and the implementation of SCR are effective means to reduce NO_x emissions, followed by EGR,
- PM and BC emissions can be significantly cut down with switch to LNG, methanol or some lower sulphur distillate fuels. Diesel particulate filters are effective but can be used only with good quality distillate/light fuels, and are applicable only for high-speed engines until now, meanwhile the first tests on medium-speed engines are being realized. In addition, scrubbers can also reduce the PM and BC emissions to some significant extent,
- Improving energy efficiency and moving to alternative non-fossil fuels and new emerging propulsion systems would also effectively reduce both air pollutant and greenhouse gas emissions,

- On-shore power supply system at berth can reduce significantly the emissions of pollutants and GHG from ships during hoteling. Shore- or barge-based exhaust gas cleaning systems also provide significant emission reductions and require no specific ship modifications but as yet to be further proven.

Finally, the cost determination of each technique (when available) is given in order to assess the required investments depending on the different emission reduction rates achieved. The following table summarizes the collected information, separating primary and secondary techniques. One must note that the range of costs can be quite large depending on the available data, the technology maturity, the range of engine powers, etc. However, it is observed that switching to LNG or installing a scrubber are the most costly options, which can be justified by their relative high efficiency in reducing emissions. A LNG switch is the most expensive operation but this can be balanced with the operational and maintenance costs where savings can be realized. Besides a switch to low sulphur fuels or biofuels where low or even no investment costs are required, installing slide valves is the most economic technique (with no operational and maintenance costs) but its emission reduction efficiencies are rather low compared to other techniques.

Reduction techniques :	SO_2	NO_x	PM	BC	fuel penalty	Investments costs (€/kW)	Operation & maintenance costs
Primary measures:							
- Switch to low sulphur fuels	up to 97%[1]	-	50-90%	0-80%[2] (median: 30%)	-	-	88-223 €/t fuel
- Switch to LNG	90-100%	64-90%	60-98%	75-90%	- 5-10%	219-1603	- 43 €/t fuel (+ fuel savings)
- Switch to water-in-fuel emulsions	-	1-60%	20-90%	0-85%	+ 0-2%	11-44	33-271 k€/year[6]
- Switch to biodiesel and biofuels	-	-	12-37%	38-75%	+ 8-11%	-	-
- Switch to methanol	100%[3]	55%	99%	97%[4]	+ 9%	150-450	10-15 €/MWh for fuel and 3-4 €/MWh for other O&M
- Slow steaming	13-50[5]%	21-64%	18-69%	0-30%	- 15-50%	71	- 42-77% (fuel savings)[7]
- Slide valves	-	20%	10-50%	25-50%	+ 2%	0.33-1.43	(assumed to be null)
Secondary measures:							
- Exhaust Gas Recirculation (EGR)	-	25-80%	-	0-20%	+ 0-4%	36-60	17-25€/kW, so 2-3 €/MWh assuming 8,000 hours/year
- Selective Catalytic Reduction (SCR)	-	70-95%	10-40%	-	0-2%	19-100	3-10 €/MWh
- PM filters (DPFs)	-	-	45-92%	70-90%	+ 1-4%	30-130	+1-4% in fuel penalties
- Scrubbers	90-98%	-	0-90% (median: 14-45%)	0-70% (median: 16-37%)	+ 0.5-3%	100-433	0,6[8]-12 €/MWh (~2% of capital investments)

[1]: theoretical conversion from a 3.5 wt% fuel to a 0.1 wt% fuel

[2]: only valid for distillate fuels

[3]: methanol does not contain sulphur

[4]: expected achieved reduction (based on drop in particle number)

[5]: not directly reported but proportional to fuel savings

[6]: based on a lifetime of 12 years for all equipment but injectors, which are supposed to have a lifetime of 4 years

[7]: do not consider the eventual needs of additional ships in the fleet

[8]: the lower end of the range corresponds to open-loop scrubber where the only operational costs are due to fuel penalty of 1-3%

1. Introduction

According to the Decision 2018/7[1] of the Executive Body (EB) of the Convention on Long-range Transboundary Air Pollution (LRTAP) (thirty-eighth session, Geneva, 10–14 December 2018)[2], the revised mandate of the Task Force on Techno-economic Issues (TFTEI), the Task Force "..will continue to examine, assess, validate and provide information on, emission abatement technologies for stationary and mobile sources". Among the new tasks assigned to TFTEI, described in the revised mandate, the Task Force has to initiate the work to assess information on emission abatement technologies for the reduction of air pollutant emissions, from shipping activities.

The biennial workplan (2020-2021) for the implementation of the Convention aims at translating the vision and strategic priorities, set out in the long-term strategy for the Convention (2020–2030 and beyond)[3] into a list of activities to be carried out by the respective bodies under the Convention in accordance with their revised mandates, as adopted by the Executive Body at its thirty-eight and thirty-ninth sessions. The workplan also contains additional activities of the task forces and centres, not mentioned in the mandates, which are decided by the EB, from time to time, as needed.

The work on shipping emissions assigned to TFTEI is part of the preparatory work for the review of the Amended Gothenburg Protocol (AGP, 2012), as highlighted in the document on the review prepared, between April and September 2020, by the Task Force supporting the WGSR Bureau.

The decision to review the AGP has been adopted at the 39th session of the Executive Body (EB) [1] and the work programme and schedule are expected to be officially adopted at the 40th session of the EB, in December 2020.

The work of review should last till the end of 2022, when the EB will decide on the possible revision of the AGP.

The present informal technical document is intended to focus on the NFR 1A3di International water-borne navigation (excluding NFR 1A3di(ii) International Inland waterways) and partly on the NFR 1A3dii national navigation for national sea traffic. However, inland navigation, personal watercrafts and motor-boats are out of the scope for this document and will be examined in a next phase when the annex VIII of the Gothenburg Protocol will be reviewed.

This draft document focuses on measures to address emissions from maritime shipping and journeys of vessels across the seas but also emissions from vessels, anchored at berths in ports.

In the scope of the CLRTAP (as well as the UNFCCC), the criteria for distinguishing between domestic and international traffic depends only on the origin and destination of the ship for each segment of its journey. International shipping is represented by vessels of all flags that are engaged in international water-borne navigation. The international traffic may take place at sea, on inland lakes and waterways and in coastal waters. It includes journeys that depart in one country and arrive in a different country. Domestic navigation is represented by vessels of all flags that depart and arrive in the same country. It may include small leisure boats. This

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[1] http://www.unece.org/fileadmin/DAM/env/documents/2002/eb/air/EB%20Decisions/Decision_2018_7.pdf

[2] http://www.unece.org/index.php?id=45532

[3] ECE/EB.AIR/142/Add.2, decision 2018/5, annex

document addresses measures for reducing emission of pollutants from vessels, engaged in maritime shipping, both national and international.

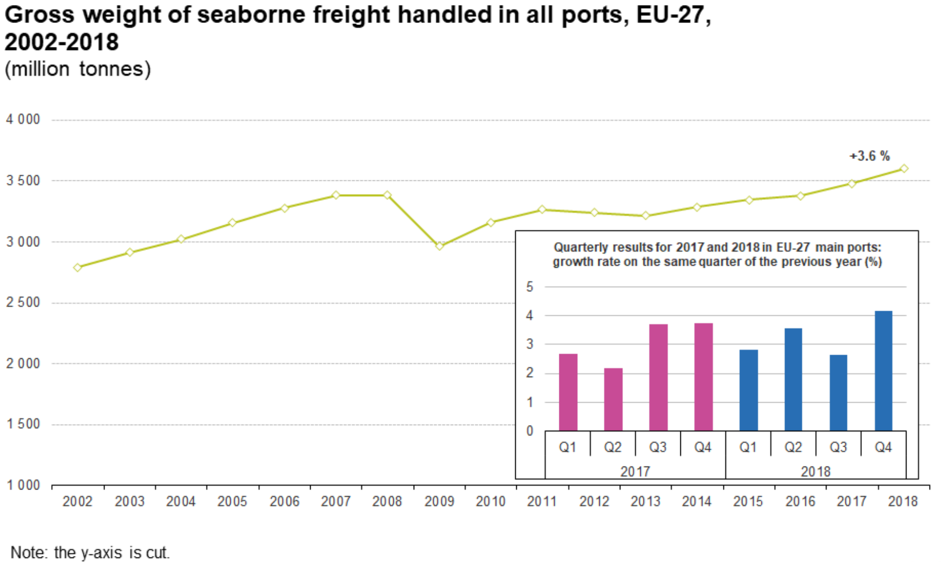
In this document, measures addressing emissions generated by engines, used as main propulsion engines during cruise, and by auxiliary engines, used to provide power and services within vessels, are considered. A focus is provided on measures for vessels hoteling and maneuvering in ports. Other sources of pollutants such as VOC emissions from loading and unloading fuel in tankers are also considered.

This report provides concise information on reduction techniques available to abate air pollutant emissions in the maritime shipping concerning sulphur oxides (SO_x), nitrogen oxides (NO_x), Volatile Organic Compounds (VOCs) and particulate matter (i.e. TSP (total suspended particles), PM_{10} and $PM_{2,5}$, including black carbon (BC) and polyaromatic hydrocarbons (PAH)). Throughout this document, an assessment of the emissions of the main pollutants and their evolution over time is realised, followed by the analysis of the existing and developing policies and measures. Then, a review of the available reduction techniques for SO_x, NO_x and PM including black carbon and PAH is carried out alongside with the estimations of their associated costs of implementation. A special focus is given on which techniques can be used to comply with the restrictions on NO_x or SO_x emissions in sulphur oxides emission control areas (SECAs) and nitrogen oxides emission control areas (NECAs) as defined by the International Convention for the prevention of Pollution from ships (MARPOL), entered into force in 1983. The MARPOL Annex VI, adopted in 1997, sets limits to the main air pollutants emissions contained in the exhaust gases, including SO_x and NO_x, and the emissions of ozone depleting substances (ODS) and also volatile organic compounds (VOC) from tankers.

This document has been addressed to the TFTEI experts (from both industry, NGOs and national administrations) in order to get their valuable feedback and improve the completeness and quality of the final report.

2. General information on the maritime shipping

Dealing with about 80% of world global trade volumes [1][2], the international ship transport is an active and growing economic sector. In 2018, 3.6 billion tons of goods were transported throughout EU harbours, which is an increase of 3.6% compared to 2017 [3]. The global activity in the EU's ports has intensified over the past decades and has even recovered from the economic downturn of 2009, surpassing the preceding peak of goods transported of 2007 by 6.5% (see Figure 1))[3]. Among other countries, Poland, Belgium, Greece, Portugal, the United Kingdom and the Netherlands lead this global increase of the maritime freight transport in the EU since the economic recession as they all recorded significant relative increases [4][5]. The number of passengers passing through EU ports has also increased by 5.6% between 2017 and 2018 and reached 410 million [3]. The worldwide fuel consumption of the maritime transport was estimated to be around 280 Mt in 2000 [6], about 217 Mt in 2004 [7], and 300 Mt in 2012 [2][13]. In the Fourth IMO GHG Study, the total marine fuel consumption is estimated to grow from 248 Mt to 276 Mt between 2012 and 2017, and 299 Mt to 330 Mt over that same period, for top-down and bottom-up estimates **Erreur ! Source du renvoi introuvable.**. According to the Third IMO GHG Study (300 Mt estimated for 2012)[13] the previous fuel consumptions mentioned in [2][6][13] should be compared to bottom-up figures. The evolution of the marine oil product consumptions of shipping since 1971 from **Erreur ! Source du renvoi introuvable.**(a priori top-down fuel consumptions) is displayed in Figure 2 and reveals an overall increasing trend. In 2004, it was estimated that 11 out of the 217 Mt of total fuel consumed were meant for hoteling and maneuvering operations in ports [7].



Note: the y-axis is cut.
Source: Eurostat (online data code: mar_mg_aa_cwh and mar_go_qm)

Figure 1: Evolution of the gross weight of seaborne freight transported to and from EU ports, from 2002 to 2018 (source: [3])

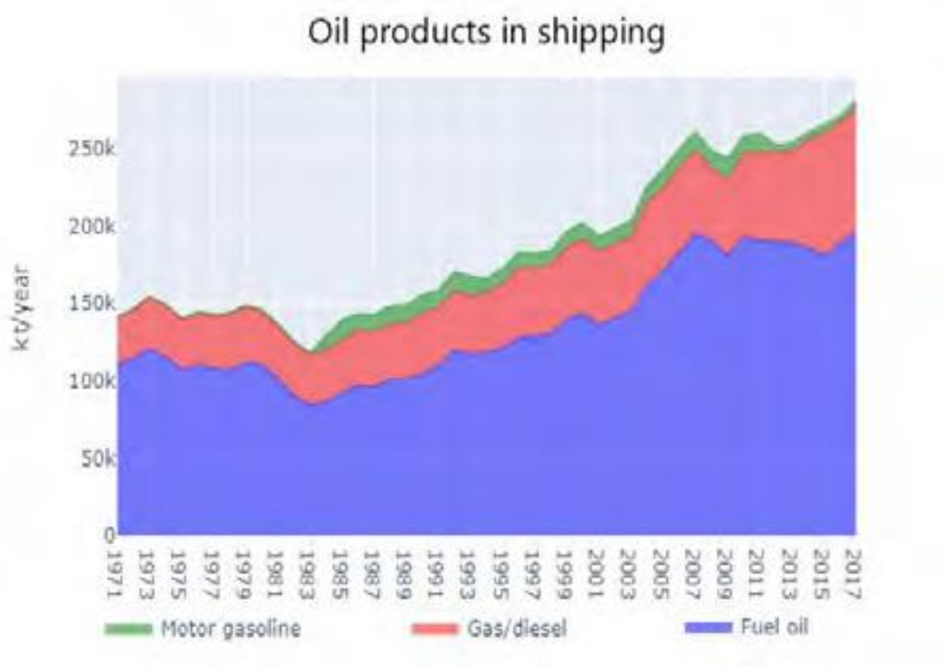


Figure 2: Evolution of the oil product consumptions of shipping (international, domestic and fishing) between 1971 and 2017 (source: Erreur ! Source du renvoi introuvable.**)**

The world's merchant fleet of early 2019 was constituted by 96,295 ships being over 100 gross tons, representing a total of 1,976 million dead-weight tons of capacity, which undergone an increase of 2.6% compared with early 2018 [8]. Bulk carriers and oil tankers account for more than 70% of the ship fleet (with respectively 42.6% and 28.7%), while 13.4% of the fleet is composed of container ships (see Table 1)[8], and the rest being split between cargo, gas carriers and ships for non-trading purpose such as offshore industry, fishing or service [7].

Table 1: Split of world fleet per type of vessels for 2018 and 2019, in percentage (source: [8])

Principal types	2018	2019	Percentage change 2019/2018
Oil tankers	29.2	28.7	0.98
Bulk carriers	42.5	42.6	2.87
General cargo ships	3.8	3.7	0.07
Container ships	13.1	13.4	4.89
Other types:	*11.3*	*11.5*	*4.06*
Gas carriers	3.3	3.5	7.25
Chemical tankers	2.3	2.3	4.14
Offshore vessels	4.1	4.1	2.79
Ferries and passenger ships	0.4	0.4	2.53
Others	1.2	1.2	-0.07

3. Emissions of pollutants from maritime shipping

3.1. Introduction

The emissions from the shipping navigation are mostly the result of the combustion of fuels in the engines used as main propulsion engines during cruise, and by auxiliary engines, used to provide power and services within vessels. Thus, the typical greenhouse gases (GHG) and air pollutants emitted are the ones associated with the engine technology and the fuel speciation, and include [6]:

- carbon dioxide (CO_2);
- NO_x (NO and NO_2);
- SO_x and other sulphur compounds (mostly SO_2);
- particulate matter (TSP, PM_{10}, $PM_{2.5}$ and other size of PM);
- volatile organic compounds (VOC);
- carbon monoxide (CO);
- black carbon (BC);
- polyaromatic hydrocarbons (PAH);
- heavy metals (HM).

These are the main substances emitted by maritime transport. However, there are also some fugitive emissions related to the loading and unloading operations, especially volatile organic compounds (VOC), and from the use of refrigerants or air conditioning, which emit HFC **Erreur ! Source du renvoi introuvable.**. In addition, NO_x and some other ozone precursors such as methane and VOCs lead to the formation of tropospheric ozone (O_3) (secondary pollutant). SOx, NOx, VOCs are also precursors of secondary PM.

The emissions implied by the whole sector of the transport are among the only anthropogenic emissions which keep on rising over the years (+77% from 1990 to 2018) [9] and, in 2019, it was reported that the transport sector, all means considered, constituted about 24% of the global CO_2 emissions. The maritime transport is though considered to be quite environmentally friendly compared to other means of transport and, surprisingly, its emissions were barely considered to be a matter of great importance before 1980. Nevertheless, due to its intensive activity, the maritime transport contributes to a lot of emissions of pollutants and greenhouse gases over the world's oceans [7] but as well over inland territories [17].

3.2. Inventories of emission

In the UNECE region covered by the CLRTAP (Convention on Long-Range Transboundary Air Pollution, also called Air Convention), the data of annual, party-specific emissions of pollutants related to maritime transport are reported and available on the CEIP web site under the NFR codes 1.A.3.d.i, 1.A.3.d.ii and 1.A.4.c.iii (i.e. SNAP codes 080402, 080403, 080404 and 080304) [1][11][12]. The NFR 1.A.3.d.i is itself composed of the NFR 1.A.3.d.i(i) for international maritime navigation, which is reported in the UNECE inventory as a memo-item, which means it is estimated but not included in the country national total, and of the NFR 1.A.3.d.i(ii) for international inland waterways, accounted in the national total.

Several methodologies of emission estimation are presented in the guidelines of EMEP/EEA 2019 [12], associated with different levels of accuracy and needs of data, which are called Tiers. The simplest methodology is the Tier 1 whereas the most complex and accurate one is Tier 3.

Tier 1

In the Tier 1 approach, the consumptions of the different types of fuel (e.g., bunker fuel oil, marine diesel oil, marine gas oil and gasoline) used in ships are multiplied to the corresponding emission factors (EF), for each pollutant [12]. The following equation can be used:

$$E_i = \sum_m (C_m \; x \; EF_{i,m})$$

with: E_i the emission of pollutant i, C_m the consumption of the fuel of type m, and $EF_{i,m}$ the emission factor for the pollutant i and the fuel type m.

Tier 2

For the methodology of Tier 2, in addition to the Tier 1 and the distinction made on the fuel type, the type of engine is also distinguished, and different EF are used depending on it. The distinct types of engine encountered are the following ones (this list is informative but not exhaustive): slow-, medium- and high-speed diesel engines, gas turbines or steam turbines for large ships ; diesel, gasoline two-stroke and four-stroke for small vessels [12]. The equation for the estimation of pollutant emission then changes as follows:

$$E_i = \sum_{m,j} (C_{m,j} \; x \; EF_{i,m,j})$$

with j the engine type, and now the emission factor EF and the fuel consumption C need to be disaggregated per type of engine in addition of the type of fuel.

Tier 3

Finally, for the Tier 3 approach, the additional parameter to be considered is the phase of sailing: cruise, hoteling or manoeuvring. When the fuel consumption per sailing phase is not known, a model based on the following equation can be used [12]:

$$E_{i,lon,lat,t} = \sum_{m,j,p} (\Delta t_p \; x \; P_e \; x \; LF_e(lon, lat, t) \; x \; EF_{i,m,j,e,p})$$

in which:

- lon = ship's longitude, and lat = ship's latitude,
- t = date and time of the ship on each lat/lon location data,
- p = the different phase of trip (cruise, hoteling, manoeuvring),
- Δt = duration since the last geographical position,
- e = engine category (main, auxiliary),
- LF = engine load factor (%) at each geographical position,
- P = engine nominal power (kW).

3.3. Historical situation and recent evolution

3.3.1. Overall situation

The global annual emissions of CO_2 in 2000 were estimated to be around 800 Mt for shipping [6] and increased to about 938 Mt in 2012 [13] and up to 1,056 Mt in 2018, which is equivalent to about 2.9% of all anthropogenic CO_2 emissions Erreur ! Source du renvoi introuvable.**. Compared to other transport means and considering the carried good amounts, marine shipping has relatively low emissions of GHG – only rail transport has lower GHG emissions per ton-kilometre (see Table 2 and**

Table 3)[88]. Marine shipping emits slightly less NO_x emissions than large trucks per ton-kilometre, but higher PM_{10} emission levels. Moreover, marine shipping has the highest SO_2 emission levels per tonne-kilometer (cf.

Table 3)[88]. SO_x emissions are mainly due to the high mean sulphur content of the marine fuels while NO_x emissions are mainly due to the high operating temperatures and pressures in the engines.

Due to the implementation of limits on the fuel sulphur contents in global seas as well in SO_2 emission control areas (SECA), it can be expected that the SO_2 emissions have recently decreased while NO_x emission aftertreatment requirements are only on specific NO_x control areas. However, at a global level, the emissions of SO_2, NO_x, VOC, PM_{10}, $PM_{2.5}$ and BC have all been observed to increase between 2012 and 2018 (see Figure 3). SO_2 and PM emissions increased over the period 2012-2018, in spite of the reduction of the consumption of heavy fuel oil (HFO, - 3%) for marine diesel oil (MDO, + 69%) and liquified natural gas (LNG, +30%), due to the increase in the average fuel sulphur content **Erreur ! Source du renvoi introuvable.**. However, large emission reductions should be achieved for 2020 thanks to the sulphur content limit imposed to 0.5 wt% (cf. Chapter 4). However, this analysis shows the necessary efforts required to improve environmental impact of shipping at the worldwide level.

Table 2: Representative emission factors per mode, for bulk/packaged cargo transport (TTW: tank-to-well emissions, correspond to fuel combustion, while WTW: well-to-wheel emissions, include in addition the overall chain of fuel extraction, refining and distribution) (source: [88])

Mode	Vehicle/Vessel	Type of freight	CO_2 (g/tkm) (WTW)	CO_2 (g/tkm) (TTW)	$PM_{10,c}$ (g/tkm) (TTW)	NO_x (g/tkm) (TTW)	SO_2 (g/tkm) (TTW)
Road	Large van	Med.-weight	1,153	895	0.148	5.03	0.006
	Truck, medium-size (10-20 t)	Med.-weight	259	201	0.017	1.75	0.001
	Tractor-semitrailer, heavy	Med.-weight	82	64	0.003	0.29	0.0004
	Truck, medium-size (10-20 t)	Heavy	243	189	0.016	1.6	0.001
	Tractor-semitrailer, heavy	Heavy	78	61	0.003	0.3	0.0004
	Large heavy vehicle	Heavy	76	59	0.003	0.3	0.0004
Rail	Electric, medium-length*	Heavy	10	0	0	0	0
	Diesel, medium-length*	Heavy	18	14	0.005	0.19	0.0001
Inland shipping	Rhine-Herne canal (RHC) vessel	Heavy	38	30	0.017	0.46	0.0002
	Large Rhine vessel	Heavy	21	16	0.008	0.23	0.0001
Short-sea	General Cargo 10-20 dwkt	Heavy	15	12	0.005	0.25	0.007

Table 3: Representative emission factors per mode, for container transport (TTW: tank-to-well emissions, correspond to fuel combustion, while WTW: well-to-wheel emissions, include in addition the overall chain of fuel extraction, refining and distribution) (source: [88])

Mode	Vehicle/Vessel	Type of freight	CO_2 (g/tkm) (WTW)	CO_2 (g/tkm) (TTW)	$PM_{10,c}$ (g/tkm) (TTW)	NO_x (g/tkm) (TTW)	SO_2 (g/tkm) (TTW)
Road	Tractor-semitrailer, heavy (2 TEU)	Med.-weight	102	80	0.004	0.36	0.0005
Rail	Electric, long (90 TEU)*	Med.-weight	16	0	0	0	0
	Diesel, long (90 TEU)*	Med.-weight	30	23	0.009	0.31	0.0001
Inland shipping	RHC vessel (96 TEU)	Med.-weight	44	34	0.019	0.53	0.0002
	Large Rhine vessel (208 TEU)	Med.-weight	24	18	0.009	0.26	0.0001
Short-sea	Container (Panamax-like, 4,060 TEU)	Med.-weight	21	16	0.008	0.35	0.01

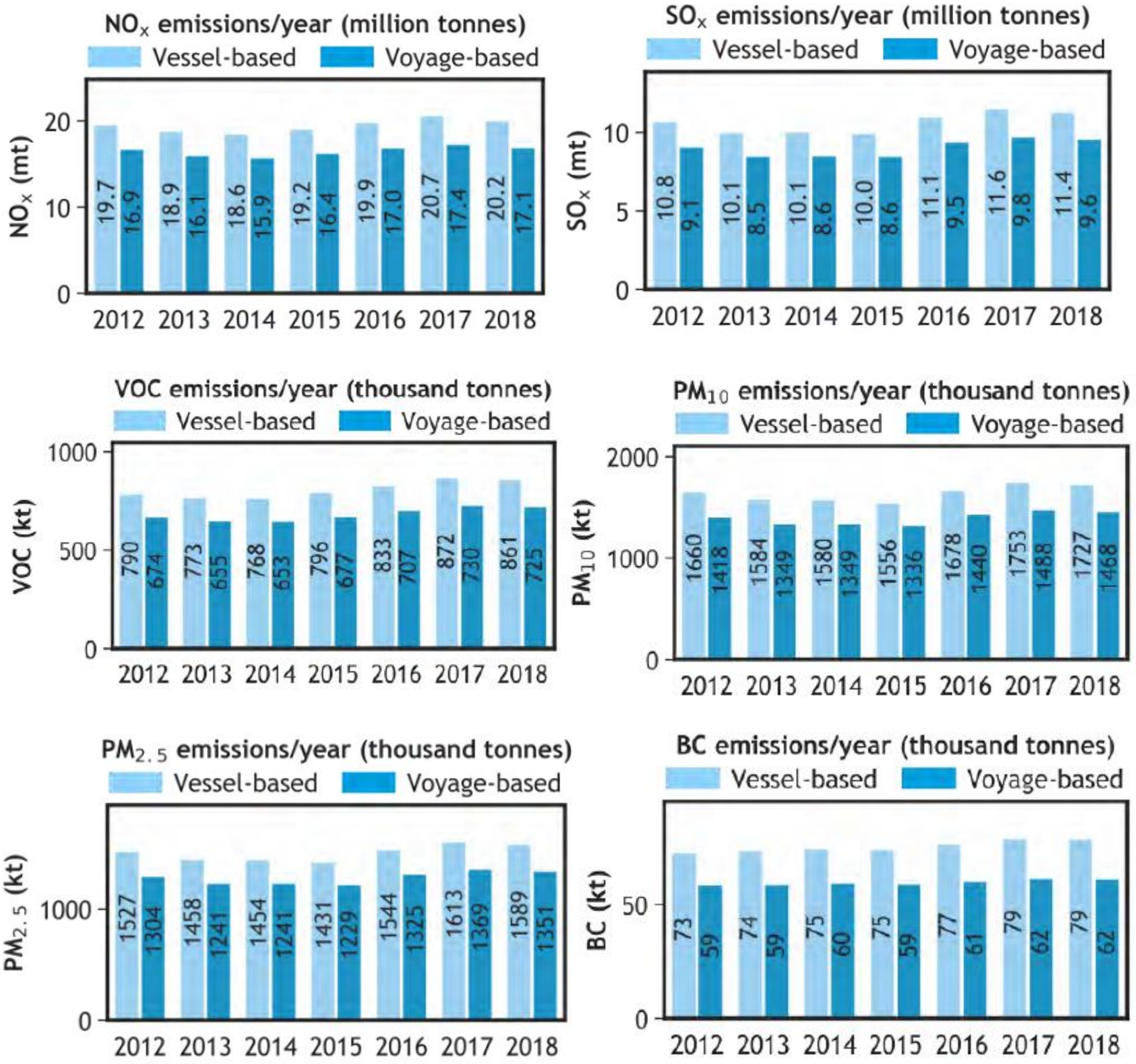
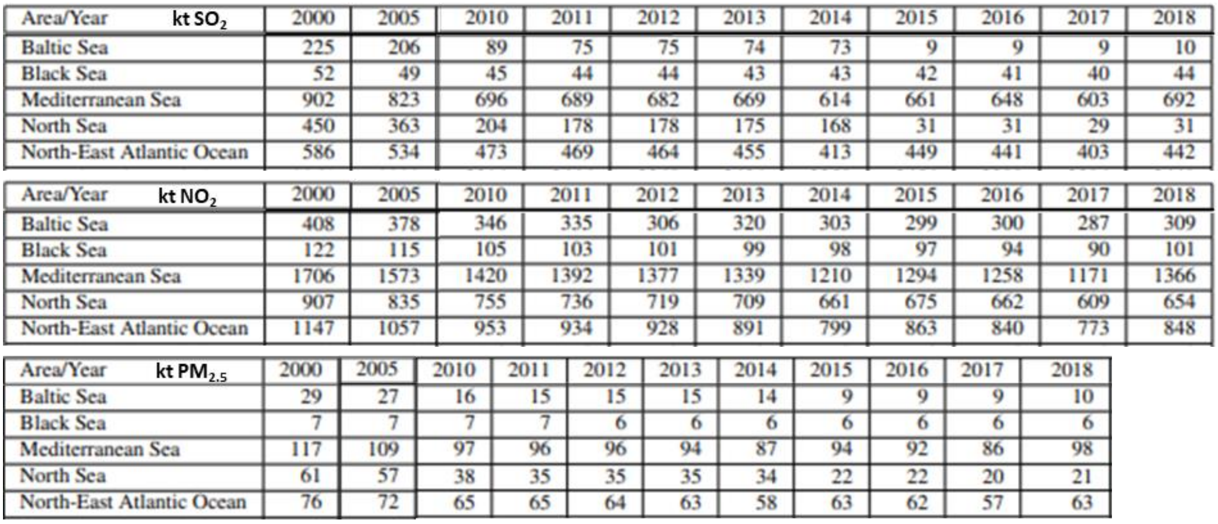


Figure 3: Evolution of NO_x, SO_2, VOC, PM_{10}, $PM_{2.5}$ and BC bottom-up estimated emissions from international shipping from 2012 to 2018, separated between voyage-based and vessel-based (source: Erreur ! Source du renvoi introuvable.)

At the European level, it can be observed in Table 4 and Figure 4 that the emissions of SO_2, NO_2, $PM_{2.5}$, NMVOC and CO from international shipping in the EMEP area have all decreased between 2000 and 2018, although the progress is in general slower since 2010 [87]. However, for SO_2 and $PM_{2.5}$, the observed reductions are very uneven between the Baltic and North Seas, which are SECAs with regulated fuel sulphur contents which achieved large reductions, and the other seas, which decrease their emissions at a slower pace and even undergo emission fluctuations recently.

The emissions of the European national shipping can contribute significantly to the total European emissions, especially for SO_2 and NO_x as it is revealed in the Table 5 (based on emissions reported from countries for the year 2004). Considering the fact that international shipping emissions are not included in this analysis, the impact of the overall marine shipping emissions could be even more important. However, this analysis is based on emissions for the year 2004 and, as seen from the Table 4, reductions have been globally achieved and this analysis could also over-estimate the current contributions of some pollutants.

Table 4: Total emission trends of SO_2, NO_2 and $PM_{2.5}$ from international shipping, between 2000 and 2018, over European seas and the European part of the Atlantic ocean (source: [87])



Area/Year kt SO_2	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018
Baltic Sea	225	206	89	75	75	74	73	9	9	9	10
Black Sea	52	49	45	44	44	43	43	42	41	40	44
Mediterranean Sea	902	823	696	689	682	669	614	661	648	603	692
North Sea	450	363	204	178	178	175	168	31	31	29	31
North-East Atlantic Ocean	586	534	473	469	464	455	413	449	441	403	442

Area/Year kt NO_2	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018
Baltic Sea	408	378	346	335	306	320	303	299	300	287	309
Black Sea	122	115	105	103	101	99	98	97	94	90	101
Mediterranean Sea	1706	1573	1420	1392	1377	1339	1210	1294	1258	1171	1366
North Sea	907	835	755	736	719	709	661	675	662	609	654
North-East Atlantic Ocean	1147	1057	953	934	928	891	799	863	840	773	848

Area/Year kt $PM_{2.5}$	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018
Baltic Sea	29	27	16	15	15	15	14	9	9	9	10
Black Sea	7	7	7	7	6	6	6	6	6	6	6
Mediterranean Sea	117	109	97	96	96	94	87	94	92	86	98
North Sea	61	57	38	35	35	35	34	22	22	20	21
North-East Atlantic Ocean	76	72	65	65	64	63	58	63	62	57	63

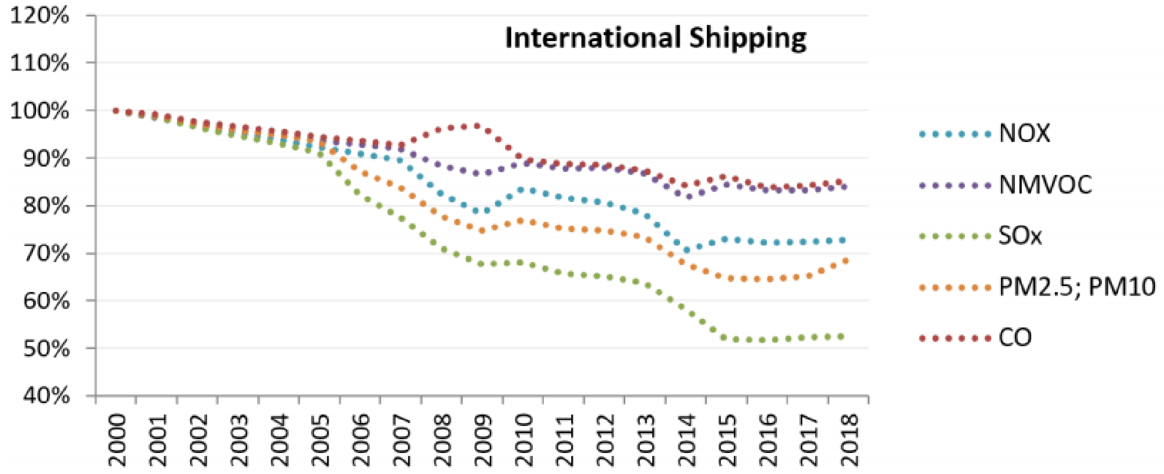
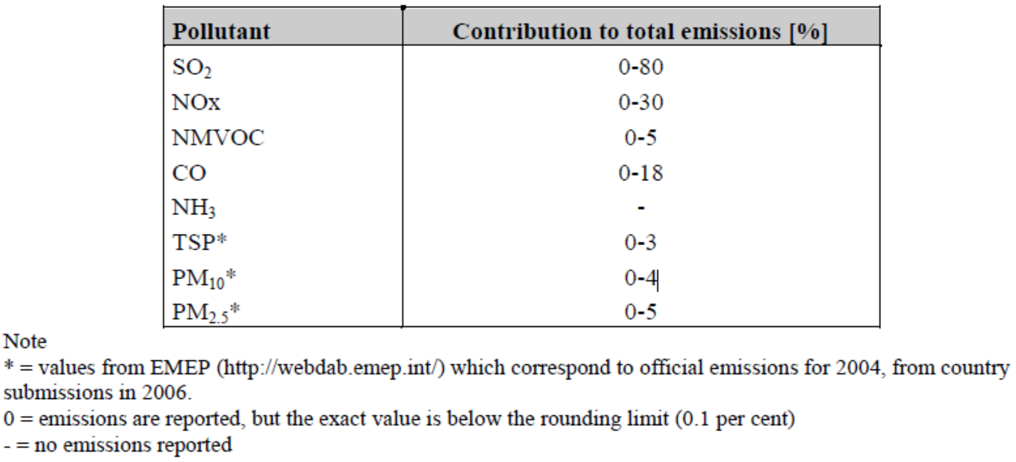


Figure 4: Evolution of international shipping emissions in the EMEP area between 2000 and 2018, for NO_x, NMVOC, SO_x, $PM_{2.5}$ and CO (source: [87])

Table 5 : Ranges of contribution of national shipping to total emissions in Europe (based on emissions from 2004) (source: [12])



Pollutant	Contribution to total emissions [%]
SO_2	0-80
NOx	0-30
NMVOC	0-5
CO	0-18
NH_3	-
TSP*	0-3
PM_{10}*	0-4
$PM_{2.5}$*	0-5

Note

* = values from EMEP (http://webdab.emep.int/) which correspond to official emissions for 2004, from country submissions in 2006.

0 = emissions are reported, but the exact value is below the rounding limit (0.1 per cent)

\- = no emissions reported

Another impactful parameter to be considered is the fact that ship emissions mostly occur along heavily-frequented, trading routes connecting ports. For instance, some independent studies showed that about 70% of the shipping emissions occur at less than 400 km away from the shores [14][15] and they can be transported hundreds of kilometers onshore [16]. The latter study, carried out in 2007 [16], revealed that the PM emissions from shipping can be held responsible for nearly 60,000 premature deaths per year near the coastlines of Europe, East and South Asia. Another study reveals that the implementation of additional SECAs in EU waters could avoid 4,000 and 8,000 cases of premature deaths by 2030 and 2050, respectively, and similar health benefits could be possible with the application of the Tier-III NO_x standards [24].

According to the European Commission (EC), acting on the maritime pollution could be more effective than reducing in-land emissions for SO_2, NO_x and PM (see Figure 5). Moreover, the EC stated in 2011 that, in Europe, the maritime emissions could exceed the global in-land emissions by 2020 if no further actions are taken, even though the transport sector represented less than 5% of EU's GDP [17]. As a consequence, cutting down the maritime emissions is quite important in order to improve the air quality and the environmental aspects, both onshore and offshore.

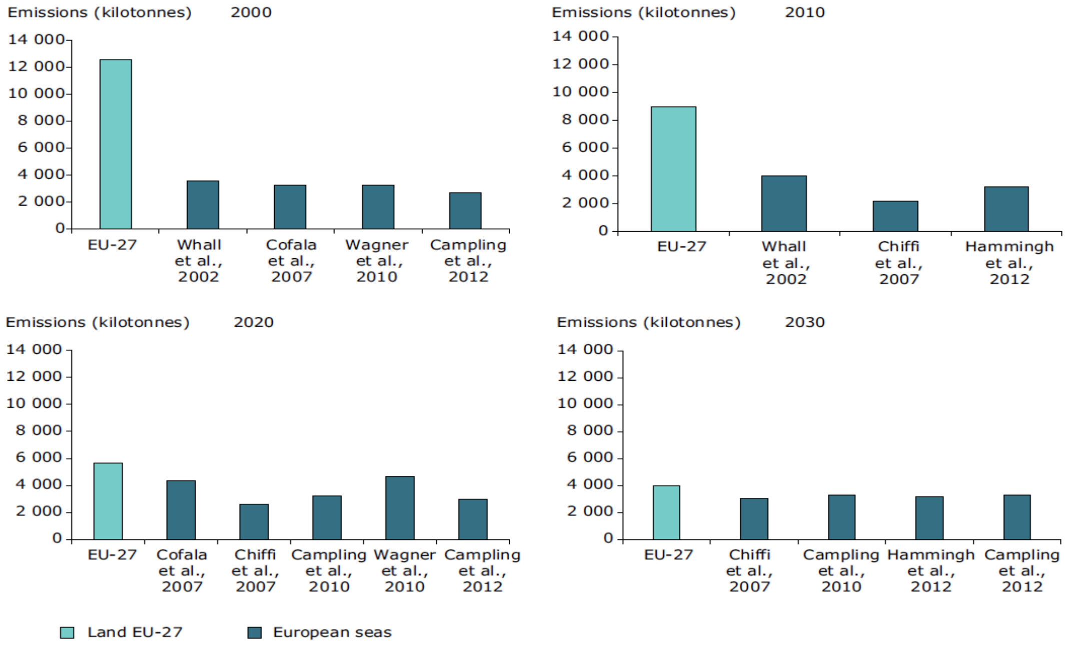


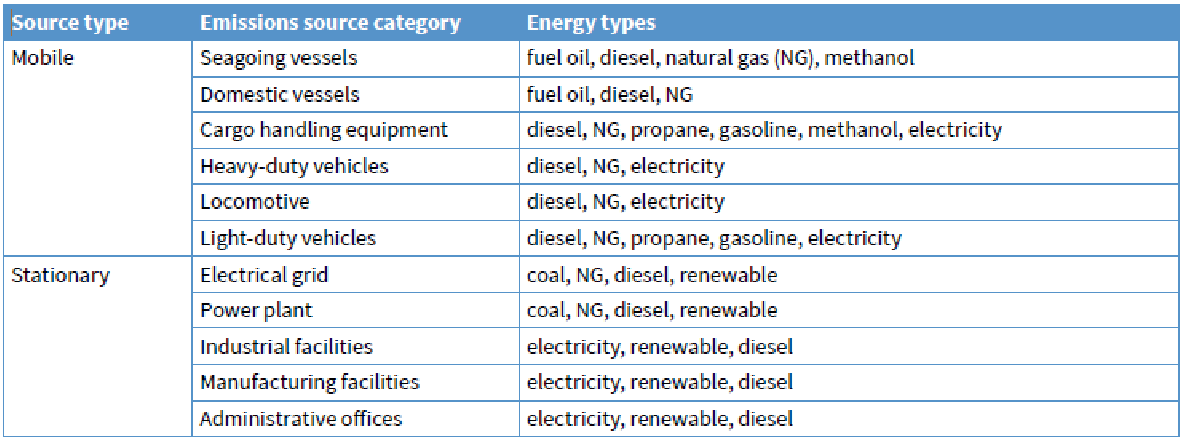
Figure 5: Comparison of EU in-land NO_x emissions with emissions of NO_x from maritime trafic in European seas for 2000, 2010, 2020 and 2030 from a survey and forecast made in 2013 (source: [18])

3.3.2. In ports

There is a growing pressure on worldwide ports to tackle air pollution from cargo operations in order to minimize its impact on health and environment [93][94]. The pollution in ports can be even more dramatic on health than pollution over seas and oceans as the proximity of the population increases. The attention is mostly driven on atmospheric pollutants such as NO_x (associated with ground-level ozone), PM and SO_2 [93] as their impacts are also localised and of short term.

There are various emission sources which can be found in ports depending on its size, its geographical location and layout, its activity, its configuration and the traffic type encountered [93]. All these features influence the estimated emission levels [95]. There are two types of emission source in ports, mobile and stationary sources, which depend on the consumed energy type and which can be summarized as in Table 6 (non-exhaustive list) [93]. Another source of PM emissions, can be unpaved areas with the vehicle movements, but this is often not included in port emission assessments as difficult to estimate [93]. This document only focuses on emissions related to water-borne navigation vessels, which contribute the most to the port emissions [96].

Table 6: Examples of port-related emission sources by energy type (source: [93])



Source type	Emissions source category	Energy types
Mobile	Seagoing vessels	fuel oil, diesel, natural gas (NG), methanol
	Domestic vessels	fuel oil, diesel, NG
	Cargo handling equipment	diesel, NG, propane, gasoline, methanol, electricity
	Heavy-duty vehicles	diesel, NG, electricity
	Locomotive	diesel, NG, electricity
	Light-duty vehicles	diesel, NG, propane, gasoline, electricity
Stationary	Electrical grid	coal, NG, diesel, renewable
	Power plant	coal, NG, diesel, renewable
	Industrial facilities	electricity, renewable, diesel
	Manufacturing facilities	electricity, renewable, diesel
	Administrative offices	electricity, renewable, diesel

In seagoing vessels, there are three types of energy systems: the propulsion engines, the auxiliary engines and the auxiliary boilers. Propulsion engines provide power directly (direct drive or gear drive) or indirectly (diesel-electric) based on the ship's configuration. Auxiliary engines provide electric power to house loads, pumps, loading/unloading equipment, etc [95]. Auxiliary boilers provide steam power for pumps, inert gas for volatile organic bulk liquid operations, crew needs, etc. [95].

In ports, the ships can be in two different operating modes, which are maneuvering, while the ship operates in confined channels or at its departure or arrival to the harbour, and hoteling, when the ship is docked at berth or anchored [93]. In the maneuvering mode, the ship travels at its lowest speeds, hence the propulsion engines are at very low loads, meanwhile the auxiliary engines are at high loads and the auxiliary boilers are at low loads [93][95]. In the hoteling mode, the ship does not move, the propulsion engines are then off while the auxiliary engines can be at high loads if the ship is self-discharging. Moreover, the auxiliary boilers can also be used to generate steam to keep the propulsion engine warm enough for eventual departure [93][95] or avoid damage from low temperature contractions [99].

While being in maneuvering and hoteling modes in ports, the emissions of the ships are quite important compared with the cruising phase, as it can be seen from Figure 6 and Figure 7 [74][96]. For instance, for chemical and oil tankers, around 20% of the GHG emissions (i.e., the fuel consumptions) are due to the phases at or near port areas [74]. Among the different ship types, the emissions at berth are globally higher than the ones during the port approach or departure (i.e., maneuvering phase). Outside the temporary use of scrubbers and if no fuel switch is done depending on the sailing phase, SO_2 emissions are directly proportional to the fuel consumptions and the sulphur content. From Figure 7, we can hence assume that fuel consumptions at berth are quite considerable compared to the other sailing phases and can even go up to about 20% of the overall consumption for oil tankers. As a consequence, the emissions of NO_x and $PM_{2.5}$ are also relatively high due to the significant fuel consumption as well as the specific operating conditions. For some ship types such as "Ferry-pax only", the emissions of NO_x and $PM_{2.5}$ in port areas represent about 30% and more than 20%, respectively, of their total emissions. For 2011, the emissions from ships at berth have been estimated to be about 0.4, 0.2 and 0.03 Mt for NO_x, SO_2 and PM_{10} respectively [96]. Therefore, these analyses and graphs reveal the need to act on emission in those particular sailing phases.

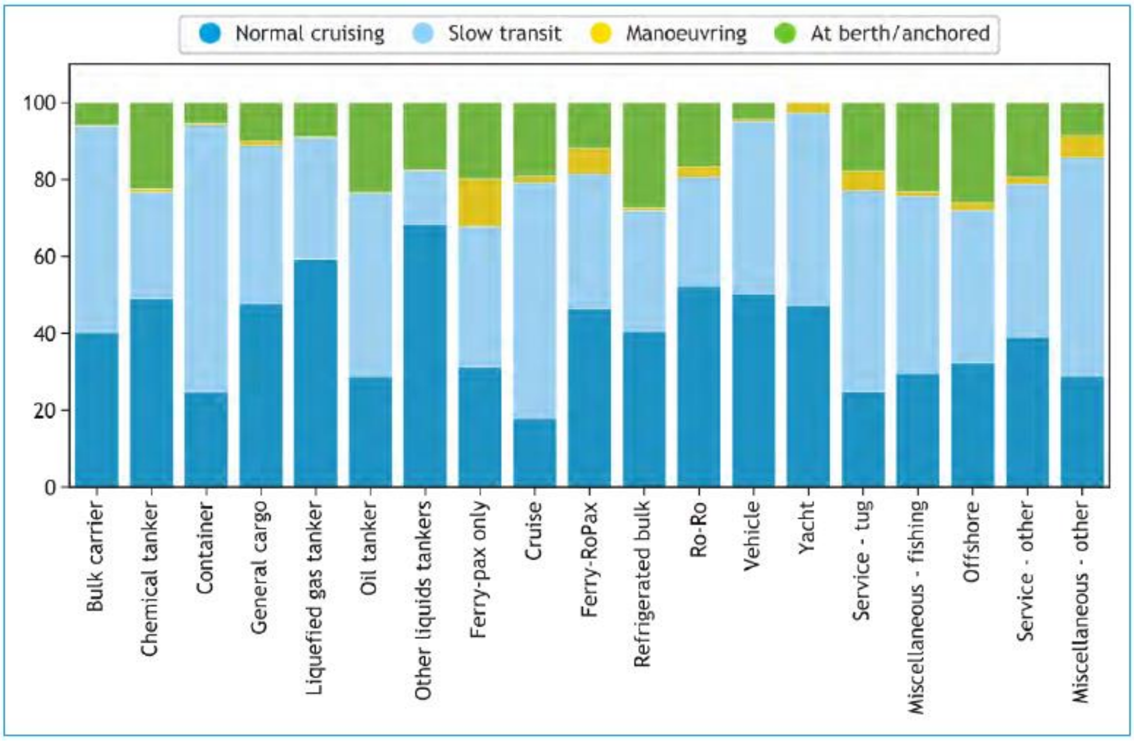


Figure 6: Share of GHG emissions (in CO_2e) of international shipping in 2018 per ship type and per sailing phase (based on voyage-based allocation of emissions) (source: [74])

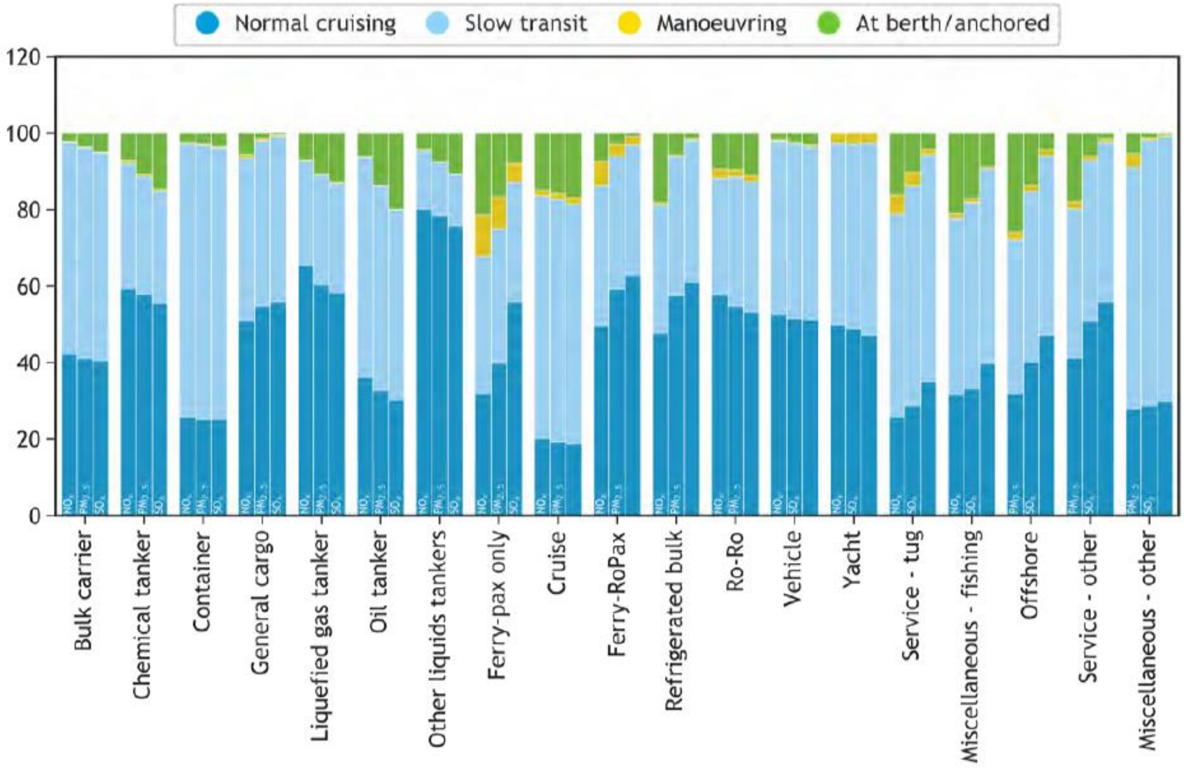
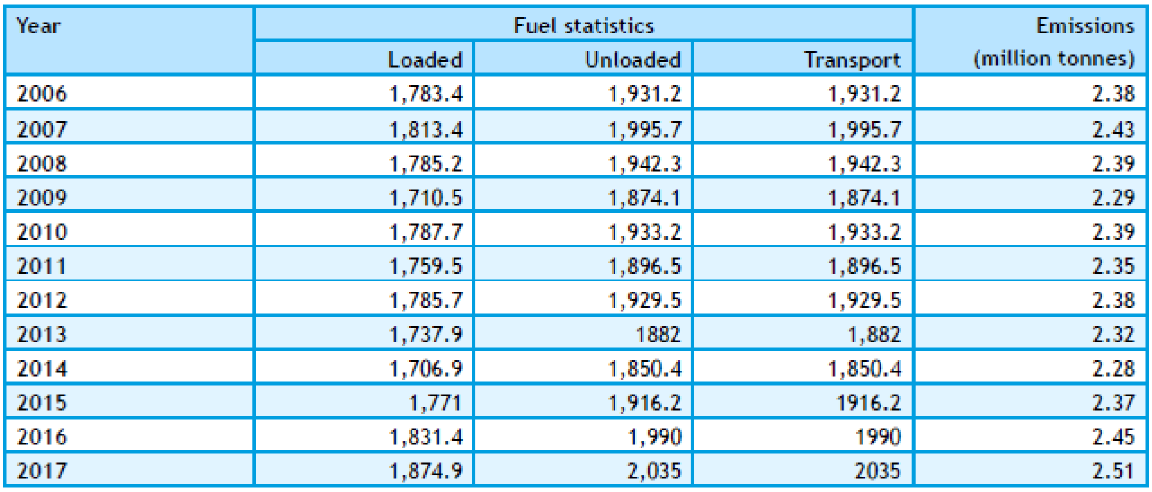


Figure 7: Share of NO_x, $PM_{2.5}$ and SO_x emissions (voyage-based), in that specific order of presentation, per ship type and per sailing phase in 2018 (source: [74])

Fugitive emissions from shipping are associated with the loading and unloading of volatile organic bulk liquid cargoes, and include emissions of VOC from hatches, pressure relief valves, flanges, etc. as cargos are moved to and from shore-side facilities. These non-exhaust emissions are really significant compared with overall shipping exhaust emissions (2.5 vs 0.8 Mt in 2017, see Figure 3 and Table 7) and increase over time as the amounts of liquid and gaseous fuels increase.

Table 7: Estimations of fugitive NMVOC emissions, related to oil and gas transport and distribution (top-down estimates) (source: [74])



Year	Fuel statistics			Emissions
	Loaded	Unloaded	Transport	(million tonnes)
2006	1,783.4	1,931.2	1,931.2	2.38
2007	1,813.4	1,995.7	1,995.7	2.43
2008	1,785.2	1,942.3	1,942.3	2.39
2009	1,710.5	1,874.1	1,874.1	2.29
2010	1,787.7	1,933.2	1,933.2	2.39
2011	1,759.5	1,896.5	1,896.5	2.35
2012	1,785.7	1,929.5	1,929.5	2.38
2013	1,737.9	1882	1,882	2.32
2014	1,706.9	1,850.4	1,850.4	2.28
2015	1,771	1,916.2	1916.2	2.37
2016	1,831.4	1,990	1990	2.45
2017	1,874.9	2,035	2035	2.51

Although the direct control of ports and terminals on ships' emissions is limited, their impact on ship emission reductions in the port area is double. On one hand, they can directly or indirectly provide incentives for ship owners to implement emission abatement measures on board. On the other hand, ports/terminals can facilitate port area ship emission reductions by providing solutions themselves such as on-shore power supply facilities or LNG infrastructures.

4. Maritime legislation

There is room for some improvement in terms of reduction of atmospheric emissions as highlighted in the previous section. To do so, the IMO (International Maritime Organisation) is the agency of the United Nations with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO is the global standard -setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented.

The IMO adopted in 1973 the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) which is the main international text covering pollution of the marine environment. The MARPOL Convention covers pollution from ships in the oceans and some specific areas such as the Mediterranean or Baltic seas, as well as vessels operating in US waters. Throughout the years, diverse Protocols were adopted and, in 1997, the Annex VI – called "Regulations for the Prevention of Air Pollution from Ships" – was introduced and entered into force in 2005 [12]. With this main legislative instrument MARPOL Annex VI, several regulations address NOx emissions (through regulation 12), ozone depleting substances (through regulation 12), sulphur oxides, (through sulphur in fuel in Regulation 14 and through the designation of Sulphur Dioxide Emission Control Area (SECA) in Regulation 14) and VOC from tankers (in Regulation 15) and prohibits deliberate emissions of substances likely to weaken the ozone layer [19]. A global cap on the sulphur content of fuel oil at 4.5 wt% (i.e. weight percent) was introduced alongside with mandatory technical and operational energy efficiency measures through the Tier I. Moreover, a distinction was done for the marine zones between ECA and outside ECA and the associated constraints on the sulphur content in fuels. An ECA is a specific, delimited area where strict requirements for a certain pollutant are imposed to protect their environment, which are designated by the IMO. The Baltic Sea was the first SECA, set in 2006, where the sulphur content of marine fuel oil was limited to 1.5 wt%. Following that, the North Sea and the English Channel were introduced as SECA in 2007.

The Marine Environment Protection Committee (MEPC) of IMO adopted amendments to MARPOL Annex VI in 2008 and after, in order to strengthen the emission limit values (ELVs) for NO_x and the sulphur contents of fuel oils used in ship engines. In a practical way, new regulations on the sulphur content and Tiers II and III to regulate the NO_x emissions were introduced. The sulphur content in fuels used in SECA was decreased to 1 wt% (2010) then 0.1 wt% (2015) while for fuels used outside SECA, the sulphur content was reduced to 3.5 wt% (2012) and has then been reduced to 0.5 wt% from 2020 onwards [12]. Concerning the NO_x emissions, the ELVs are addressed to diesel engines with a power output higher than 130 kW of ships which were constructed, or engines which underwent a major conversion, after January 1, 2000. The Tiers I and II concern this whole category of ships, depending on the construction date (before or after January 1, 2011), whereas the Tier III is for the same type of ship, constructed after January 1, 2016, but only when they operate in NECA.

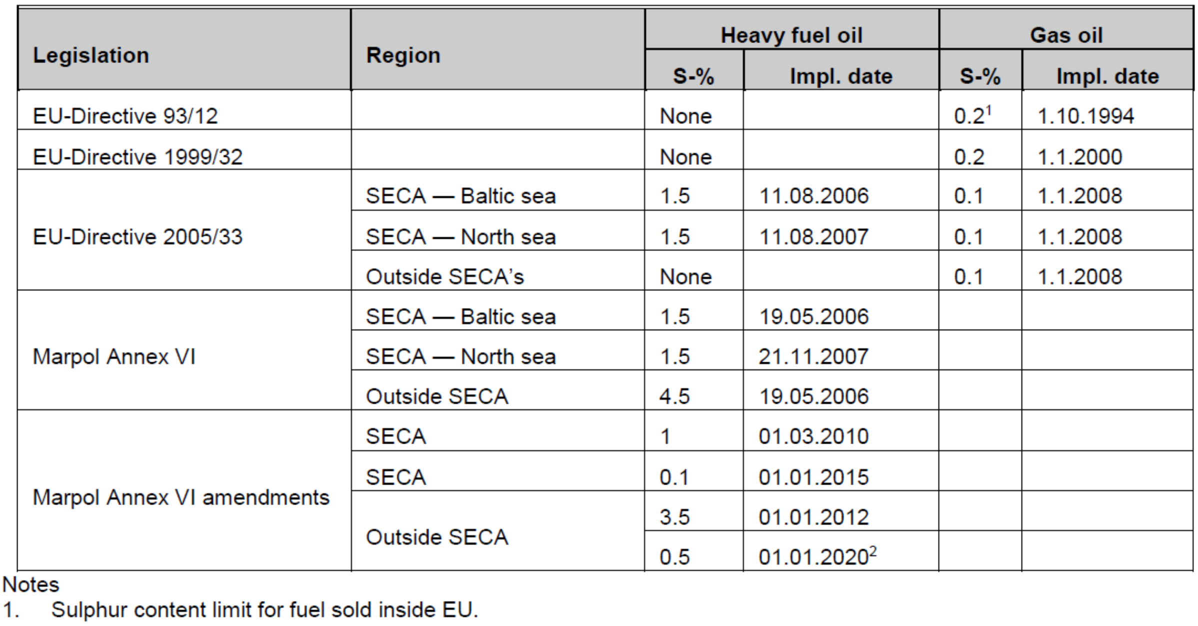
Table 8 : Tier I-III NO_x emission limits for ship engines (Marpol Annex VI and amendments) (source: [12])

Regulation	NOx limit (g/kWh)	Rated engine speeds (rpm)
Tier I	17	$n < 130$
	$45 \times n^{-0.2}$	$130 \leq n < 2000$
	9.8	$n \geq 2000$

Regulation	NOx limit (g/kWh)	Rated engine speeds (rpm)
Tier II	14.4 $44 \times n^{-0.23}$ 7.7	$n < 130$ $130 \leq n < 2000$ $n \geq 2000$
Tier III	3.4 $9 \times n^{-0.2}$ 2	$n < 130$ $130 \leq n < 2000$ $n \geq 2000$

Following the MARPOL Convention Annex VI, the EC implemented the Directive 1999/32/EC, with measures to reduce emissions of sulphur contained in marine fuels. However, this Directive does not treat the ship emissions of NO_x or TSP emissions. Then, the Directive 2005/33/EC was implemented and basically copied the MARPOL Annex VI but differed on the application dates. In addition to the MARPOL Annex VI, it imposes a restriction on the sulphur content at 0.1 wt% for ships at berth in EU ports from 2010 onwards (Directive 2012/33/EU). Since then, revised versions of the Directive such as Directives 2012/33 and 2016/802 fixed the sulphur content of fuel first to 1.5 wt% for passenger ships outside SECA, and then to 0.5 wt% since early 2020.

Table 9 : Evolution of the legislation on sulphur content in marine fuel quality (source: [12])



Legislation	Region	Heavy fuel oil		Gas oil	
		S-%	Impl. date	S-%	Impl. date
EU-Directive 93/12		None		0.2[1]	1.10.1994
EU-Directive 1999/32		None		0.2	1.1.2000
EU-Directive 2005/33	SECA — Baltic sea	1.5	11.08.2006	0.1	1.1.2008
	SECA — North sea	1.5	11.08.2007	0.1	1.1.2008
	Outside SECA's	None		0.1	1.1.2008
Marpol Annex VI	SECA — Baltic sea	1.5	19.05.2006		
	SECA — North sea	1.5	21.11.2007		
	Outside SECA	4.5	19.05.2006		
Marpol Annex VI amendments	SECA	1	01.03.2010		
	SECA	0.1	01.01.2015		
	Outside SECA	3.5	01.01.2012		
		0.5	01.01.2020[2]		

Notes
1. Sulphur content limit for fuel sold inside EU.

Several studies investigated the impacts of the aforementioned policies on the ship emissions, as well as on the challenges for ship manufacturers and owners (mostly about the need of updated technologies and the eventual shift in the trading routes) and the fuel suppliers [20][21][22][23][24][40]. One of their main conclusions was that policies and measures are crucial if emission abatements want to be achieved because reduction technologies are often not enough implemented if no limit values are imposed. A recent study conducted by a consortium led by INERIS together with Citepa and other partners [25] analysed the impact of the IMO's 2020 global sulphur cap policy and the implementation of a SECA and a NECA in the Mediterranean Sea. Huge reductions of SO_2 and NO_x emissions could be obtained with PM and BC emission reductions as well. Benefits on human health have been assessed and the costs estimated. Among the other results, they remarkably revealed that more than 6,000 premature deaths around the Mediterranean Sea due to $PM_{2.5}$ could be avoided and at least 17 billion €

could be saved yearly in health costs while the additional investment for such measure implementations in the Mediterranean Sea would be of no more than 5 billion € per year [25].

In addition, the Commission implementing decision 2014/738/EU, which establishes best available techniques (BAT) conclusions for the refining of mineral oil and gas, regulates VOC emissions to air from fuel loading and unloading operations. For sea-going ships with an annual throughput superior to 1 million m^3 per year, vapour recovery techniques such as condensation, absorption, adsorption, membrane separation or hybrid systems must be implemented in order to achieve recovery rate of at least 95%.

In annex VI, article 8 of the AGP, limit values for VOC emissions from the storage and distribution of petrol, do not address the loading of seagoing ships (stage I).

For ports, no international regulation imposes specific rules for port areas (e.g., IMO regulation applies) but regional or local regulation authorities may define some. In the European Union, a fuel sulphur content limit of 0.1 wt% for ships at berth is imposed by the Directive 2012/33/EU. In addition, the Directive 2008/50/EU imposes standards for ambient air pollutant concentrations, which may force ports to act on their ambient pollution or limit their activity deployment, especially for NO_x, PM_{10} and $PM_{2.5}$. In the US, similar ambient air concentration limits are imposed by the US EPA through the National Ambient Air Quality Standards (NAAQS), which can indirectly enhance port emission reduction. In California, the Ocean Going Vessels Fuel Rule imposes, for vessels within 24 nm of the Californian coastline, a fuel sulphur content limit of 0.1 wt% for main, auxiliary and boiler engines since 2014. Finally, the Californian At-Berth Regulation requires vessels of 6 different ports (Los Angeles, Long Beach, Oakland, San Diego, San Francisco and Hueneme) to plug into shore power or use alternative control techniques which achieve similar emission reductions (at least 85-90% for PM and NO_x). In 2014, at least 50% of a fleet visits must use onshore power and total onboard auxiliary engine power generation must be reduced by at least 50% (measured against the fleet baseline power generation), which increased to 70% in 2018 and 80% in 2020.

5. Available reduction techniques for ships

The emissions of pollutant in the maritime navigation can be controlled by acting at the source: using cleaner fuels (with low sulphur content, LNG or alternative fuels such as biofuels, methanol or others) and modifying the combustion technology and process (primary techniques), eventually combined with exhaust gas treatments (secondary techniques). The measures adopted in the MARPOL Annex VI impose requirements on the fuel sulphur content. In addition, a focus needs to be realized on the various combustion techniques and technologies to abate further air pollutant emissions. In the following paragraphs, a review of the abatement techniques available to decrease the emissions of NO_x, SO_2, PM and BC is given.

Regarding the technology options and investment costs, large variety in marine engines and fuels needs to be considered. The range of engines can vary from 100 kW high-speed engines to 100 MW two-stroke engines, operating either at very good quality distillate fuels to high sulphur content residual fuels. It is common that some reduction technologies apply only to certain engine technology and fuels, and also the reduction efficiency and costs may vary significantly. Hence, each measure application should then be evaluated on a case-by-case approach so that specific features are considered to assess the appropriate reduction level and costs.

Note about PM measurements:

In the following chapters, the term "PM" (Particulate Matter) is used as it is mostly encountered in the literature. However, in our understanding, "PM" can here be assimilated to the term "Total Suspended Matter (TSP)" as no specific range of particle sizes is considered. Nevertheless, the differences between TSP and PM can be rather marginal as the fractions of $PM_{2.5}$ *and* PM_{10} *in TSP in marine combustion are very large and, according to the EMEP/EEA guidebook [12], the granulometry is as follows:*

Granulometry of PM emissions (% of TSP)	PM_{10}	$PM_{2.5}$
Bunker fuel oil	*100%*	*90%*
Marine diesel oil/marine gas oil (MDO/MGO)	*100%*	*93%*

In addition, the measurement techniques for ship engines often follow the standards from the norm ISO n°8178, where dilution of the exhaust gases is realized before the measure in order to include the volatile PM fraction.

5.1. Primary techniques

5.1.1. Fuel switch: low sulphur fuels, LNG and alternative fuels

5.1.1.1. Switch to low sulphur fuels

The emissions of SO_x from ships are directly due to the content of sulphur present in the fuels. However, thanks to the MARPOL Annex VI Regulation, a sulphur cap has been defined and decreased over the years, down to 0.5 wt% since early 2020, having a huge impact on SO_x emissions.

Since the SO_x emissions are directly proportional to the fuel sulphur contents, important emission cuts down can be achieved using lower sulphur content fuels. Typically, lowering the sulphur cap of fuels from 3.5 wt% to 0.5 wt% should theoretically lead to a reduction of 85% of the SO_2 emissions from maritime shipping. In practice, some sea zones are SECAs, where the regulated sulphur content is 0.1 wt%, leading to potential reductions of up to 97% as it can be observed in literature [77], but some of the commonly heavy fuel oils used have lower sulphur contents than 3.5 wt%. For instance, prior to MARPOL 2020, the average fuel sulphur content was estimated to be around 2.5-2.7 wt% [5][25][64][72][73]. Therefore, the practical emission abatements achievable can be slightly lower but still very significant.

In addition, the switch from high-sulphur residual fuels to lower sulphur distillate/light fuels also has a positive impact on PM emissions, with achieved emission reductions varying from 50 to 90% [25][64][77]. Switching to low sulphur content, distillate/light fuels also provide BC reductions by 0 to 80%, with a medium range of about 30% [33][35][79][84]. The achieved reduction rate depends on the measurement technique, fuels used, engine types and power ranges, which could explain the wide range of reduction rates observed.

5.1.1.2. Switch to LNG

A switch to LNG instead of using fuel oils in ship diesel engines would be a sizeable solution to decrease significantly the emissions of SO_2, NO_x and PM and eliminate most of the black carbon emissions [26]. In 2015, LNG represented about 2.4% of the total fuel consumption of marine shipping [37]. Since 2010, the share of delivered ships built with LNG engines increased from 1.4% to 13.5% in 2018 [77]. The combustion of LNG is supposed to be almost negligible for SO_2 emissions compared to other oil products (from 90 to 100% reduction [26]), whereas it is estimated to emit about 90% and 88-98% less of NO_x and PM, respectively [26][40][84]. Lower reduction rates of about 64-73% and 60-68% for respectively NO_x and PM have also been observed with a LNG switch [77]. A switch to LNG is also estimated to have a positive reducing impact of up to 75% to 90% on BC emissions [33][34][37][84]. Nevertheless, major modifications are required in order to use LNG engines which implies costly conversions [26], unless the gas engine conversion is realized during a major engine overhaul. For instance, an additional physical space of about 3% of the ship's TEU (twenty-foot equivalent unit) slots is expected to be required for a switch to LNG engine [8], implicitly decreasing the space for containers. In addition, LNG is mainly used in dual-fuel engines (around 81% of all installed or ordered LNG engines), implying that some oil is also jointly consumed and can therefore increase the overall LNG engine emissions [77]. Another limiting parameter to the deployment of such a technique is the availability of LNG and the associated methane emissions [26][37][38][39]. In fact, it has been estimated that LNG production could cover about only 10% of the required shipping fuel by 2040 [8][41].

5.1.1.3. Water-fuel emulsions (WFE)

In WFE, water is added continuously into a mixture of fossil fuel and emulsifiers or stabilizing agents by mechanical measures, prior to the combustion chamber [33][53][55][64][69]. These emulsions are typically denoted as water in fuel emulsions. However, in some cases, the amount of added water needs to be very large to reach the required emission limits, such that it could be rather considered as a fuel in water emulsion. A more general denomination water-fuel or fuel-water emulsion cover both cases. The fuel-water emulsions can be either based on diesel or heavy fuel oil mixtures [32][64]. The use of WFE generally increases the fuel oil consumption [15][33][53][55], but fuel penalty is marginal when the water content is 30% or less [53][55] and estimated to be around 1-2% for 30% water contents or more [33][55][69].

When the emulsified mixture is injected into the combustion chamber, the combustion temperatures are lowered due to the water evaporation and additional heat required to heat up liquid water to the boiling point, leading to a lower formation of NO_x [33][55][64][69]. Then, NO_x emission reduction of about 1% is expected for 0.7 to 1% of water added to the fuel [15][55][64][69], with maximum reductions achievable about 50-60% [55][62][64][69]. Conjointly with NO_x, PM emissions can be decreased by 20 to 63% using WFE in marine diesel engines [32][35][53], whereas it is also reported that 60-90% PM reductions can be achieved [53]. In addition, BC emission reductions of 45-50% can be obtained according to [33], while reductions up to 85% are reported in [35][53][84]. Potential impacts on SO_2 emissions are not reported in the literature and are assumed to be minor but slight reductions can be expected [35][53]. One limiting factor to the use of WFE in existing marine engines is the delivery capacity of the fuel injection system while maintaining the same power level [64]. In addition, the large amounts of required water and the corresponding energy consumption for water treatment need to be considered. Moreover, using this process implies the risk of sulphurous acid (H_2SO_3) formation which could lead to the engine corrosion [77].

5.1.1.4. Switch to alternative fuels

Using other, cleaner alternative fuels, such as methanol or biofuels, can be a great means of tackling pollutant emissions. Nevertheless, a switch to fuels such as biofuels or hydrogen is possible but still mostly at the research and development stages [8], and it also raised some problems about cost and availability.

- ***Biodiesels and biofuels:***

Switching to biodiesels and biofuels produced from vegetable oil is also a good means to reduce the environmental impact of shipping. They have already been introduced in various transportation sectors and enable CO_2 and PM/BC emission reductions [15][35]. In order to fully assess the CO_2 emission reductions related to the use of biofuels, the impact on the land use and land change would need to be considered as well. Among different transport means, biodiesels have been revealed to decrease PM emissions by 50 to 90%, due to the lower concentrations of aromatic hydrocarbons, the higher cetane numbers and higher oxygen content [35]. In marine applications, PM reductions from 12% to 37% have been obtained depending on the percentage of biodiesel in the fuel mixture [32]. In [84], PM reduction rates of 20-30% are observed for 20% biodiesel mixture while 100% biodiesels reduce PM by 50-70%. In addition, comparing to typical fuels, SO_2 emission reductions could be obtained while switching to these alternative fuels [32]. However, biodiesels have lower energy contents by 8-11% compared to conventional diesels, hence increasing the fuel consumption [35]. Applied to the shipping industry, a 50% biodiesel/ultra-low sulphur diesel mixture has shown a 38% BC emission reduction, whereas other tests revealed a 60-75% achieved reduction compared with HFO [35][84]. Though, it has been reported that the operating costs in marine engine propulsion would be too high [15], but this study dates from 2005 and biofuel technology was not as advanced as nowadays.

- ***Methanol:***

Another possible fuel switch is to use methanol or dimethyl ether (DME) instead of conventional fuels. The interest in methanol as a marine fuel increased while the IMO sulphur caps were implemented, as methanol does not contain sulphur [70]. Hence, SO_2 emissions can be drastically tackled, while other pollutant emissions such as NO_x and PM can be significantly lowered, as well as CO_2 and greenhouse gas emissions in some specific cases [70][77]. Actually, when produced from biomass resources such as biomass residues or black liquor gasification, 95 to 100% CO_2 emission reductions can be expected from the use of methanol/DME [35][70], as well as a 97% drop in particle number (hence, similar BC reductions can be expected but not with confidence, no reported data on this yet) [35]. If produced from natural gas, methanol has a similar carbon content as diesel and no GHG emission reduction is achieved [70]. In addition, 35% reduction in NO_x emissions can be obtained from a switch to DME [35]. In [70], NO_x and PM_{10} emissions were reduced from about 55% and 99% on a small 313 kW, spark-ignited engine running at 64% maximum continuous rating, in comparison with diesel engine tests. A pilot project from Stena Line with the switch to a dual fuel MGO-methanol engine for a RoPax Ferry revealed emission reductions of 99% for SO_2, 60% for NO_x, 95% for PM and 25% for CO_2 compared with HFO [78]. In [80], NO_x emission reduction rates vary from 30% to 60%. However, a drop in fuel efficiency of about 9% is reported with the use of DME [35], leading to additional necessary fuel consumptions.

5.1.2. Slow steaming

Slow steaming is another technique which gained interest in the recent years, as it enables to save fuel and hence reduces emissions of all pollutants at once [40]. This technique consists of reducing the sailing speed from a few knots as, in normal cruise conditions, the specific fuel consumption is almost proportional to the third power of the ship velocity [32]. Thus, by reducing the cruising speed, some fuel savings can be achieved, enhancing the shipping companies' profitability [43] and simultaneously improving environmental performances. One study shows that reducing the velocity from 23 to 18 knots should theoretically reduce the fuel consumption by 50%, meanwhile 10% and 20% speed reductions are reported to enable fuel savings from about 15-19% and 36-39%, respectively [32]. Slow steaming can be realized either by reconfiguring an existing engine so that it is efficient under reduced load, or by setting up smaller engines on ships to sail at lower cruising speed [44]. The second option requires less initial investment but presents the drawbacks of being not reversible and also worsen the performances and the fuel consumptions of the ship if it requires to sail at a higher speed or in bad weather conditions [40].

A study from the Air Resources Board of California [45] revealed that applying slow steaming speed restrictions of the 24 nautic mile (nm) zone to the 12 nm zone and the ones of the 40 nm zone to the 200 nm zone plus high seas enables additional reductions of emission of CO_2 from 13% to 29%, respectively [40]. Simultaneously, the savings of fuel enable to reduce the emissions of NO_x, SO_2 and $PM_{2.5}$ respectively from about 21% to 36%, 13% to 29% and 18% to 31% (see Table 10) [40][45]. This study from CARB was further developed in 2012 and they revealed that reducing the speed from 24 to 15 knots for container ship enable CO_2 and NO_x emission reduction per nm travelled of about 43-56% and 50-59%, respectively [68]. In addition, they showed that decreasing the sailing speed to 11 knots can further decrease CO_2 and NO_x emission per nm travelled by 63% and 64%, respectively. The $PM_{2.5}$ emissions per nm sailed were also revealed to be reduced by 69% when decreasing the speed from 24 to 12 knots [68]. However, this study also analysed the CO emissions which are negatively impacted and tend to increase, principally due to the engine performing at lower load factors [68]. Another study reveals that imposing a 12 nm speed limit in a 25 nm zone could cut PM emissions by one third [32]. BC emission reductions from 0 to 30% can also be obtained by reducing the speed from 25 to 18 knots if the engine is derated, however increase of emission can occur if the engine operates at lower load factors or if no derating is performed (average of +30% emissions if engine load is reduced to 40% without derating) [35][84]. In terms of economic impacts, the main costs come from the fact that the delivery times are higher, therefore more ships are required to achieve the same shipping of goods. Increasing the ship fleet could however counteract some of the environmental benefits achieved while decreasing the cruising speed.

Table 10: Reduction coefficients assumed for speed restrictions within the 12 nm zone, in the 200 nm zone and high seas (sources: [45][40])

Sea Zone	NO_x	SO_2	$PM_{2.5}$	CO_2	Applied to
24 nm zone	-21%	-13%	-18%	-13%	12 nm zone
40 nm zone	-36%	-29%	-31%	-29%	EEZs (200 nm zone) plus high seas

5.1.3. Slide valves

The implementation of slide valves, in replacement of conventional fuel valves, enables more complete combustion at lower peak-flame temperatures [33][53]. Slide valves are now common techniques, already implemented on some newbuild engines and often retrofitted on old engines [33][35][53].

By lowering the flame temperature, this technique enables reductions of NO_x, PM, BC and VOC emissions [33][35][53]. NO_x emissions can be decreased by up to 20% [62], while PM emission reductions by 10 to 50% are reported with an average reduction of 25% [32][33][35][53]. Conjointly with PM reduction, BC emissions are expected to decrease in a similar proportion, by 25 to 50% approximately [33][35][53][84].

It has been reported that the use of slide valves can result in a 2% fuel penalty in consumption, thus implying some additional operating costs and increasing slightly CO_2 emissions [35].

5.1.4. New emerging alternative fuels or propulsion systems

Other techniques to reduce the environmental impact of shipping based on alternative fuels such as hydrogen or ammonia or propulsion systems such as battery-electric or modern wind-propulsion have emerged.

- ***Hydrogen (H_2):***

Hydrogen can be produced by electrolysis of water with renewable electricity (about 4%) or from fossil fuels (about 95% of nowadays production)[82]. Hydrogen can be used either in fuel cells, in dual fuel engines or instead of heavy fuel oil in diesel engines [81][82]. If it is produced from renewable energy or nuclear power, CO_2-free ships can be possible [81][82]. Indeed, hydrogen used in fuel cells emits zero 'exhaust' emissions as the electrochemical reaction between hydrogen and oxygen, which produces electricity, produces only heat and water as by-products [37][81]. However, the replacement of HFO with H_2 requires five times more volume for liquefied H_2 and ten to fifteen times more volume for compressed gaseous H_2 [81][82], raising storage limits. Moreover, the compression and liquefaction of hydrogen are very expensive and energy-intensive as its liquefaction temperature is very low (-253°C)[37][82]. Finally, fuel cells are still a technology at the development stage, which is also expensive and space demanding [37].

Up to September 2020, only three pilot projects of ships running on H_2 exist, but no bunkering infrastructure is available [81][82].

- ***Ammonia (NH_3):***

Ammonia is often used as a fertilizer, but it can also be used as a fuel for combustion or in fuel cells [37][82]. Ammonia is carbon-free, hence enabling CO_2 emission suppression. In addition, it has a higher liquefaction temperature (-33°C) as well as a higher liquid density than hydrogen, which simplifies and makes less expensive its liquefaction and storage compared to hydrogen but not to oil-based fuels [82]. Up to now, 90% of the production is based on fossil fuels (mostly natural gas) as the production from renewable sources is very energy-intensive [81]. So far, its marine application is still at the research and development state [81]. Moreover, the ammonia toxicity raises some problems, which is one of the reasons why no ammonia-powered ships are operational [37][82].

- ***Battery-powered ships (electric or hybrid):***

Short-sea shipping enables to test new technologies as frequent stop and specific infrastructure are more available. Here, battery-powered ships gain attraction and there are about 450 ferries and offshore ships (in operation or ordered) which are equipped with this technology, of which about one-third is fully-electric, meanwhile Norway electrifies its ferry sector since 2015 [81][82]. Hybridisation of ships have been reported to enable CO_2 emission reductions of about 10-40%, meanwhile electric ships can suppress CO_2 from the exhaust and totally if the electricity generation is made from renewable or nuclear energies [37][82]. The installation of battery systems, including the needed replacement each 8-10 years, are significantly more costly than diesel engines [82].

- ***Wind-propulsion assistance:***

Various modern wind-propulsion solutions exist and have been tested, such as rotor sails, wingsails and towing kites. Depending on the technology and ship type, fuel savings of about 5-50% can be expected [81], but typical annual savings about 8-10% were observed on equipped ships [83]. The Finnish company Norsepower systems have claimed that its Rotor Sail technology could avoid more than 30 Mt of CO_2 per year if applied to the entire global tanker fleet [83]. However, some limitations are raised about this option such as for the deck layout, the loading processes and an increased heeling (tipping from side to side) [81]. In addition, the most encountered wind-propulsion solutions, kites and rotors, are estimated to be more effective at lower speeds (e.g., below 16 knots for kites) [37].

5.2. Secondary techniques

5.2.1. NO_x reduction techniques: EGR and SCR

In engines, NO_x emissions are influenced by different parameters such as the type of fuel and their N content, the type of combustion, the combustion air-ratio and the flame temperature. Thus, to reduce NO_x emissions, several measures can be implemented.

5.2.1.1. Exhaust Gas Recirculation (EGR)

The principle of this technology is to create a recirculation of the engine exhaust gases back into the combustion chamber so that the combustion temperatures and pressures are lowered [26][27][29]. To do so, an intercooler is positioned on the recirculating path to lower the temperature of the exhaust, which increases its heat capacity and decreases its O_2 content to a smaller concentration than in the air. Hence, the temperature of combustion in the engine is lowered which thus hinders the thermal NO_x formation [26][27]. Since the input of the EGR system must be cleaned gases to prevent corrosion or clogging of the engine, which would decrease its efficiency or increase the maintenance costs, this technology needs to be combined with diesel particulate filters (DPF) or a scrubber in re-circulation line [26][29][77]. Nevertheless, there is no operating restriction in terms of the fuel sulphur content or the load operation. In addition, an electronic control system is required to operate the EGR technology [26].

The NO_x reduction efficiency of EGR varies with the recirculation rate, but the smoke formation and the fuel consumption increase at higher rates [77].On compression ignition diesel engines, the EGR technology has a good NO_x-reduction efficiency which varies from 25% to 80% depending upon the application [26][55]. Using an EGR can also enable BC emission reductions up to 20%, since the exhaust gases need to be cleaned through scrubbers or DPFs, but the recirculation can also increase the build-up of soot in some conditions [33][35]**Erreur ! Source du renvoi introuvable.**. A test on the first generation of MAN EGR revealed that with 20% of exhaust recirculation rate, a 50% NO_x emission reduction could be achieved with a 3% sulphur residual fuel [28]. Moreover, the second generation of MAN EGR is supposed to achieve compliance with Tier III NO_x limits with 40% of recirculation rate [27]. The EGR system though implies a reduction of the engine power and a potential increase of fuel consumption of about 0-4% [26][77]. However, it was shown that EGR systems are more efficient in terms of fuel savings than doing engine adjustments and lowering the load factor, to achieve Tier III thresholds [27]. The additional electrical power required to operate the scrubber or water treatment system is estimated to be about 1.6 kW/MW for 0.1%S fuel and 3.3 kW/MW for 3.5%S fuel [29]. For the EGR unit, the additional power supply needed, related to the EGR blower, varies from 2.8 to 5.5 kW/MW for load factors of 25% and 100%, respectively [29].

The EGR system has been demonstrated to reduce NO_x emissions to ensure compliance with Tier III levels for two-stroke engines while it has not yet been applied to medium -speed engines [26][27][92], the main challenges being the high SO_2 and PM concentrations in the exhaust gas [77] and the significant fuel penalty. Furthermore, this technology is not well suited to be installed on existing engines because of the major operations of integration to perform on the engine [26].

The implementation of EGR systems can result in an increase of CO and PM emissions, if not operated according to the manufacturer instructions. In order to prevent increased wear of the engine and the need for more frequent maintenance, the recirculated exhaust gas is cleaned by an internal EGR scrubber. The EGR scrubber is a closed-loop scrubber with an integrated water treatment system which can be operated for an extended period of time in zero-discharge mode [92].

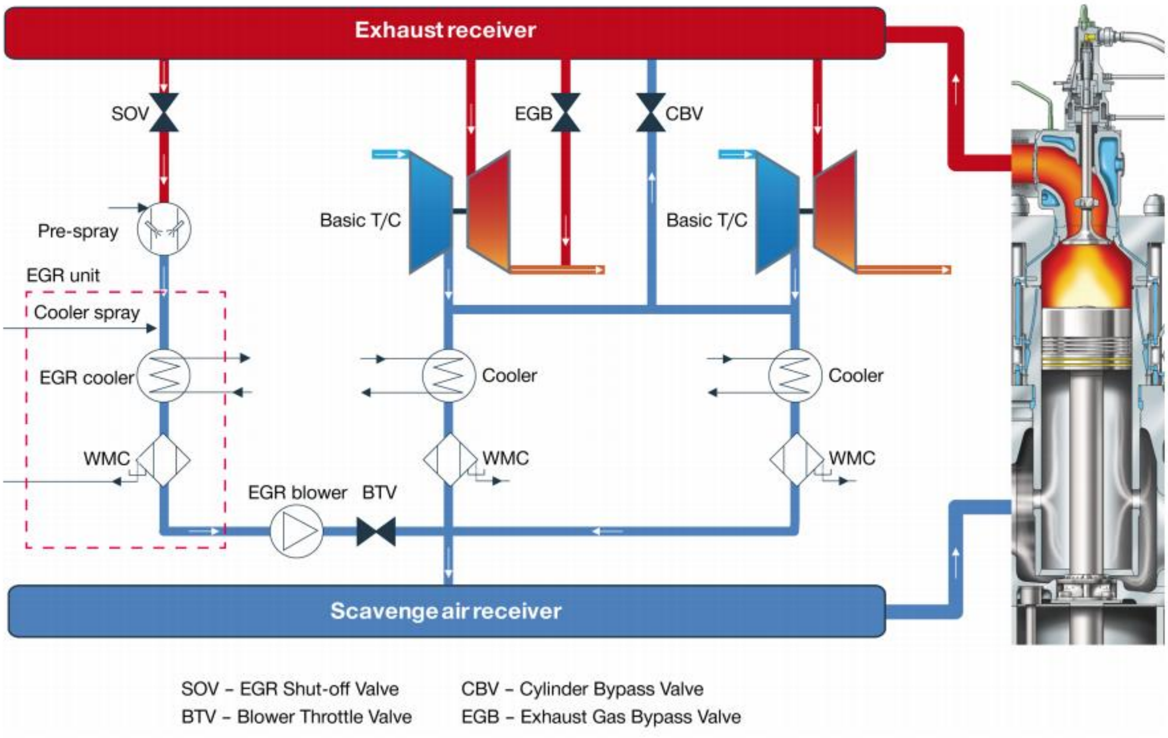


Figure 8: Exhaust-gas recirculation system - 2-stroke low-speed engine (source: [92])

5.2.1.2. Selective Catalytic Reduction (SCR)

The aim of the SCR technology is to cut-down the NO_x emissions via a chemical reaction over a catalyst [26][27][29]. To do so, nitrogen reducing compounds such as ammonia water solution (NH_3) or urea are used as the selective reducing agent so that the reaction products are nitrogen (N_2) and water (H_2O)[26][27][29]. Different forms of ammonia are used in the SCR technology, but the most common solution used in vessels is a mix of 40% of urea and water [26]. During the process, the reducing agent is injected as a spray into the exhaust duct right before the SCR reactor.

For marine application, the active catalyst material commonly used is vanadium oxide, which is combined with titanium oxide in a washcoat over a honeycomb ceramic or metallic structure [77]. Other catalyst materials such as zeolites can also be used, but these are usually sensitive to sulphur poisoning [77].

The consumption of urea solution depends on the amount of NO_x which is aimed to be reduced [26]. Anhydrous ammonia could also be used but it is classified as a toxic and dangerous substance; however, its supply system is more complex than for urea but the storage volume required is smaller and the vaporizing and mixing process are simpler than for urea [29].

The SCR technique can be used with any marine fuel oil, however the catalytic reaction is more efficient at lower SO_2 levels in the exhaust gas, and at higher temperatures [77]. It enables to reduce drastically the NO_x emissions with efficiency varying between 70% and 95% depending on the operating conditions [26][27][37][77]. BC emissions can also be reduced to some extent, if the engine can be calibrated to higher NO_x and lower BC emissions. When an oxidation catalyst is used to oxidize the remaining NH_3, it also enables to decrease the emissions of VOC, CO and PM by respectively 50-90%, 50-90% and 10-40% [26][37][77]. Potential fuel savings may be achievable with the use of SCR, . outside of NECAs, as the SCR can enable to achieve a Tier II NO_x limit for Tier I engines, which are more efficient than Tier II engines by about 4% to 4.5% [26][27]. However, due to the increased back pressure or the increased exhaust gas temperature requirements, fuel penalties of about 0-2% can be expected from the use of a SCR system on similar engines [77]. Moreover, the additional power required to supply the reducing agent, the compressed air and the heat of the SCR reactor is about 5 kW/MW [29]. In marine installations there is typically no SCR heating. It can also be noted that the production of ammonia requires a significant amount of energy.

Concerning the reducing agent, the consumption depends on the agent type, the engine load and the NO_x reduction rate but estimates to go from Tier II to Tier III are estimated at 12-16.1 l/MWh for urea solution 40% and 18.4 l/MWh for ammonia-water 24.5% [29]. The costs of implementation, operation and maintenance will be discussed in the next chapter.

In terms of environment, there is a risk of ammonia leak, even more as the SCR reactor deteriorates but controlling techniques such as calibration optimization, professional catalyst dimensioning or introduction of a clean-up catalyst exist to prevent this phenomenon [26]. The exhaust going out from the ship chimney is also less odorous. However, clean-up catalysts can only be implemented with low sulphur fuels (not possible with marine fuel oils with sulphur contents of 0.1 wt% or higher).

Several cases of diesel vessels equipped with a SCR technology already showed the great potential of the deployment of such a technique [26]. However, some issues and limitations persist about the ease to widely implement SCR systems:

- First, even though the current ammonia demand in maritime applications is about 1% of the global demand, the ammonia additives have to be made widely available through the implementation of refuelling infrastructure, as it is already the case in areas such as in the North and Baltic Seas [26].
- In addition, a certain temperature needs to be reached so that the catalytic reaction can be triggered [77], therefore an assessment of the exhaust gas temperatures is needed before then [26][29]. This can be a particular problem when the engine loads are not high enough. A special care must be taken as well while operating at low temperatures with high sulphur fuels because of the eventual formation of ammonium bisulphate (ABS) [26][27][29][30] or sulphuric acid [27][29]. For instance, an exhaust temperature of at least 300-350°C is required when the engine works with heavy fuel oil (HFO)[26][27][30], however temperatures higher than 500°C can thermally damage the catalyst [27], oxidize the NH_3 and increase the formation of SO_3 [29]. An example of required temperatures in order to prevent the formation of ABS depending on the fuel sulphur content are presented in [29] (see Figure 11). However, exhaust gas temperature control is now an integral part of an engine-SCR-system supplied by original equipment manufacturers (OEMs).
- The size of the SCR system varies depending on the gas flow and the specified engine power, but also depending on the specified lifetime of the catalyst (the longer the lifetime, the bigger the size) and the reducing agent (if ammonia instead of urea, a smaller mixer is needed and less space, but the storage is more complex as it is more hazardous) [29].

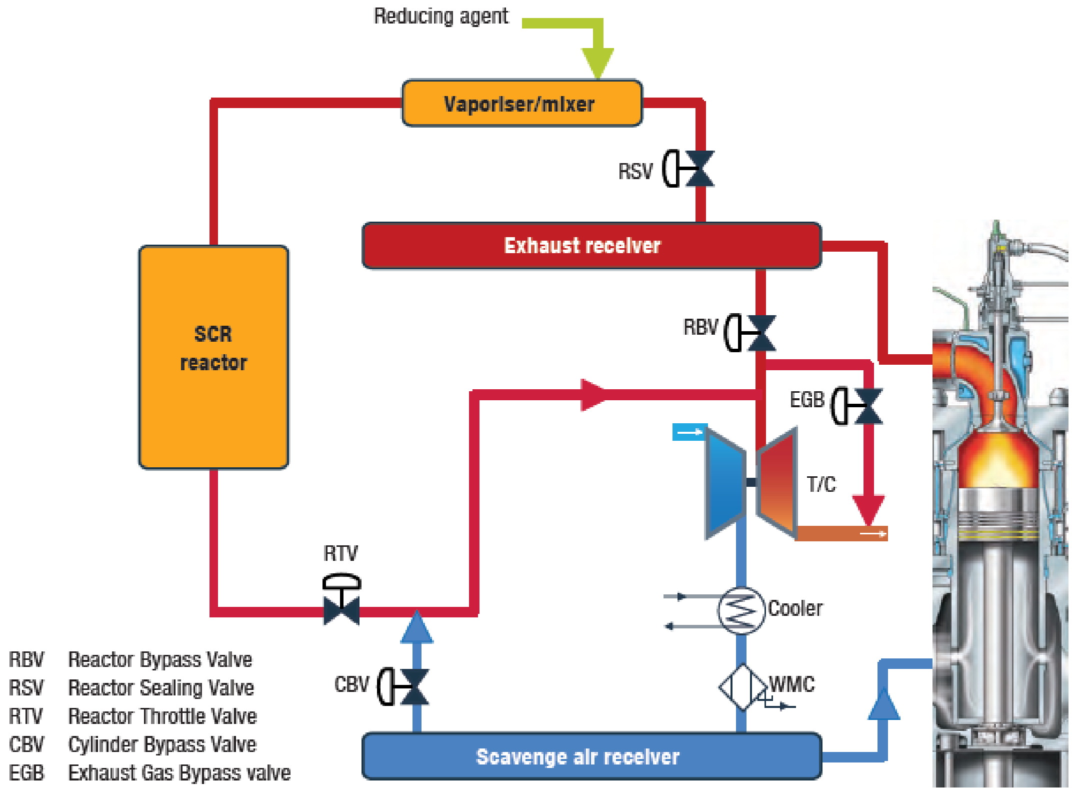


Figure 9: Selective-catalytic reactor working in high-pressure mode (source: [29])

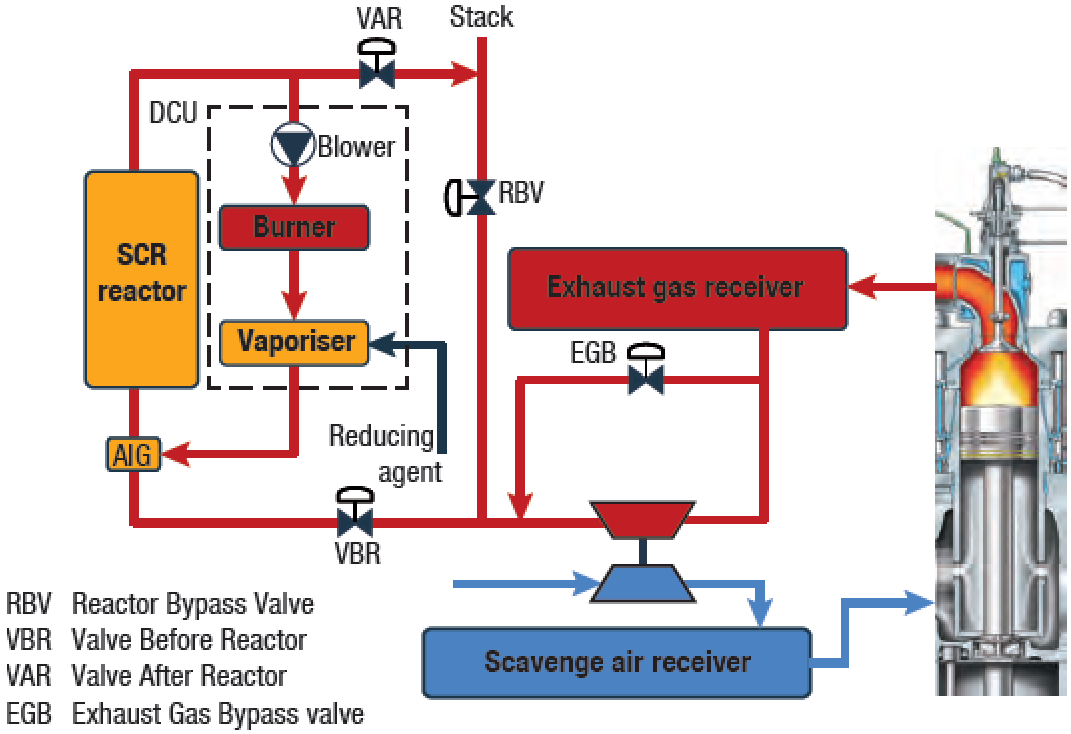


Figure 10: Selective-catalytic reactor operating in low-pressure mode (source: [29])

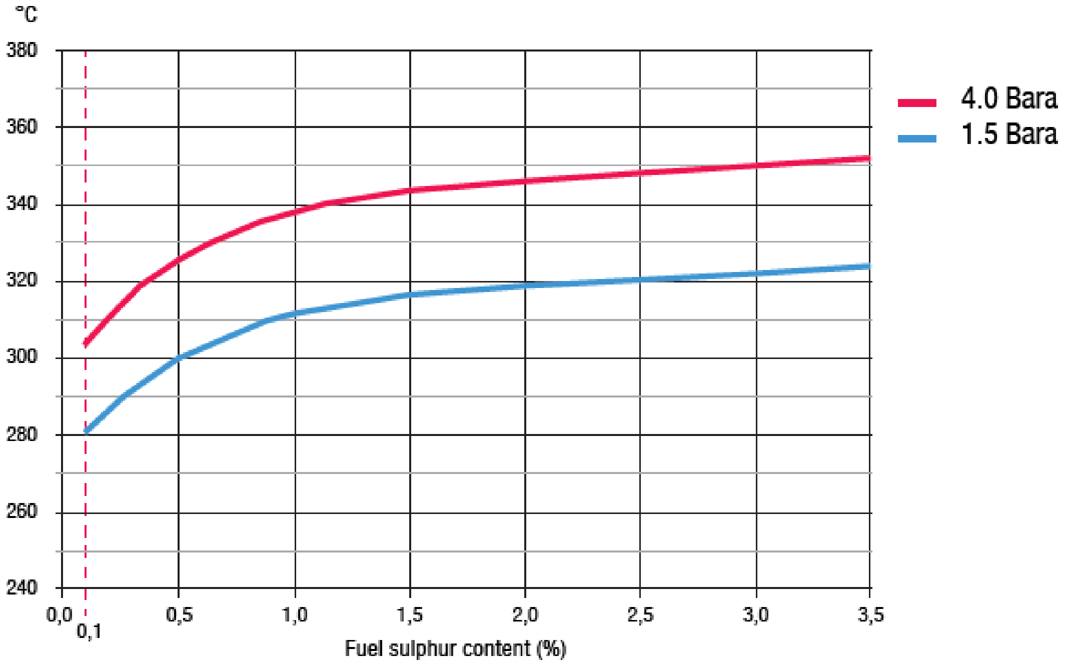


Figure 11: Required temperatures for SCR related to sulphur content at exhaust gas pressures of 1.5 bar and 4 bar (approximate pressure for low and high engine loads, respectively) (source: [29])

Periodic maintenance together with controlled operations are required in order to guarantee good performances and a long lifetime of the SCR system [26]. However, the SCR technology can be disrupted and degraded when some dust is trapped or when chemical components poisoned the catalyst, but some techniques such as a soot blower system exist to prevent that phenomenon [29], and catalysts can also be regenerated or recycled [26]. Besides that, the principal task consists of refilling urea in the tank once its gauge is low.

SCR technologies can also be combined with DPF to cut-down PM emissions, and with SO_x scrubbers which are preferentially placed downstream to optimize the efficiency in terms of heat transfer [26][77]. Space is not expected to be an issue for the combination of these reduction techniques.

5.2.2. Particulate matter (PM) and black carbon (BC) reduction techniques: diesel particle filters and baghouse filters

In order to tackle the emissions of particulate matter (PM) and black carbon (BC) from ship exhausts, a common reduction technique used in other transportation or industry sectors such as the automotive one can be used: diesel particle filters (DPF). Nevertheless, DPF can be implemented when operating with high quality distillate fuels, and is currently valid only for high-speed engines. In addition, baghouse filters, which are commonly used in industrial sectors, are an emerging technique for tackling PM emissions in marine applications.

Diesel particulate filters (DPF)

This technology consists of a porous ceramic substrate on which particles get trapped and only the cleaner exhaust can pass through [26]. After some use, the filtered particles accumulate onto the filter, which increase the pressure drop. Therefore, a means to burn off or remove the aggregated soot particles is provided with the DPF, and a common way is to burn or oxidize them when exhaust temperatures are appropriate [26][30]. For passive filters, diesel oxidation catalyst (DOC) or catalytic coating is used to convert NO to NO_2, and then enabling the soot combustion at lower temperatures. Active regeneration filters use other heat sources such as fuel burning or electric heaters [26]. The information of when the filter needs to be cleaned can be assessed with an electronic device controlling the back pressure. The accumulation of soot is the main parameter which affects the performance of DPF [26][30].

For a compression ignition diesel engine, the emissions of PM can be cut-down by 45-92% with the use of a DPF [26][30][31][55][77] and BC emissions can be reduced by up to 70-90% [33]**Erreur ! Source du renvoi introuvable.**[79][84]. The implementation of the latter can also enable reductions of VOC and CO by about 60-90% when it has a catalytic coating in wall-flow design [26] or when a diesel oxidation catalyst (DOC) is mounted [30][55](although it is realized on a rather small engine, 200 kW, over a short-time period). The effect of the increasing concentration of VOC and CO with a decreasing load factor of the engine can also be suppressed with a DPF equipped with a DOC as the substances get fully oxidized [30]. Nonetheless, DOC application is limited by the sulphur content in the fuel (< 50 ppm or about 0.005%)[77] and is mainly viable for sulphur free fuels such as EN-590, GTL or LNG. In addition, the abatement of emissions may not be as effective as for road vehicles and non-road mobile machinery (NRMM) as different fuels with higher sulphur and ash contents can be used in marine ships [26][31], which will block the filter with inorganic ash components. Some short-term tests have been reported, but no long-term validation exists [73]. In terms of side effects, the installation of a DPF on a diesel engine can cause an increase in the fuel consumption of around 1-3%, therefore increasing slightly the associated emissions [26][55][77]. The costs of the implementation of such a technique are still hard to estimate and will be discussed in the next chapter.

Concerning the environmental impact, there are some concerns about the emissions of NO_2, as a fraction of NO_x, because some catalysed DPF generate NO_2 in order to help the clear off of particles at lower temperatures [26]. Moreover, during the particle burn-off, some water and CO_2 are formed in minor quantities.

So far, the implementation of DPF on sea-going ships is still at an experimental phase [77], further knowledge is needed because its applicability in ship engines is different from the one in automotive applications. The PM emission level of diesel engines must be not too elevated in order to ensure that the DPF is functional as well as a small content of oil in the exhaust gases [26]. Hence, DPF requires low-sulphur content fuels with a sulphur concentration inferior to 0.5% (i.e., 5,000 ppm) in order to be operational as well as the monitoring of the exhaust gas temperatures to ensure the requirements are met [26]. A limitation of available space can raise from the installation of a DPF because, as for a SCR system, the exhaust backpressure is increased and can thus lead to the need of a larger aftertreatment system.

The size of the DPF unit is significantly larger than for SCR, and together with burners for regeneration, create challenges for the installation.

In addition of the burn-off of particles, extra maintenance is periodically needed to clear the non-combustible materials such as ash.

As aforementioned, DPF can be associated with EGR or SCR to reduce NO_x emissions [26].

Baghouse Filters

Baghouse Filters are high-performing filters mainly composed of inlet distribution duct, a chamber-type design with vertically arranged cylindrical bags, a bag supporting plate, a clean gas chamber and a clean gas discharge plenum.

The technology is matured and widely used on land-based power plants, biomass plants and incineration plants.

The particles bag filter using bags have a higher cut-down than DPFs with emission reduction higher than 99% for both PM and BC.

The other advantages of the bag particle filters are the possibility to treat in the same device the SO_x *emissions by injection of a reactive agent such as sodium bicarbonate as well as the* NO_x *emissions by using catalytic bags with urea injection upstream. These additional treatments do not increase significantly the pressure drop of the system and, compared to wet scrubbers, the electrical consumption is very low.*

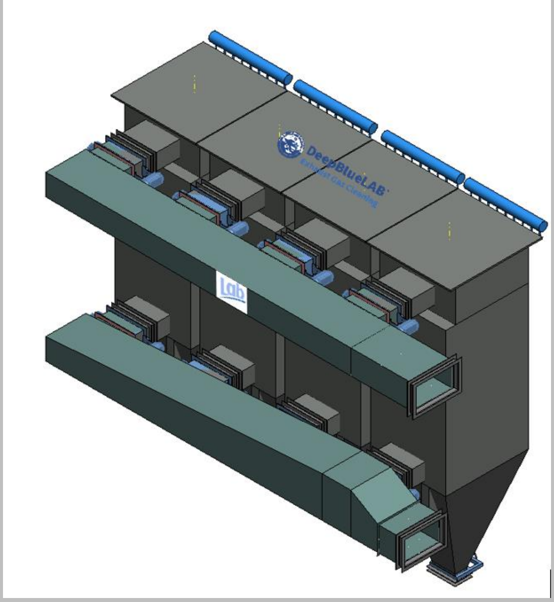


Figure 12: Schematic view of design bag particle filters (source: LAB)

5.2.3. SO_x reduction techniques: scrubbers

Despite the sulphur cap imposed by the MARPOL Annex VI regulation, fuels with sulphur contents higher than 0.5 wt% can be used if the exhaust gases are treated so that the SO_2 emissions are equivalent to the ones related to the combustion of a fuel with 0.5 %s overall and with 0.1 %s in SECAs [29]. In addition, the maritime transport is still a major contributor to the global SO_x emissions and, therefore, additional efforts are necessary to reach low levels of emissions. An efficient reduction measure to do so is the use of scrubbers. From a recent publication, the number of ships with installed or ordered scrubbers increases over time and reaches 4,000 in 2020 (see Figure 13)[75][77]. In 2019, about 36% of the container carrying capacity had scrubbers installed [75].

Two distinct types of scrubbers exist: dry or wet. Dry scrubbers either operate with an absorber unit which brings the exhaust gases in contact with an alkaline agent such as calcium hydroxide in solid form or with the injection of sodium bicarbonate powder into the exhaust gas combined with a dedusting device, whereas wet scrubbers use seawater or freshwater with added alkaline chemicals. Similar emission reduction rates of SO_2 and PM can be achieved with both technologies [27]. Unlike wet scrubber systems, dry scrubbers do not require washwater treatment systems such as pipework, tankage or monitoring systems and their electrical power consumption is estimated to be 4 to 8 times lower than for wet systems [27]. However, the use of dry scrubbers implies higher operational costs due to the discharge of the solid waste.

In general, marine engines are mainly fitted with wet scrubbers up to these days [29], and among them, more than 80% of them are open-loop scrubbers, 17% are hybrid and less than 2% are closed-loop [75][77].

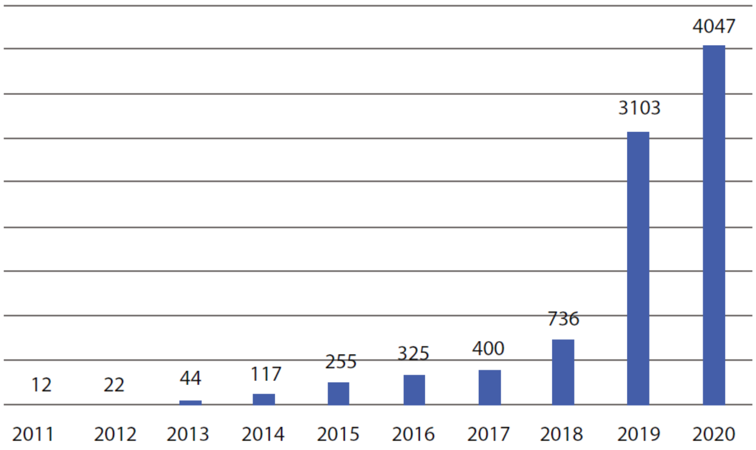


Figure 13: Evolution of the number of ships with scrubbers installed or in order (source: [75])

5.2.3.1. Wet scrubbers

There are different configurations in which a wet scrubber can be operated, which influence the costs of investment and installation and its efficiency:

- Open-loop: seawater is used to decrease the SO_x concentration of the exhaust gases via a chemical reaction where sulfuric acid is formed [26][29]. Additional chemicals are not necessary since the natural alkalinity of seawater neutralizes the SO_x [26][29]. This system is specifically meant for sea and ocean ships as seawater is directly available [26]. A SO_x reduction rate of about 98% is expected from this type of scrubber, decreasing emissions of a 3.5%S heavy fuel oil down to the equivalent emissions from a 0.1%s fuel [27]. The flow rate of the washwater in an open-loop system is about 45 to 60 m^3/MWh when a 3.5% s heavy fuel oil is used [27][29][77].
- Closed-loop: once the exhaust gas goes into the scrubber, it is sprayed with a solution of fresh water and caustic soda (NaOH) which reacts and neutralizes the SO_x [26][27][29], forming sodium sulphate [27][29]. Then, the mixed-water is recovered and recirculates to the scrubber. This principle is meant for ships travelling in waters with low alkalinity and/or where washwater cannot be discharged [26][27]. In closed-loop system, the washwater recirculating flow, and hence the power consumption, is about half the one in an open-loop scrubber (approximately 20 to 30 m^3/MWh [27][29]) and about 0.5-1% of the engine power [27]. On contrary to open-loop scrubber, the washwater flows through a process tank where it is cleaned before recirculating, and about 0.1 to 0.3 m^3/MWh of washwater is discharged to decrease the concentration of

sodium sulphates [27][29][77] after getting controlled to meet the IMO guidelines criteria [29].

- Hybrid mode: this technology combines both open and closed-loop systems and enables ships to be flexible depending on whether they are maneuvering in ports or travelling further away in the sea [26][27][29]. This is obviously more sophisticated and more complex thus making it ideal mainly for ships which require a full flexibility [26][27].

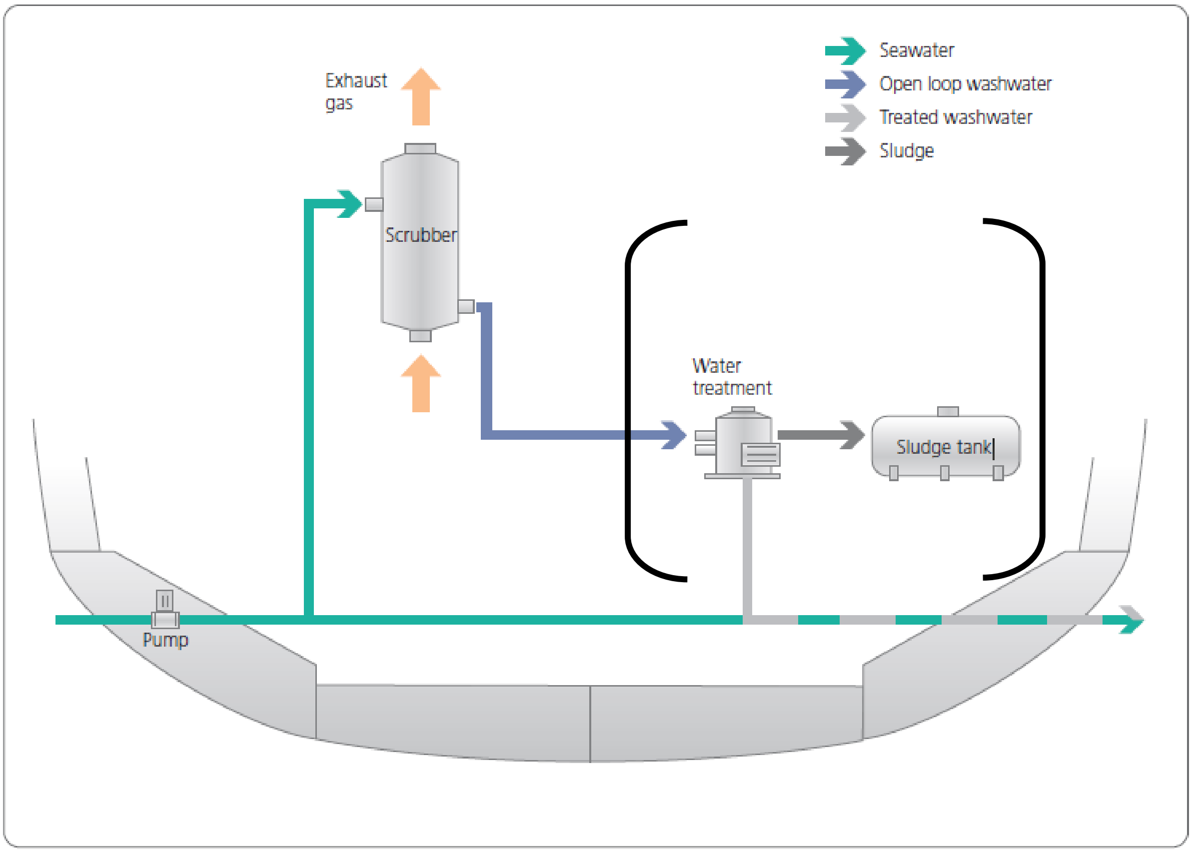


Figure 14: Open-loop wet SO_x scrubber (source: [27]) (parentheses added for the water treatment system as it is optional/not common for open-loop systems)

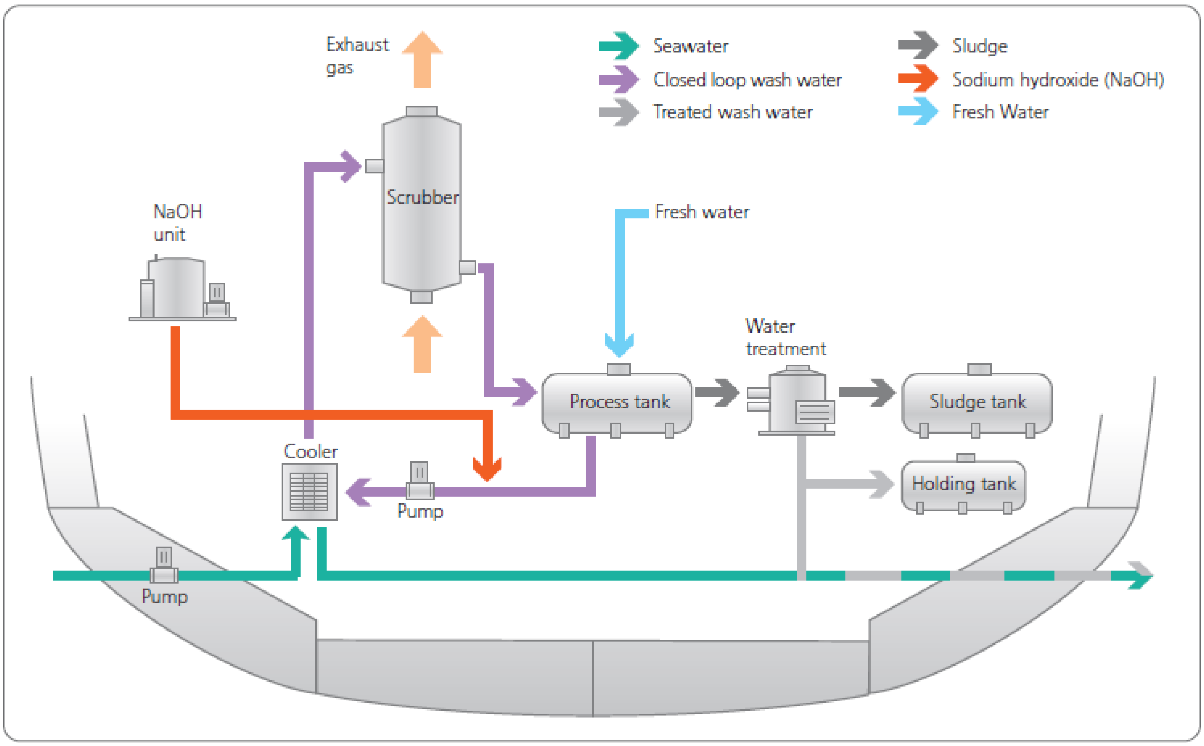


Figure 15: A closed-loop wet SO_x scrubber (source: [27])

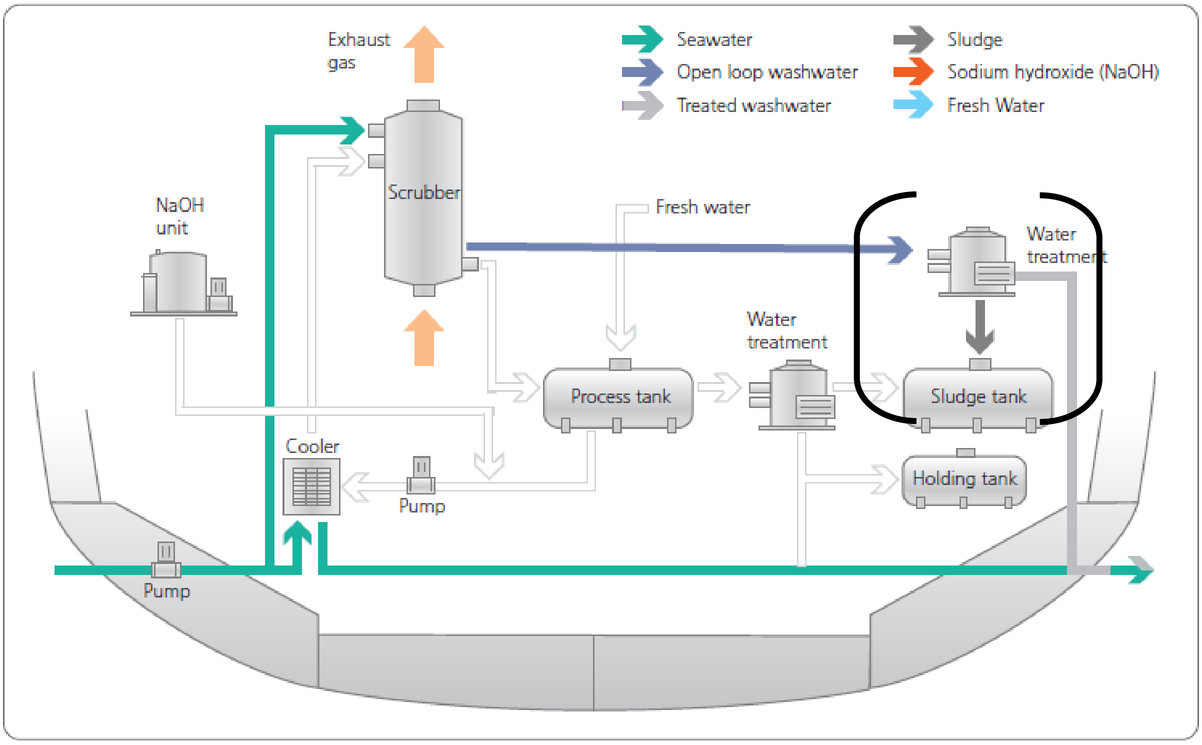


Figure 16: A hybrid SO_x scrubber operating in open loop mode (source: [27]) (parentheses added for the water treatment system for open-loop mode as it is optional/not common for open-loop)

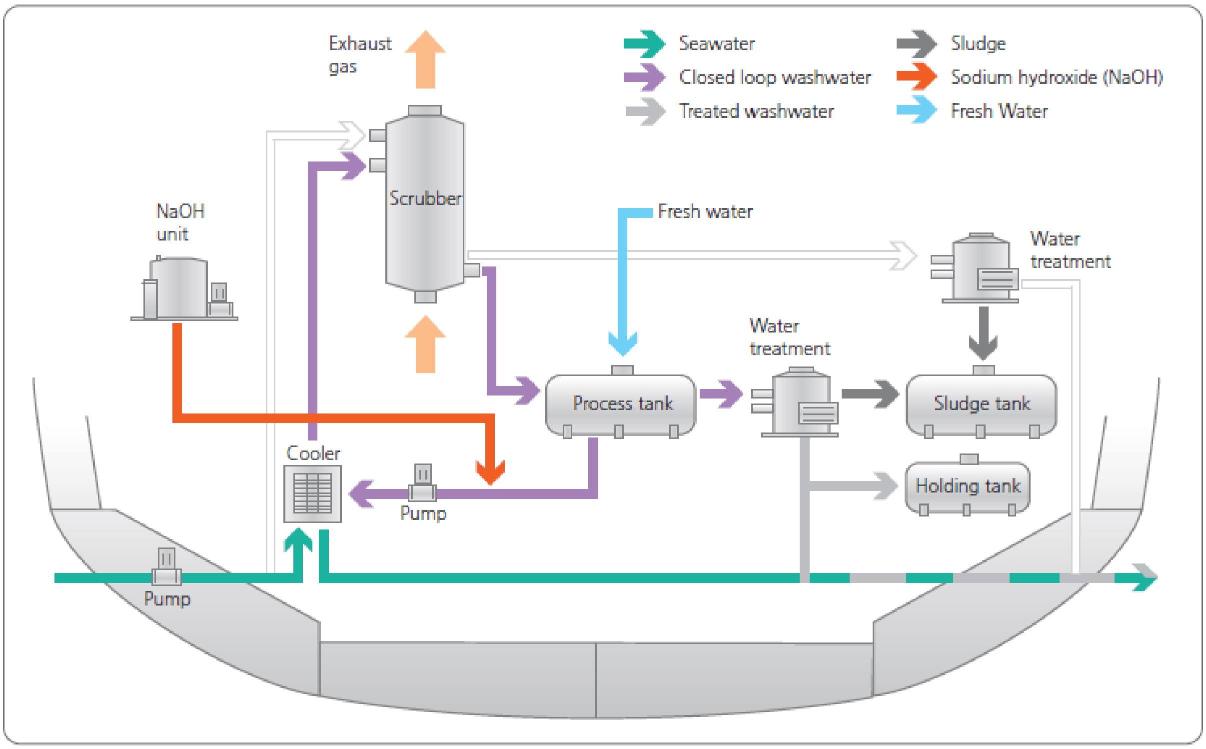


Figure 17: A hybrid SO$_x$ scrubber operaing in closed loop mode (source: [27])

There are also two types of configurations and designs to install the wet scrubbers:

- In-line scrubbers: replacing silencers, this design avoids the by-pass of the exhaust duct. This compact configuration enables an easy arrangement with a direct installation in the funnel. However, the by-pass avoidance requires for wet and dry operations both a high corrosion and temperature resistance (super austenitic steel for example).

Figure 18: In-line scrubber design and examples (source: LAB)

- Off-line scrubbers: this design is based on an installation in parallel with existing exhaust ducts in by-pass. It avoids the temperature resistance requirement. This configuration allows Glass Reinforced Plastic (GRP) use with very high corrosion resistance with easy maintenance and repair. Nevertheless, this system requires more space than in-line design and also dampers to isolate the scrubbers especially in multi-engine configuration.

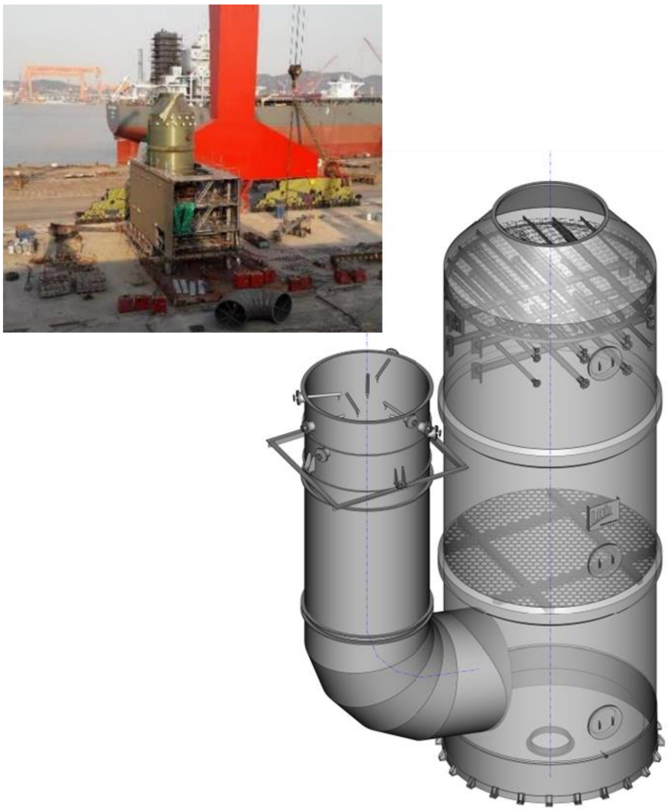


Figure 19: Off-line scrubber design and examples (source: LAB)

Thanks to scrubbers, reductions of emissions about 90-98% for SO_x, 0-90% for PM (mid-range observed between 14-47% [77]) and 0-70% for BC (mid-range observed between 16-37% [77]) are achievable for diesel engines [26][27][29][32][33][34][37][48][53][77]. In terms of emission levels, test data revealed emission rates for PM_{10} of 0.23 g/kWh with 0.24 %S distillate fuel and 1.35 g/kWh with 2.46 %S residual fuel [27]. The required efficiencies of the scrubbers depending on the sailing area and on the fuel sulphur content are displayed in Table 11 [29]. If the scrubber removal rate of PM is about 70%, the expected sludge production rate is between 2,8 kg – 27 kg per ton fuel consumed depending on the type of water treatment system and if sludge drying is available, necessitating a sludge tank of about 0.5 m^3/MW of engine power [27] depending on operational pattern. The implementation of scrubbers induces a slight increase in the fuel consumption of about 0.5-3% [26][77]. The investment and maintenance costs of such a technology depend on several parameters and will be addressed in the next chapter.

Table 11: Required SO_x scrubber efficiency depending on the fuel sulphur content and the regulated areas (SECA or not) (source: [29])

Fuel sulphur S%	Scrubber efficiency in ECA, % Sulphur limit: 0.1%	Scrubber efficiency in non-ECA, % Sulphur limit: 0.5%
3.5	97.1	85.7
3.0	96.7	83.3
2.5	96.0	80.0
2.0	95.0	75.0
1.5	93.3	66.7
1.0	90.0	50.0

An example of dry exhaust gas cleaning system implementation in marine application:

This proven technology has been used on land since more than 30 years and has now been adapted to marine application. The completely dry process is based on the injection of powdered sodium bicarbonate ($NAHCO_3$) directly into the exhaust gas duct. Due to the high temperature, the sodium bicarbonate decomposes to sodium carbonate with a high active surface area. This activated sodium carbonate immediately reacts with the SO_3 and SO_2 present in the exhaust gas [103]. The reaction product consists of solid sodium sulphate and sodium carbonate, the latter resulting from the excess of injected sodium bicarbonate.

The gas is then passed through a filter such as a bag filter to remove the reaction products as well as soot, black carbon and heavy metals resulting from the combustion. These residues are collected in a silo and brought off board for treatment on land [103].

The exhaust gas treatment system is displayed in Figure 20.

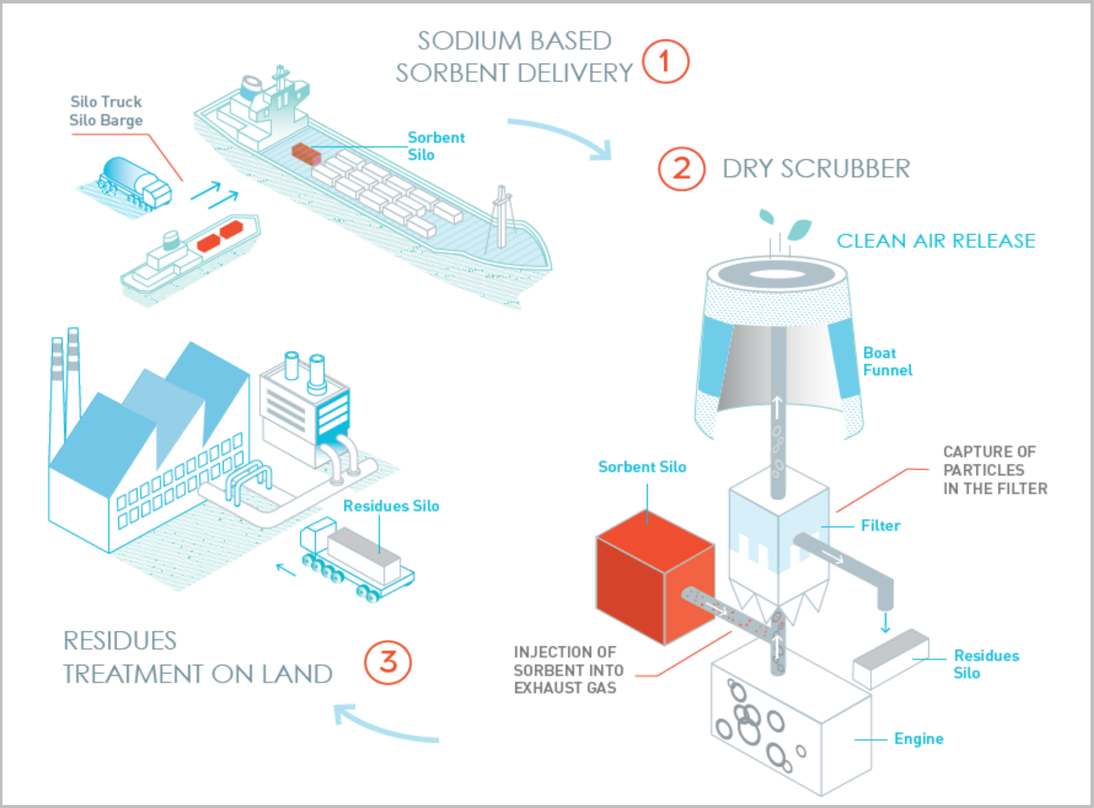


Figure 20: Dry exhaust gas cleaning system for simultaneous SO_x and PM removal (Source: SOLVAY)

This technology has been proven to achieve emission reduction rates higher than 99% for SO_x *and as well as for both* PM_{10}*,* $PM_{2.5}$ *and* PM_1 *[103]. For* SO_x*, the removal rates of such a technology enable to achieve emission levels compliant with levels equivalent to 0.1 wt% sulphur fuel use.*

Contrarily to open-loop scrubbers, no wastewater or other residual material is disposed onto the sea. Moreover, in contrast to wet scrubbers, the exhaust gases are not cooled down and hence it can be easily combined with a SCR.

This technology has been tested over 6 months in 2019 on a RoPAx ferry on one main (9.6 MW) and one auxiliary (1.26 MW) engines [103]. The ferry operates in the Mediterranean Sea. The MARPOL MED G approval (by DNV GL) as well as the IAPP certificate have been issued after the test. The integration of a SCR system with catalytic filter material is currently under investigation.

This technology has been shown to imply a rather low energy consumption (about 30 kW) as no wash water pumps are required, and induces a low pressure drop (< 15 mbar) [103]. There is no risk of corrosion and the alkaline sorbent is completely harmless. Finally, the system has been revealed to be easy to operate and have a low failure risk, meanwhile its installation is rather simple (no dry-dock or shipyard stay needed).

5.2.3.2. Summary and conclusions on scrubber technologies

Different features of the distinct types of scrubber are summarized in the following table [26]:

Table 12: Comparison of the different technologies of scrubbers depending on various performances (adapted and modified from source: [26])

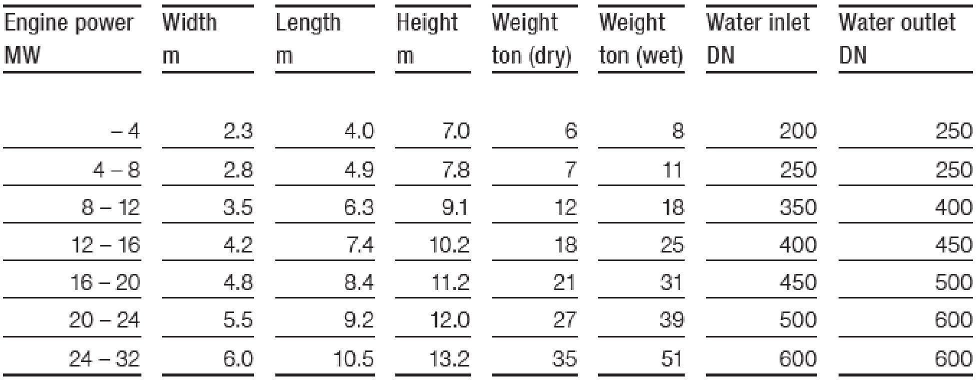
	Wet scrubber			Dry calcium-based scrubber	Dry sodium-based EGCS
	Open-loop	Closed-loop	Hybrid		
Main system components	- Scrubber - Washwater piping - Washwater pumps Optional: - Washwater treatment equipment - Sludge handing equipment	- Scrubber - Washwater piping - Washwater pumps - Washwater processing and holding tanks - Alkaline agent storage tank - Washwater treatment equipment - Sludge handing equipment	- Scrubber - Washwater piping - Washwater pumps - Washwater processing and holding tanks - Alkaline agent storage tank - Washwater treatment equipment - Sludge handing equipment	- Absorber - Fresh granulate hopper - Used granulate hopper - Granulate transport system - Additional granulate storage (new and used granules)	- Filter - Storage and dosing for sodium based sorbent - Storage system for residues
Operation in fresh water	× (✓ if NaOH boosting)	✓	✓(only in closed-loop mode)	✓	✓
Operation without discharge to sea	No	For a limited time depending on the size of the washwater tank		Yes	Yes
Weight (typical values for a 20 MW scrubber)	11-55 t (Excluding washwater system and treatment equipment)	30-55 t (Excluding washwater system, treatment equipment, washwater processing tank and holding tank)	30-55 t (Excluding washwater system, treatment equipment, washwater processing tank and holding tank)	≈ 200 t (Including granules stored adjacent to the abosrber but excluding additional granulate storage)	≈ 62 t (Excluding storage and dosing system)
Power consumption (% of engine power)	1-3%	0.5-3%	0.5-3% (Depending on mode)	0.15-0.2%	0.2-0.3%
Scrubbing chemical consumable	No consumable	Sodium or magnesium hydroxide solution, or sodium carbonate solution	In closed-loop mode only: Sodium or magnesium hydroxide solution, or sodium carbonate solution	Calcium hydroxide granules (≈ 10 kg/MWh %s)	Sodium bicarbonate ($NaHCO_3$) powder (≈ 11 kg/MWh %s)
Compatibility with waste heat recovery system	Yes, provided the scrubber is installed after the waste heat recovery system			Yes, can be placed before or after.	Yes, can be placed before or after.
Compability with SCR system	Only if placed after the SCR			✓	✓
Compatibility with EGR system	✓	✓	✓	✓	✓
Particulate matter removal	✓	✓	✓	✓	✓

Knowledge on closed-loop scrubber pilot projects for marine vessels was still quite limited in 2015, and the implementation of a scrubber on an existing engine raises some limitations about space, weight and ship stability [26]. Some information about expected room space and weight of a scrubber for different engine powers is presented in Table 13 [29]. In-line scrubbers have a lower footprint and often the silencers are simply replaced with the scrubber tower. Moreover, for closed-loop systems using sodium hydroxide, the NaOH solution needs to be at a minimum temperature of 16°C to avoid crystallizing (below 12°C), hence a controlled-temperature room or an insulated membrane with heating system is required for its storage [29]. The necessary space needed for the NaOH tank depends on the sailing time, the fuel sulphur content, the solution itself and the planned bunker period [29].

Nonetheless, scrubbers are rather easy to operate, and solutions can be found to counteract some technical drawbacks. For instance, a fan can be installed on the cold side to reduce the back pressure drop or air can be added to the discharged water to complement its oxygen level [26].

As mentioned previously, scrubbers can be combined with SCR and EGR technologies. However, for the combination of a wet scrubber with SCR, the latter would have to be placed before the scrubber for sufficient exhaust gas temperature (see Table 12). In addition, the degradation over time of the scrubber performances is quite insignificant if properly operated and maintained [29].

Table 13: Examples of typical dimensions of an SOx scrubber for a range of engine sizes (source: [29])



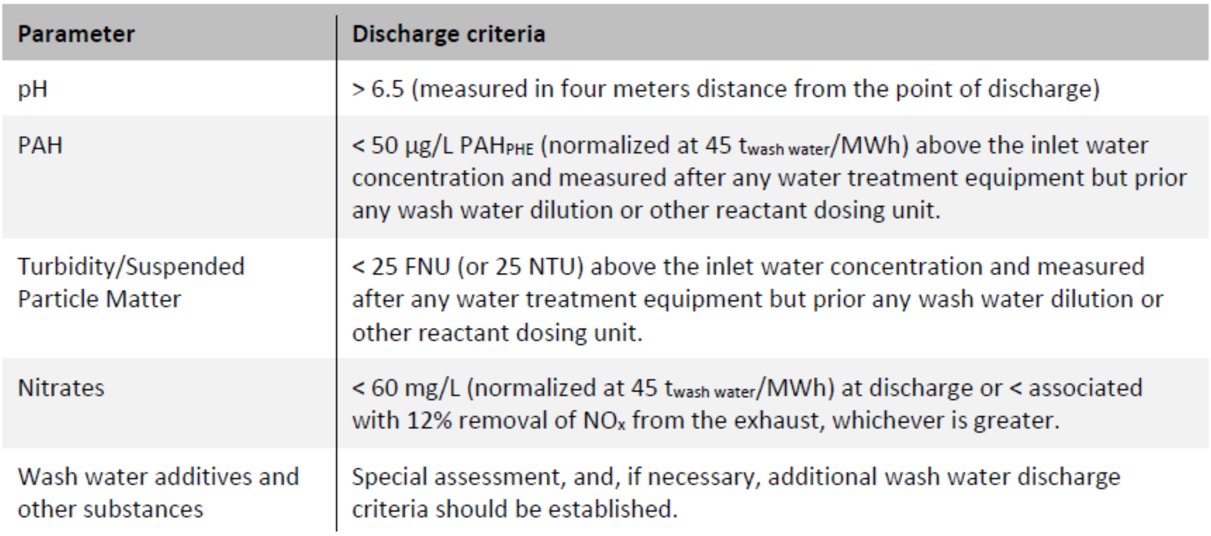
Engine power MW	Width m	Length m	Height m	Weight ton (dry)	Weight ton (wet)	Water inlet DN	Water outlet DN
– 4	2.3	4.0	7.0	6	8	200	250
4 – 8	2.8	4.9	7.8	7	11	250	250
8 – 12	3.5	6.3	9.1	12	18	350	400
12 – 16	4.2	7.4	10.2	18	25	400	450
16 – 20	4.8	8.4	11.2	21	31	450	500
20 – 24	5.5	9.2	12.0	27	39	500	600
24 – 32	6.0	10.5	13.2	35	51	600	600

5.2.3.3. Discharge of washwater

During the use of scrubbers, the SO_2 is not avoided but instead transferred to the washwater, which may contain also heavy metals, PM and polycyclic aromatic hydrocarbons (PAH) [85][89][91]. Thus, due to the increasing use of scrubbers, some guidelines to follow for exhaust gas cleaning system (EGCS) use have been developed in the MEPC 59, lastly updated in 2015 in the MEPC.259 (68), according to Regulation 4.3 of MARPOL Annex VI. The discharging criteria imposed by MEPC.259 (68) concerning the pH, as well as the PAH, suspended PM and nitrate concentrations, are summarized in Table 14 [85]. Moreover, the MEPC intends to revise their guidelines and approved a new output “Evaluation and harmonization of rules and guidance on the discharge of liquid effluents from EGCS into waters, including conditions and areas” for 2021. At the European level, the EU Sulphur Directive (2016/802/EU) refers to the MARPOL regulation. In addition, the EU Directive 2019/883 on port reception facilities for the delivery of waste from ships defines standards for scrubber sludge and bleed-off water.

The washwater discharged from wet scrubbers has low pH and elevated temperatures, and contains sulphur, PAH, heavy metals and nitrate depending on the system, the fuel used, the water treatment and the chemicals added [85][91]. Hence, the high amounts of potentially hazardous washwater being released into oceans raise some concerns. Among them, the ocean acidification caused by scrubber water effluents, in addition of the one already observed due to the uptake of atmospheric CO_2, gains much attention [89].

Table 14: Washwater discharge criteria of the MARPOL 2015 EGCS guidelines, section 10.1 (MEPC.259 (68)) (source: [85])



Parameter	Discharge criteria
pH	> 6.5 (measured in four meters distance from the point of discharge)
PAH	< 50 µg/L PAH_{PHE} (normalized at 45 $t_{wash\ water}$/MWh) above the inlet water concentration and measured after any water treatment equipment but prior any wash water dilution or other reactant dosing unit.
Turbidity/Suspended Particle Matter	< 25 FNU (or 25 NTU) above the inlet water concentration and measured after any water treatment equipment but prior any wash water dilution or other reactant dosing unit.
Nitrates	< 60 mg/L (normalized at 45 $t_{wash\ water}$/MWh) at discharge or < associated with 12% removal of NO_x from the exhaust, whichever is greater.
Wash water additives and other substances	Special assessment, and, if necessary, additional wash water discharge criteria should be established.

In fact, overall pH decrease of about 0.004 to 0.01 has been reported over the Southern North Sea and the English Channel for different maritime traffic scenarios [89][90]. The potential threat of scrubber use has been revealed as the pH change due to open-loop scrubbers is estimated to be 2 to 4 times bigger than the contribution of climate change (about 0.0017-0.0027 pH units per year) when averaged over the whole study area, and up to 10 to 50 times bigger on local levels [89][90].

Another report performed measurements on the different characteristics of the wash water from sea-going operating EGCS in order to assess the potential impacts [85]. The results can be summarized as follows:

- The low or no alkalinity of water effluents combined with the lower pH may decrease the pH of the surrounding seawaters and local acidification can be expected [89],
- Similar suspended PM (SPM) concentrations were observed for open-loop scrubbers but analysis of the composition in sediments, algae, etc. oppositely to ash, soot or other combustion residues should be performed. In closed-loop scrubbers, the SPM concentrations were significantly increased after the EGCS and soot particles were visible,
- The PAH concentrations in the washwater were about 1,000 times higher than the North Sea concentrations, revealing the negative impact of the scrubbing process. PAH levels in the washwater depend on the fuel type, combustion conditions, engine and EGCS performance as well as the amount of washwater,
- Analysing various heavy metal concentrations revealed that vanadium and nickel undergo an important enrichment in the washwater compared to North Sea waters (especially for closed-loop scrubbers, see Figure 21), mostly due to their presence in heavy fuel oils,
- The comparison of on-board measurements of pH, PAHs (in phenanthrene equivalent) and turbidity with ship monitoring revealed that additional efforts are necessary to

provide reliable data and ensure the discharge is not significantly impactful for the environment.

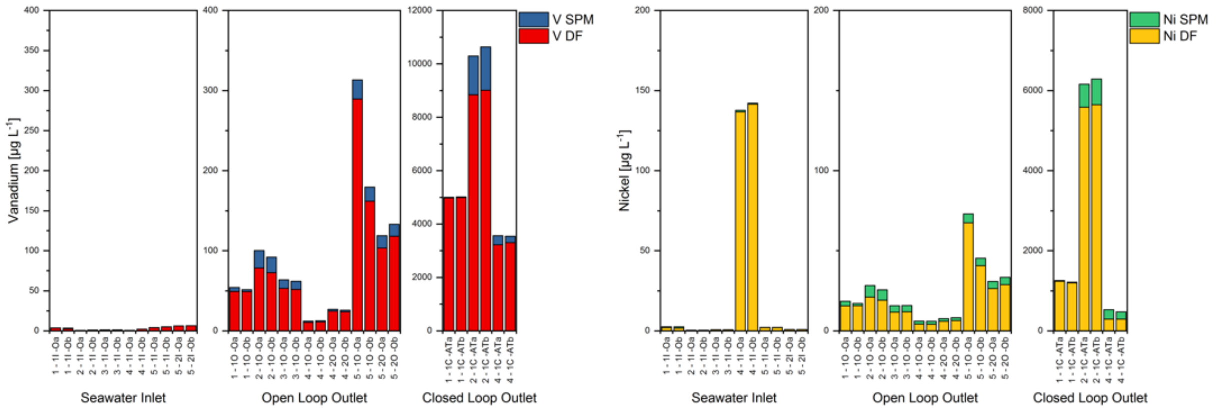


Figure 21: Vanadium (V) and nickel (Ni) concentrations in the dissolved (DF) and suspended particulate matter (SPM) fraction of EGCS washwater at different sampling points (source: [85])

Finally, the modelling of the impact of wash water discharge on the North and Baltic Seas concentrations has been realized over a three-year period [85]. The results revealed seasonal concentration cycles in the North Sea with only a small visible enrichment, whereas pollutant concentrations clearly increased in the Baltic Sea where there is low water exchange [85].

In the light of these findings, several ports, countries or specific areas have banned the washwater discharge in their waters. Among them, China, Singapore, Belgium, Ireland, Latvia, US states Connecticut and California, Pakistan, Bermuda, Malaysia and Oman all banned the discharge of washwater into their port areas and inland waters when applicable [86][91]. The discharge of water effluents from EGCS is also prohibited in other specific areas such as the inland waters and the Rhine for Germany, the Suez Canal in Egypt, the Norwegian fjords or the Panama Canal [86].

Hence, this topic needs further investigation in order to better understand the potential impact of EGCS water effluents on oceans and seas which are highly-frequented trading routes. In addition, IMO also currently investigates the subject to eventually revise the guidelines about the water discharge.

5.3. Summary of the different reduction techniques

The different emission reduction efficiencies of each aforementioned measure, per pollutant, as well as the implied fuel penalties by implementing these techniques, are summarized in Table 15. In summary, the following conclusions can be drawn:

- scrubbers and switches to lower sulphur fuels such as marine diesel oil, marine gas oil, LNG or methanol are efficient techniques to tackle SO_2 emissions,
- a switch to LNG and the implementation of SCR are generally applicable to all marine engines as effective means to reduce NO_x emissions, while EGR is currently only applied to two-stroke engines,
- PM and BC emissions can be significantly cut down with a switch to LNG, methanol or some lower sulphur distillate fuels. Diesel particulate filters are effective, but can be implemented only with good quality distillate/light fuels, and are validated only for high speed engines until now meanwhile the first tests on medium speed engines are

performed. The implementation of baghouse particle filter could be a good option, but are large in size and it may require to be combine with other exhaust gas cleaning systems and need further investigation and test for its implementation in marine applications,

- Improving energy efficiency and moving to alternative non-fossil fuels and propulsion systems would effectively reduce both air pollutant and greenhouse gas emissions.

Table 15: Summary of the reduction efficiencies of all measures and their associated fuel penalties

Reduction techniques :	SO_2	NO_x	PM	BC	fuel penalty	Additional comments
Primary measures: - Switch to low sulphur fuels	up to 97%[1]	-	50-90%	0-80%[2] (median: 30%)	-	
- Switch to LNG	90-100%	64-90%	60-98%	75-90%	- 5-10%	availability limitation for marine applications; increase in CH_4 emissions but CO_2 reduction due to lower carbon content and fuel savings
- Water-in-fuel emulsions	-	1-60%	20-90%	0-85%	+ 0-2%	dependent on injected water amouts; corrosion risk
- Switch to biodiesel and biofuels	-	-	12-37%	38-75%	+ 8-11%	important reductions of CO_2 emissions; limit of cost and availability
- Switch to methanol	100%[3]	55%	99%	97%[4]	+ 9%	important reductions of CO_2 emissions if produced from biomass
- Slow steaming	13-50[5]%	21-64%	18-69%	0-30%	- 15-50%	CO_2 reductions proportional to fuel savings; can require increasing ship fleet for on-time supply
- Slide valves	-	20%	10-50%	25-50%	+ 2%	
Secondary measures: - Exhaust Gas Recirculation (EGR)	-	25-80%	-	0-20%	+ 0-4%	can induce CO and PM emission increases; complex to retrofit on existing engines
- Selective Catalytic Reduction (SCR)	-	70-95%	10-40%	-	0-2%	VOC and CO reduction of both 50-90% if DOC; use of urea, hence increase risk of NH_3 slip
- PM filters	-	-	45-92%	70-90%	+ 1-4%	potential VOC and CO reductions of 60-90% if DOC use; low sulphur fuels required (< 0.5 wt%)
- Scrubbers	90-98%	-	0-90% (median: 14-45%)	0-70% (median: 16-37%)	+ 0.5-3%	NaOH, $Mg(OH)_2$ or Na_2CO_3 solution required for closed-loop and additional storage space; open-loop cannot be operated in some protected areas

[1]: theoretical conversion from a 3.5 wt% fuel to a 0.1 wt% fuel

[2]: only valid for distillate fuels

[3]: methanol does not contain sulphur

[4]: expected achieved reduction (based on drop in particle number)

[5]: not directly reported but proportional to fuel savings

6. Available reduction techniques in ports

6.1. Generic reduction techniques

Incorporating reduction techniques on ships in port areas has been shown to achieve large emission reductions. For instance, the Los Angeles and Long Beach Ports which have decreased their ship-related emissions of PM, NO_x and SO_x by respectively 81%, 55% and 89% between 2005 and 2013 thanks to a reduction strategy [95].

Switching to cleaner fuels, implementing exhaust gas cleaning technologies, hybridising the vessels or adopting vessel speed reduction, as it was presented in chapter 5, are all techniques which are also effective to tackle pollutant emissions in port areas [102]. In the chapter 5, the reduction techniques were discussed for propulsion engines only, but the secondary measure systems may not be available for operating at very low loads. Moreover, the auxiliary engines contribute as much or even greater to the ship emissions in the port areas [95]. Hence, in the situation where the measures implemented concern only the exhaust gases from the main propulsion engines or when it is not available for operation, similar technologies could be implemented for auxiliary engines. In addition, the possibility of providing electricity supply from on-shore power grid and shore-based after-treatment systems are also great options to tackle ship emissions at berth, which are further discussed after [94][95][102].

For the ports and terminals, optimizing the schedule to reduce at-berth time, automated mooring systems and shore-side pumps for bulk liquid unloading operations are available options to reduce the impact of ships [95][102]. For the loading and unloading operations of volatile bulk liquids, a vapor recovery system can be applied in order to drastically reduce VOC emissions (~99% reduction efficiency)[95]. Among the different emission sources encountered in ports, cargo handling equipment can also decrease its environmental contribution by a renewal of the machines with ones compliant with off-road standards, by switching to cleaner fuels and/or by implementing exhaust gas treatment systems [94][102].

6.2. On-shore and barge power supply systems

Shore power, also referred as cold ironing, focuses on reducing emissions of ships while at berth [94][102]. Shore power reduction technique consists of supplying electricity to the vessel in order to turn off the auxiliary engines [94][95][102]. This technique is efficient only if the electricity mix has a low carbon content, hence the generating power plant burns cleaner fuels and/or is equipped with control reduction strategies [96][99][102]. The emissions from the ship exhaust stack are therefore suppressed as the engines are off. In areas where electricity generation is regulated, emission reductions for NO_x, PM, SO_2 and VOC up to 95% have been observed while using on-shore power supply [95]. From port-related assessment studies, the reduction rates observed vary from 62 to 99% for NO_x and from 39 to 90% for PM [96]. In [98], considering the use of MDO at 0.5 wt% S in auxiliary engines and electricity generation made from desulphurised and equipped coal-based power plants at 65.5% and the remaining being made from renewable energies or nuclear power, emission reductions of SO_2, NO_x, PM and CO_2 of 81%, 97%, 77% and 22%, respectively, were observed when implementing shore power [98]. Full compliance with shore power supply has been estimated to decrease in-port emissions of CO_2, SO_2, NO_x and BC by respectively 48-70%, 3-60%, 40-60% and 57-70% for container terminals depending on the country electricity generation [99]. For CO_2, shore-side electricity implementation in Europe has been estimated to reduce emissions by 39%, whereas at local levels, CO2 reductions from 54 to 99% can be observed [96] (99% being in Oslo, Norway, probably due to the low electricity carbon content). If the electricity is made from renewable energies, the potential GHG and pollutant emission reductions are even greater and are near 100% [97][99]. Some challenges about the frequency of the grid, the voltage system on-board, the dynamic or static loading of power, the grounding, the number of connecting points, the berth configuration, the ship possibility to retrofit as well as the electricity cost are raised while considering on-shore power supply system. However, shore power can also have the benefits of reducing the overall port noise and ship vibrations, and implicitly encourage shift to electric or hybrid batteries [96][98].

The best candidates for cold ironing are container ships, reefer ships, and cruise ships because they tend to operate in regular liner-type services and require substantial electricity while at berth [102].

On-shore power technique can also be adapted into barge power supply systems, which provide power to ships at berth as well but this time generated by an engine cleaner than the ship engine. Typically, LNG or alternative fuels can be used into barge power engines [95]. This technology has the advantage of being movable from a berth to another, contrary to on-shore power grids, as well as it does not require space to be implemented on the dock [95]. The same limitations as for on-shore power raise on the ship part. The emission reduction rates achieved depend on the engine, fuel and post-treatment technology used for the power barge compared to the ship auxiliary engine. However, assuming a LNG powered Otto Cycle engine, emissions reductions up to 80% for NO_x, 98% for PM, 100% for SO_2 and 30% for CO_2 can be expected [95].

If the power supply system cannot provide all the needed power and the auxiliary engines need to be kept on, other alternative technologies such as external exhaust gas cleaning systems can be used [94][95].

6.3. Shore- or barge-based exhaust cleaning systems

Other systems such as shore- or barge-based exhaust scrubber system, which can be attached to the vessel exhaust stack, can be used at berth to filter pollutants [94][95][102]. These systems collect ship stack exhaust gases using special ducting and treat the emissions from both the ship and itself in shore/barge-based emission control units which include exhaust gas scrubber in combination with SCR [95]. These systems are intended to achieve emission levels similar to the ones using on-shore power supply systems [95]. It has been estimated that it could achieve emission reductions higher than 85% for NO_x, SO_2, PM and VOC [95]. The emission reduction rates for PM and NOx applying this technology are estimated to be about 98% and 95%, respectively [98]. This technique has the advantage of requiring no specific modification from the ships compared to on-shore power systems, and barge systems can operate either at anchorage or at berth [95]. The limitations to this technology deployment can be the port and berth configurations, the terminal space and the eventual interferences with the loading and unloading operations [95]. This technology is not yet fully mature and needs to be further investigated in order to show its effectiveness at various exhaust loads [95].

7. Summary of costs for emission reduction

In this section, estimations of costs and investments needed to set the aforementioned reducing techniques up are presented. When the prices are only given in dollar, the conversion rate of September, 2020 will be used to give indicative prices, which is 0.8504 €/$.

7.1. Fuel switch

One of the simplest options to decrease simultaneously several pollutant emissions such as NO_x, SO_2, PM, and eventually other substances such as VOC, is switching original, high-sulphur content fuels such as residual fuel oils for lower sulphur fuels such as distillate oils, or LNG or for alternative fuels such as methanol or biofuels. However, this fuel switch often comes with a certain investment as heavy fuel oil is often privileged for its relative low costs compared to other fuels.

7.1.1. Low-sulphur fuel oils

Based on prices from Purvin et al. [46], the costs for changing from high sulphur residual oil to low sulphur distillates with 0.5 and 0.1 wt %s are respectively 106 and 223 €/t (in € of 2005) [40], based on European standards for prices expected after 2020 and taking into account investments necessary to meet the demand for low sulphur fuel due to the new regulation. These costs are slightly higher than in [24] where they were estimated to be around 88 €/t and 126 €/t to switch to 0.5 and 0.1 wt %s, respectively. In [25], the price differences used in the projection scenarios from heavy fuel oil with 2.7 wt %S to marine gas oils with 0.5 and 0.1 wt %S are of 157 and 176 €/t (in € of 2015). In a more recent study, the differences of price in 2019 between a 0.1 %S oil and a traditional bunker fuel oil one were about 150-300 $/t [8][47], so about 128-255€/t using the current Euro-Dollar conversion rate.

In September 2020, now the MARPOL Annex VI regulation is in place, the global average bunker prices of MGO and very low sulphur fuel oil (VLSFO, which is a mix between various residual and distillate fuels) are 478 $/t and 367 $/t [71], so about 406 and 312 €/t (with 0.8504 €/$). In comparison, higher sulphur-content fuels such as IFO380 have current average global prices of 320.5 $/t (i.e., 272.6 €/t) [71]. These prices can vary depending on the market situation, the region of the world and the port where it is bought from.

This volatility is a challenge for the installation of capital-intensive solutions and could lead to very short-term view decision.

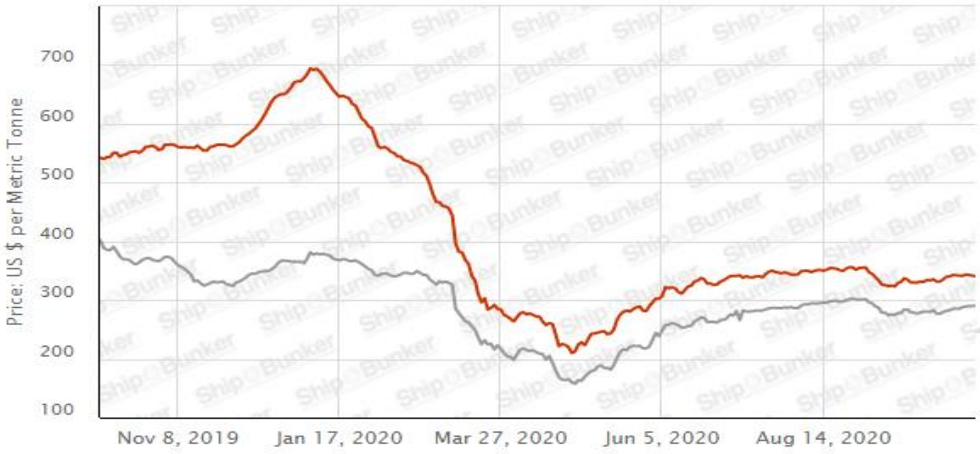


Figure 22: Spread evolution between LSFO and HFO in 2019-2020

7.1.2. LNG

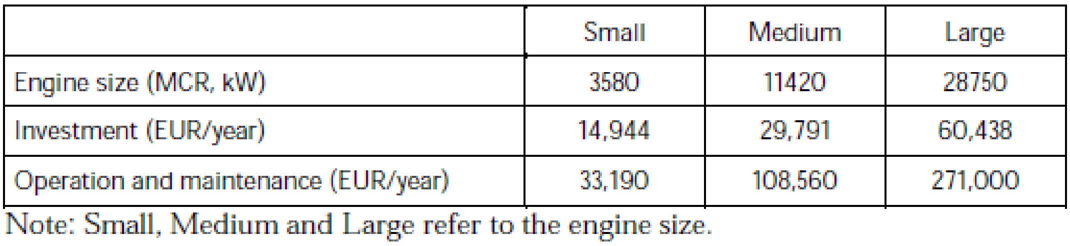
LNG is another option to cut down significantly pollutant emissions. In terms of fuel price comparison, the switch to LNG is estimated to have a positive impact on fuel costs of about 8% smaller per GJ than gas oil [55] or about 50 $/t (i.e., 43 €/t) less compared to heavy fuel oil [32]. Compared to other types of ship, the additional original investments for a LNG newbuild ship are about 10-20% of the total building cost, principally due to the sophisticated LNG storage tank, the fuel piping system and the additional safety measures [55][62], which corresponds to about 1-5.5 M$ (i.e., 1.3-4.3 M€) for installing engines. Investments costs for LNG engines have been reported to range from 219 to 940 €/kW for newbuild engines whereas they vary from 391 to 1603 €/kW for existing engines [25] while capital costs of 450 $/kW (i.e., 383 €/kW) are used in [58]. Another study estimated the investment costs for low and high pressure dual fuel engines to be around 625-675 €/kW [48][51]. Based on pilot projects, the additional costs of a new LNG marine engine were estimated about 745 €/kW [55]. The average additional investment costs for LNG engines over 6 MW are estimated to be about 600-710 €/kW for newbuild engines and 710-900 €/kW for retrofits [77]. For smaller engines (< 6 MW), the additional capital costs are estimated to range from 1300 to 2400 €/kW, with 1800 €/kW on average [77]. One study uses required additional investments for LNG engines which correspond to the upper end of the ones in other references, varying from around 1079 to 1500 €/kW [61].

In terms of operational costs, LNG engines do not require extra additional costs compared to engines running on conventional fuel oils, and some savings on fuel consumption of about 5-10%, corresponding to 2.5-5 g/kWh, are even achieved with LNG engines [62].

7.1.3. Water-fuel emulsions (WFE)

WFE is an effective means to tackle conjointly NO_x and PM emissions. Cost estimates for installing this technology are about 250,000 $ (i.e., 213,000 €) for the equipment and its installation on a main engine of a typical container ship, whereas lower capital costs of about 100,000 to 150,000$ (i.e., 85,000-128,000 €) can be expected for auxiliary engines [53]. The investment cost for WFE is estimated to be about 16 €/kW in [77]. One review study assesses the price for an engine power of 40 MW to be 13 $/kW (i.e., 11 €/kW) without retrofitting, and for retrofits to be 27 $/kW (i.e., 23 €/kW) without off-hire and 52 $/kW (i.e., 44 €/kW) with off-hire [35]. Another study reports equipment costs depending on the engine size, which vary from 100 k€ to about 430 k€ for engine powers of 3,580 kW and 28,750 kW, respectively [55]. Considering the fact that injectors have a lifetime of approximately 4 years whereas the rest of the equipment have an average lifetime of 12 years, they revealed the annualized costs of investment and operation and maintenance to vary as follows depending on three different engine sizes:

Table 16: Total annual investment costs of WFE retrofit in 2-stroke engines (source: [55])



	Small	Medium	Large
Engine size (MCR, kW)	3580	11420	28750
Investment (EUR/year)	14,944	29,791	60,438
Operation and maintenance (EUR/year)	33,190	108,560	271,000

Note: Small, Medium and Large refer to the engine size.

In terms of pollutant emission abatement, the investments to reduce NO_x emissions are estimated to vary from 1,260 to 1,360 €/t NO_x [55]. Finally, other costs related to the eventual additional fuel consumption need to be taken into account.

7.1.4. Methanol

A fuel switch to methanol enables large reductions of SO_2, PM and NO_x, while the fuel price of methanol made from natural gas were similar to marine gas oil (MGO) on an energy basis but are recently higher by 10-15 €/MWh (see Figure 23)[70]. However, these prices are based on the producer Methanex but only a few applications of methanol as a marine fuel have been realized, thus it does not represent price information as supply of a bunker fuel [70]. Production costs of renewable methanol are estimated to be higher than methanol from natural gas.

The overall project costs to implement a 24 MW methanol engine in a RoPax Ferry conversion from Stena Line were of 22.5 m€ [78]. The additional investment costs are estimated to be about 150-225 €/kW for newbuild engines and 225-450 €/kW for retrofits [77]. The operational and maintenance costs are estimated to vary from 2.7 to 4.1 €/MWh [77]. In [80], the additional costs for a 24 MW methanol engine are about 5.6 m$ for newbuilds (~ 4.8 m€) and 10.5 m$ (~ 8.9 m€) for retrofits [80], which equals to about 200 €/kW and 371 €/kW.

The operating costs other than the fuel price for switching from diesel fuel to methanol are the supply of nitrogen as inert gas blanket in the methanol tank as well as the staff training on hazards [70]. Additional pilot projects will be required to have more robust cost data for methanol [70].

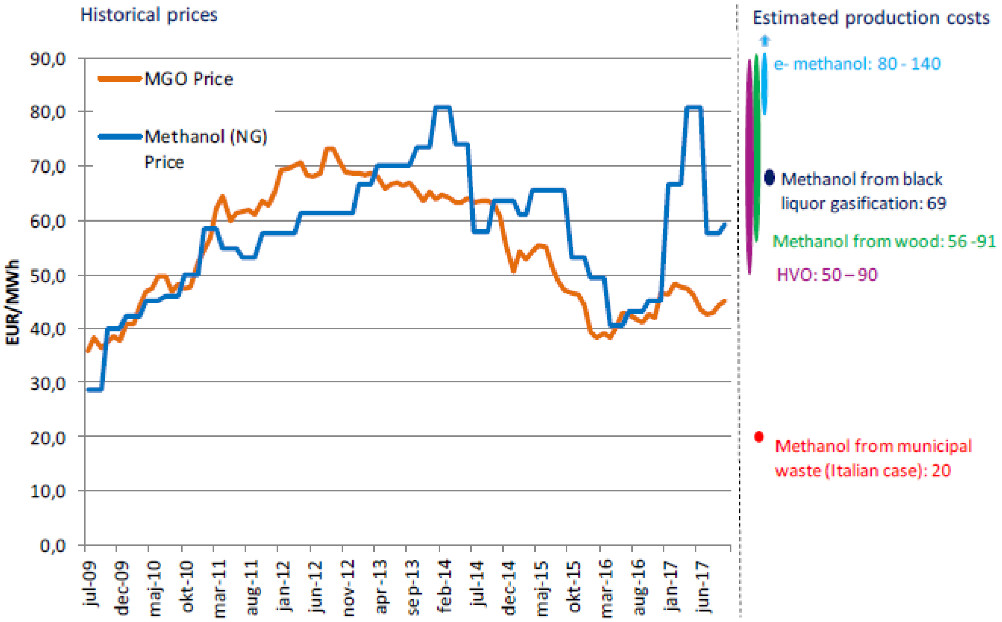


Figure 23: Historical prices for MGO and methanol produced from natural gas between July 2009 and June 2017. Estimated production costs for renewable methanol (Source: [70])

7.2. Slide valves

Replacing common fuel valves by slide valves is a good way of reducing PM and NO_x emissions, especially on old marine engines, but it comes with a cost. Including incremental costs, installation costs and retrofitting for old engines. It has been reported that the valve cost could be about 270 $ per valve (i.e., 230 €), while the labour costs are about 400 $ (i.e., 340 €), leading to cost estimates of about 0.39 to 1.68 $/kW (i.e., 0.33-1.43 €/kW) for slide valves [53]. However, contrarily to other reducing techniques, the operational and maintenance costs are assumed to be null for slide valves [53].

7.3. SO_x Scrubbers

One alternative to the use of low sulphur fuels is the use of scrubbers. The economic resources required to implement scrubbers are rather costly and vary from about 0.5 to 10 million $ (i.e., 0.4 to 8.5 million €) depending on the operating conditions and the achieved emission rate [8][26][42].

Assuming the scrubber system operates with a 2.94 wt %s residual oil to achieve emission levels equivalent to the use of a 0.1 wt %s, the investments necessary to set a new scrubber up were estimated to be about 100 and 200 €/kW for respectively open- and closed-loop scrubbers [40][47]. If the scrubber is retrofitted on an existing engine, the estimated costs of investments are double compared with a setup on a new engine (200 and 400 €/kW) [47]. These capital investment costs are comparable with other studies where open-loop scrubbing system capital investments are estimated to be about 122 €/kW and 156 €/kW for new and retrofit scrubbers [49], respectively, or between 118 and 168 €/kW for newly designed system in **Erreur ! Source du renvoi introuvable.**[50]. One study estimated the costs of installation of a scrubber (of an unknown type i.e., can be open- or closed-loop system) to be 180 €/kW for newbuild engines and 225 €/kW for retrofits [51] whereas another study reported total investment and installation cost of a retrofitted closed-loop scrubber to be 363 €/kW [52]. In [61], investment costs for new and retrofitted scrubbers around 108-120 €/kW and 138-216 €/kW, respectively, are used for

open mode whereas, for closed-loop scrubbers, they are about 216-278 €/kW and 290-433 €/kW, respectively. The operating and maintenance costs during the lifetime of the scrubber are estimated to be about 2-3 % of the total investment for both open- and closed-loop systems, assuming an operating time of 4,000 hours [40][47][49], or about 3% of the main engine energy consumption [54]. Aggregated investment plus installation costs of about 300 €/kW and 375 €/kW are used for newbuild open and closed mode scrubbers in [48]. The maintenance costs are estimated to be about 0.25 €/MWh [48] or 0.4-1.0 $/MWh (0.3-0.9 €/MWh), corresponding to about 1-4% of the annual capital costs [58]. In [77], the maintenance costs are estimated to be about 0.3-1.2 €/MWh for closed loop scrubbers and 0.6-0.9 €/MWh for open-loop ones.
A report from IIASA [24] estimated the investment costs of a hybrid scrubber to be around 225 and 338 €/kW for respectively new and retrofitted scrubbers [24][48]. The operating and maintenance costs of a hybrid scrubber depend mostly on the time spent in open and in closed modes. Investment and operational costs required to use a scrubber are summarized in Table 17.

Table 17: Costs of implementation and operations of scrubbing systems

	unit	hybrid [24]	open-loop [40][47][48][49]**Erreur ! Source du renvoi introuvable.**[61]	closed-loop [40][47][61]
capital investments:				
new scrubber	€/kW	225	100-168	200-278
retro-fitted scrubber	€/kW	338	138-216	290-433
operational costs:		[24]	[40][47][48][77]	[40][47][48][61][77]
NaOH price	€/l	0.55	-	0.5-0.6
NaOH use (2,4 to 0,5)	l/MWh	10.3	-	6
NaOH use (2,4 to 0,1)	l/MWh	13.2	-	15
NaOH use (0,5 to 0,1)	l/MWh	1.28	-	12
water price	€/t	20.3	-	22
water use	l/MWh	100	-	100
sludge disposal	€/l	0.09	-	0.1-0.12
sludge volume	l/MWh	0.2	-	1.3
fuel penalty	%	1 (closed) 2 (open)	1-3	0.5-3
fuel cost	€/t	n.d*	307	307

*: n.d for “not determined”, meaning no specific information is given for this parameter

The total costs for the retrofit installation of a Hybrid-Ready scrubber on a Cape Size BC (20 MW) were about 2.5-2.6 m€ (including off-hire, installation, equipment, class and naval Architect), which equal to 125 €/kW. The water treatment retrofit cost about 1 m€ for the closed-loop part, which increases the overall cost to 175 €/kW. Most scrubbers may use sea water instead of fresh water, even in closed-loop mode. The NaOH (50% solution) consumption equals to 4.5-5 liters per % sulfur per MWh. The sludge disposal is also estimated to be between 300 and 900 €/ton.

In general, it was revealed that open-loop scrubbers or hybrid scrubbers operating in open mode require investments lower than the operational costs for changing to low sulphur fuels [24][40]. One limitation to the scrubbers could be the availability of residual fuel oil in ports in the future which could become a rather rare fuel [24].

Moreover, it is not always straightforward to estimate investments costs of scrubbing systems, and the prices per unit power of engine (i.e., kW) can vary based on the range of output engine powers as it can be observed from Figure 24. In addition, the capital investments for an open-loop scrubber implementation are estimated to be vary about 210, 290 and 780 €/kW for > 15 MW, 6-15 MW and < 6 MW ships [77]. For closed-loop, for the same power ranges, the investments change to 320, 390 and 1,090 €/kW, respectively [77].

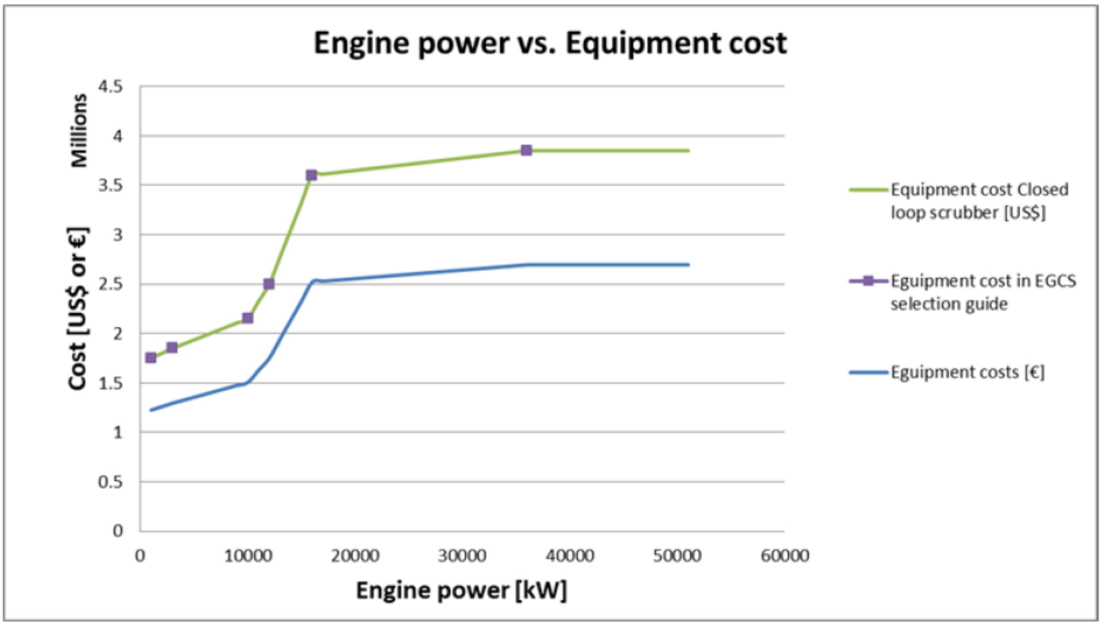


Figure 24: Costs of closed-loop scrubbers depending on the engine power (source: [59])

7.4. PM filters

One common way of reducing PM emissions from mobile sources is the use of diesel particulate filters (DPF). For the application to marine engines, information about costs and pilot projects is rather scarce [40][55].

Some investment costs for filters in marine applications were estimated based on the performances of the Nauticlean S technology developed by Hug Engineering [54], which consists of two reactors with a SCR and a catalytically coated silicon carbine (SiC) PM filters, equipped with a diesel full-flow regenerative burner achieving up to 99% of PM reduction (supposedly for the solid fraction only, not the volatile compounds)[40]. The investment costs of newbuild and retrofitted DPFs are revealed to be respectively around 30 and 45 €/kW [24][40]. In [77], the investment costs are estimated to vary from 30 to 63 €/kW for newbuilds and from 54 to 130 €/kW for retrofits, which correspond to average values found in [84]. The operational and maintenance costs such as an increase in fuel consumptions need to be considered and are estimated to be about 1-4% in fuel penalties [53][55][77], although, for low sulphur fuels, they are estimated to be rather low [40]. No solution for residual fuels exists, and also with distillate fuels there is no long-term experience with DPFs on large marine engines.

7.5. EGR

Exhaust gas recirculation (EGR) system is an efficient technique to reduce NO_x emissions down to levels compliant with IMO Tier III. The costs of installation and hardware of EGR technology vary from about 0.3 to 2.5 M€ depending on the application (see Figure 25) [26][55][56].

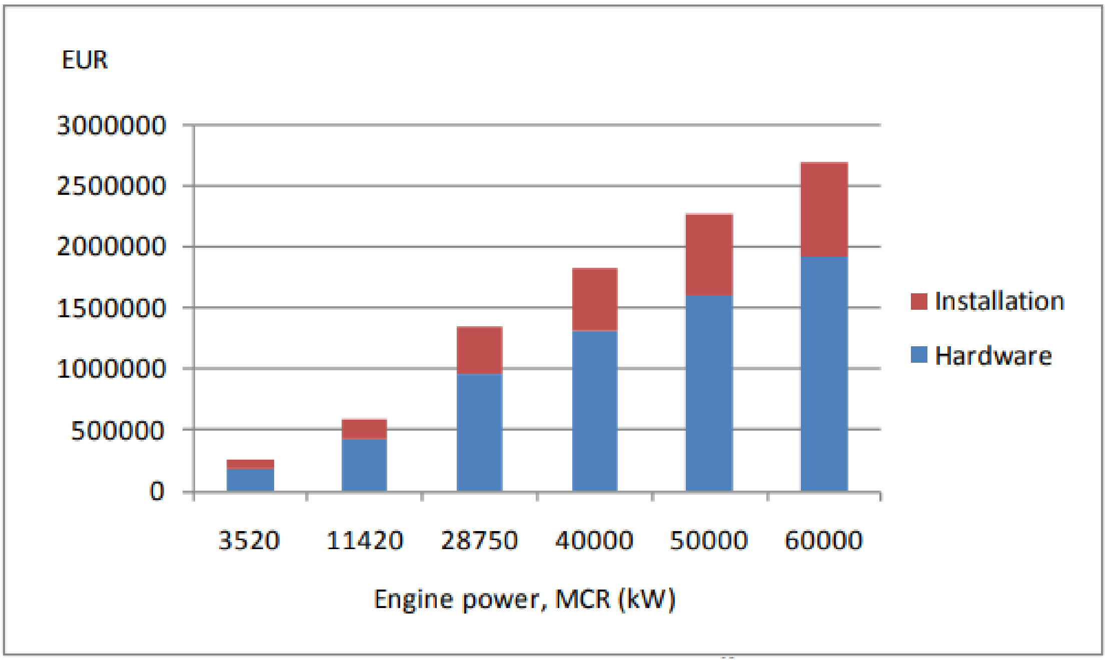


Figure 25: Cost of installing EGR NO_x reduction systems, depending on the engine power (kW) (source: [55][56])

As it can be observed from Figure 25, the highest contribution to the investments is due to the hardware. For a 60 MW engine, the total cost of installation is estimated to be about 2.7 M€, corresponding to about 45 €/kW [55][56]. This investment cost is comparable with the range given in [57][60][62][77] where it is estimated to be between 36 and 60 €/kW. The operational costs of an EGR system, depending on which type of Tier the engine complies originally with, are presented in Figure 26 [55][56], which corresponds to 16.7 €/kW for Tier I engines and 25 €/kW for Tier II engines, or to around 3% of the annual fuel consumption cost [55]. According to [57], the operational and maintenance costs can be estimated to be about 1.34-2.10 €/MWh. The difference in operating costs between Tier I and Tier II engines is due to the fuel consumption difference [55]. An average fuel penalty of about 1-2% of the annual fuel consumption is possible due to the implementation of EGR [26][60][77], which corresponds to prices about 0.20-0.24 €/MWh [57]. However, this fuel penalty can be compensated by the fuel savings achieved by downgrading an engine from Tier II to Tier I [55].

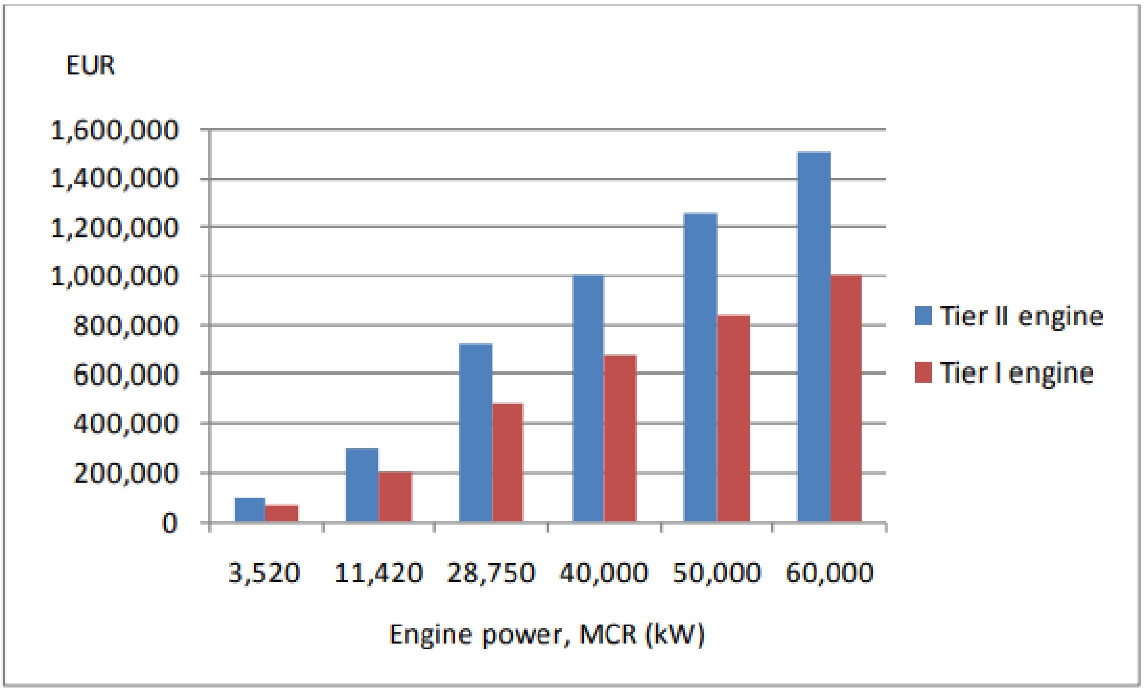


Figure 26: Total annual operational cost of EGR system on existing ships (source: [55][56])

7.6. SCR

Selective catalytic reduction (SCR) systems are a well-known and widespread reducing technique in the industry and its use in marine vessels to tackle NO_x emissions and achieved IMO Tier III levels is in constant increase [25].

In the literature, the initial investment costs necessary to implement a SCR are estimated to range from 19 to 103 €/kW for newbuild engines and from 24 to 97 €/kW for retrofits [25][57][60]. These figures are of the same order of magnitude as the costs presented in [63], varying from 20.5 to 107.5 €/kW, without further notice if it is for new or retrofitted engines. Similar capital investments were observed in other studies where cost analyses are developed. In [77], the installations costs are about 53-78 €/kW for newbuild engines and 53-80 kW for retrofitted engines. In [26], initial costs of about 37 €/kW are presented for a 10 MW engine, based on the cost-analysis tool of IACCSEA, whereas [61] applied an initial investments of 67 €/kW. The capital costs for implementing a SCR used in [40] are of 49.3 €/kW for a new engine and 74 €/kW for retrofitted systems, whereas values of 62 and 93 €/kW are used in [24], respectively for new and retrofits. In addition, distinguishing the engine type, capital costs ranging from 28 to 56 €/kW and from 25 to 62 €/kW were estimated for two- and four-stroke engines, respectively [62]. Finally, the investment costs also depend on the engine power size and they are revealed to vary from about 72, to 73 and to 53 €/kW on average for < 6 MW, 6-15 MW and > 15 MW engines, respectively [77].

The operating and maintenance costs of a SCR are estimated to be around 4.3-10 €/MWh for two-stroke engines and around 2.7-7.2 for four-stroke engines [62]. Among the operational costs, the main contributors are the replacement of the catalyst, the consumption of urea and the labour. In the literature, the costs for catalyst replacement range from 0.25 to 0.92 €/MWh, while the annual labour prices are estimated to vary from 256 to 405 € [24][25][57][55][60][61][77]. For the urea use, the urea consumption is estimated to be about 6.5-16.5 kg/MWh and the costs vary between 166 and 310 €/t (i.e., from about 1 to 5 €/MWh)

[24][25][57][60][61]. The maintenance costs are estimated to be about 1.2% of the investments [25]. The information about operational and investment costs are summarized in Table 18.

Table 18: Costs of implementation and operations of SCR

		[24][25][40] [55][60][61]	[62]	[62]
	unit	Generic (average)	Two-stroke	Four-stroke
Capital investments:				
new SCR	€/kW	19-100	28-56	25-62
retrofitted SCR	€/kW	24-97		
Operational costs:		[24][25][55] [60][61][63][77]		
catalyst replacement	€/MWh	0.25-0.92		
urea price	€/t	170-310		
urea consumption	kg/MWh	6.5-16.5		
labour price (based on use of 8 h/year)	€/year	280-405		
maintenance	%	1.2		
fuel penalty	%	0-2		

*: n.d for "not determined", meaning no specific information is given for this parameter

However, the investment costs of SCR may vary with the output power of the engine and, for instance, for 4 stroke engines, it was observed that the higher is the engine power, the lower are the capital costs (see Figure 27)[62].

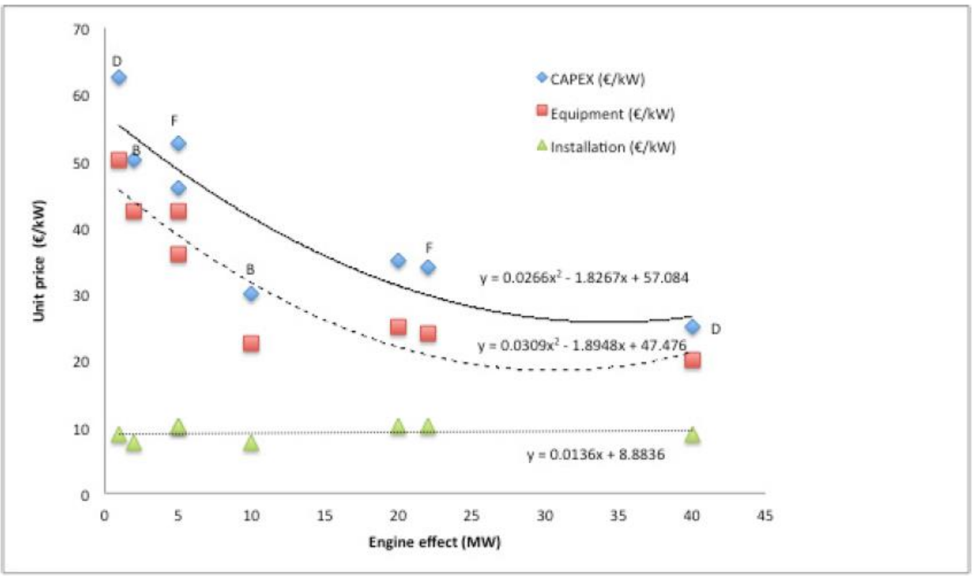


Figure 27: Installation cost of SCR technology to MW installed in newbuild 4-stroke engines. For installations larger than 40 MW, no prices were supplied. Letters denote data from different manufacturers. (source: [62])

7.7. Slow steaming

Finally, slow steaming, which consists of reducing the sailing speed of ships, is a great way of reducing emissions of pollutant and improve company's profitability, and following the economic crisis this has become an increasingly widespread technique [33][40]. The main investments related to slow steam implementation are mostly related to the eventual need of tuning the engine and the efficiency of delivering the goods. Indeed, as the ships go slower, a higher number of ships is needed to achieve the same supply of goods.

If no overcapacity is considered, it can be assumed that a decrease of speed by x% will result in a need of [1/(1-x)-1] additional active ships [65]. Therefore, a reduction of 25% in speed will conduct to an extra need of 33% of the ship fleet. One simple example was developed by the authors [65]:
- considering a fleet of 3 ships of the same type, making 12 trips of 1,000 km per year, each transporting 1,000 tons per voyage and sailing at 40 km/hour on average: the overall productivity would be 36 million ton.kilometers per year and each ship would sail 300 hours a year,
- if the speed is decreased by 25% (i.e., 30 km/hour), a ship would need 33% more time for one trip: then, one ship could only make 9 trips in 300 hours and the productivity of the fleet would go down to 27 million ton.kilometers per year,
- hence, 4 ships instead of 3 ships would be necessary to achieve the same fleet productivity, implying an additional investment for purchasing or renting the required extra ship. This additional ship hence diminishes the overall emission reductions achieved for the original fleet of three ships.

Considering the fact there is a current overcapacity of the European fleet, which means there is no need to enrol new ships in the fleet to compensate the loss of productivity, one study analysed the savings in European seas if slow steaming is imposed in 12 nm or 200 nm zones [40]. Using fuel costs of 413 €/t for fuel with 0.5% S (non SECA) and 530 €/t for fuel with 0.1% S (SECA) [46], imposing slow steaming in the 12 nm zone in the EU implies savings up to 276 M€ and

410 M€ in 2020 and 2030, respectively [40]. If the reduced sailing speeds are imposed up to the exclusive economic zone (EEZ, i.e., 200 nm zone) in the EU, the potential savings increase up to 2,892 M€ and 3,447 M€ in 2020 and 2030, respectively [40]. These results present only the benefits from fuel savings but not the eventual issues such as the additional operational and maintenance costs, the necessity to increase the vessel fleet or the possible issues with delivering times [40]. Another study revealed that, for a 4,000 twenty-foot equivalent unit (TEU) ship, reducing the speed from 23 to 17 knots reduce the bunker contribution to the total operational costs from 68% to 51% for fuel oil (IFO 380) and from 77% to 62% for marine gas oil (MGO) [66]. Lack et al. [35] revealed that average fuel oil cost savings of 42% and 45% are achievable respectively without and with a rated engine [33]. However, the engine conversion to electronically controlled engine is costly, and the conversion from 6S50MC-C motor of 9,480 kW to a 6S50ME-B motor with the same effective power is estimated to cost 84 $/kW (i.e., 71 €/kW) [35]. The capital investments are expected to decrease by 45-50% if electronic engines are already installed [35]. Theoretically, reducing the speed from 23 to 18 knots is expected to cut more than 50% [32]. A speed reduction of 10% has revealed to induce a fuel saving of 15-19% while a 20% speed decrease implies savings of 36-39% [67]. Considering the need of additional vessels [66], it was revealed that it is more economic to decrease the sailing speed of 4 knots and more (from 23 to 19 knots and less) with four vessels running on MGO than operating with three vessels at 23 knots (see Figure 28)[66].

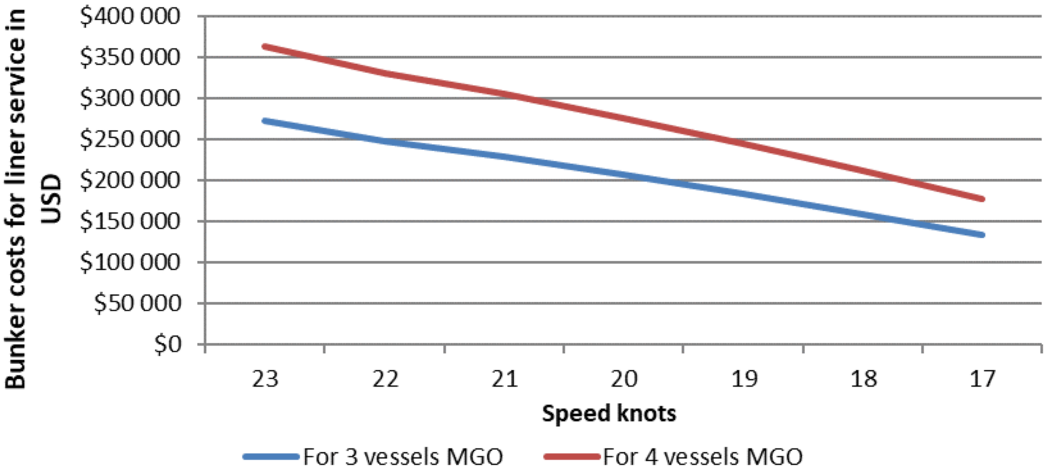


Figure 28: Daily fuel costs (USD) at different speeds (17-23 knots) for 3 and 4 vessels, running on marine gas oil (source: [66])

7.8. At berth reduction techniques

The most expensive component to cold ironing is the shore-side infrastructure. Typically, it must include: power connection to the utility grid, underground electrical vaults, power converter/transformer and land for the facility, receptacle pits, receptacles, cabling, synchronization equipment and wharf infrastructure [94][102]. Considering the cold ironing infrastructure prior to the port building reduces the costs [102]. Based on several feasible studies done by US and Canadian ports, the costs to provide shore power at a berth vary between 1 and 15 m$ (about 0.85-13 m€)[94][102]. In [95], some investments for shore power systems are reported for different US ports: 180 m$ (about 153 m€) for Los Angeles port for 25 container and 3 cruise berths, 185 m$ (about 157 m€) for Long Beach port for 12 container berths, 70 m$ (about 60 m€) for Oakland port for 11 container berths, 4.25 m$ (about 3.6 m€) for San Diego port for one cruise berth or 19.3 m$ (about 16.4 m€) for a 14 MW cruise berth for the port authority of New York and New Jersey. For the ships, the vessel retrofit costs for implementing shore-power connection are about 0.5-1.1 m$ (about 0.4-0.9 m€) [95][101]. In [102], these costs are estimated to be about 0.4-2m$ (about 0.3-1.7 m€) depending on the ship design but they are decreasing as the retrofitting knowledge increases. The cost for retrofitting shore-power onboard of a small Ro-Ro vessel with an auxiliary power of 6,000 kW and an engine load at berth of 30% is estimated to be of 0.4 m$ (about 0.34 m€) [100]. If the vessel travels four times a week between two ports in SECAs, equipped with on-shore power supply systems, the payback period is estimated to be between 4 and 20 years [100]. These costs are only necessary in case of retrofit, nowadays on-shore power supply is installed on most of newbuild ships.

Other temporary solutions which use large, portable LNG generators placed on the dock near the front of the ship and connect to a ship's bow thruster electrical circuit are possible and cheaper [102]. These systems require about 0.2 m$ (i.e., 170,000 €) to refit each ship and approximately 1,000 $ (about 850 €) per hour for the generator [102].

In the light of the implementation of the 0.1 wt% sulphur limit at berth in EU ports, the assessment of implementing shore-power at different levels of magnitude compared with the use of ultra-low sulphur fuel oil (ULSFO) for the Piraeus Port (Greece) is shown in Figure 29 [101]. In this study, the external costs are related to the pollution effects on populations (e.g., morbidity and mortality) as well as the acidic effects of SO_2 on materials and the effects of NO_x on arable crop yield, whereas the private costs concern the port or the ship companies for the consumption of fuel or electricity as well as the investments related for the use of shore-power. The private costs of the different scenarios implementing shore-side power are all higher than the use of ULSFO, however the overall costs considering external costs are significantly higher in the case of a switch to ULSFO [101]. This shows the interest of governments and local authorities to help ports and ship companies to implement on-shore power supply systems.

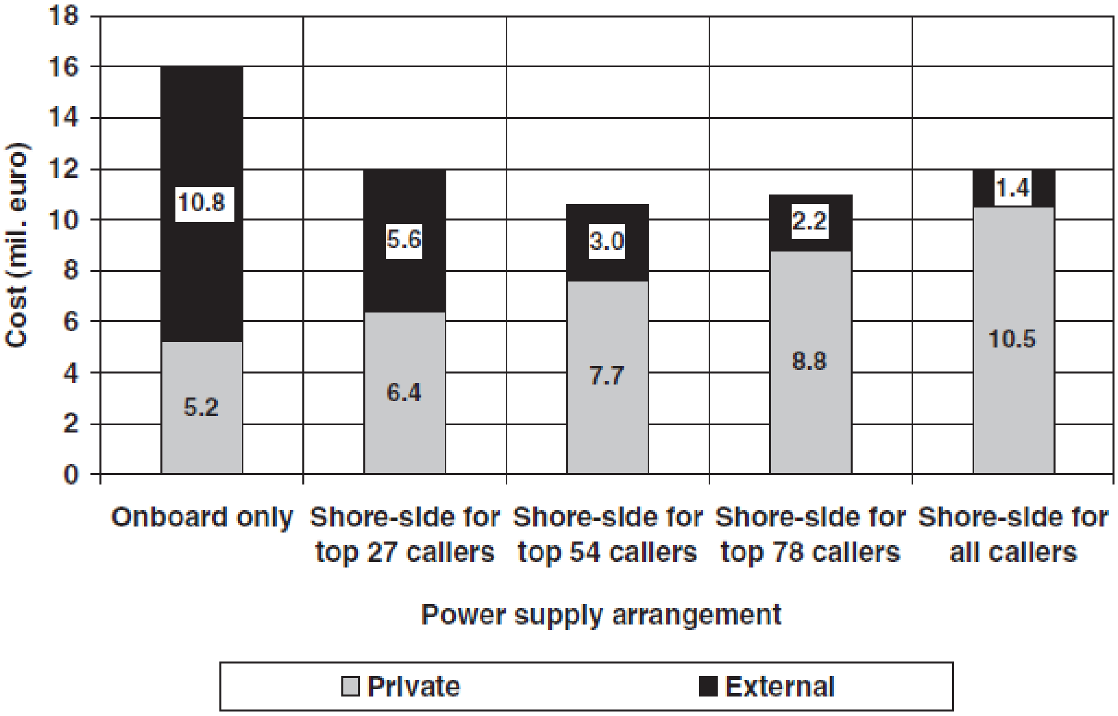


Figure 29: Cost assessment for the Piraeus port (Greece) between the switch to ultra low sulfur fuel oil with 0.1 wt%s ("Onboard only") and the implementation of shore-side power at different levels (source: [101])

Cost estimates on alternative barge-based scrubber systems are still rather scarce, but one manufacturer estimated that each system costs about 8 m$ (about 6.8 m€) when dozens of systems are built [94].

8. Conclusions

In this technical document, the different reduction techniques of pollutant emissions available for marine shipping are presented as this activity represents a large source of pollutant emissions, at sea as well as in port areas. The different reduction efficiencies are also provided in order to evaluate how ships can change and be equipped to reduce emissions of pollutants and comply with new regulations, and eventually upcoming stricter rules. The available reduction techniques are reviewed with their different characteristics, their emissions reduction efficiencies, their limitations, their advantages and their drawbacks. Globally, the main findings are as follows:

- Scrubbers and switches to lower sulphur fuels such as marine distillate fuels (diesel or gas oil), LNG or methanol are efficient techniques to tackle SO_2 emissions,
- A switch to LNG and the implementation of SCR are effective means to reduce NO_x emissions, followed by EGR,
- PM and BC emissions can be significantly cut down with switch to LNG, methanol or some lower sulphur distillate fuels. Diesel particulate filters are effective but can be implemented only with good quality distillate/light fuels, and are validated only for high-speed engines until now, meanwhile the first tests on medium-speed engines are being realized. In addition, SO_2 scrubbers can also reduce the PM and BC emissions to some significant extent,
- Improving energy efficiency and moving to alternative non-fossil fuels and new emerging propulsion systems would also effectively reduce both air pollutant and greenhouse gas emissions,
- On-shore power supply system at berth can reduce significantly the emissions of pollutants and GHG from ships during hoteling. Shore- or barge-based exhaust gas cleaning systems also provide significant emission reductions and require no specific ship modifications but as yet to be further proven.

Finally, a cost-analysis is realized in order to assess the necessary investments to implement each reduction technique. The following table summarizes all this information, separating primary and secondary techniques. The direct comparison of the operational and maintenance costs is rather complex as they are expressed in different units. It should be noted that the variety of engine size (100 kW-100 MW) and technical solutions in marine vessels is remarkable, and also the efficiency and costs of emission reduction solutions can vary depending on these. Some of the referenced reports are from the time when the technologies have been under development and therefore include uncertainty in cost estimates for full scale installations. In general, costs of technologies are expected to decrease with technological developments and increasing demand. However, it is observed that switching to LNG or installing a scrubber are the most costly options, which can be justified by their relative high efficiency in reducing emissions. A switch to LNG is the most expensive operation but this can be balanced with the operational and maintenance costs where savings can be realized. Besides a switch to low sulphur fuels or biofuels where low or even no investment costs are required, installing slide valves is the most economic technique (with no operational and maintenance costs) but its emission reduction efficiencies are rather low compared to other techniques.

Reduction techniques :	SO_2	NO_x	PM	BC	fuel penalty	Investments costs (€/kW)	Operation & maintenance costs
Primary measures:							
- Switch to low sulphur fuels	up to 97%[1]	-	50-90%	0-80%[2] (median: 30%)	-	-	88-223 €/t fuel
- Switch to LNG	90-100%	64-90%	60-98%	75-90%	- 5-10%	219-1603	- 43 €/t fuel (+ fuel savings)
- Switch to water-in-fuel emulsions	-	1-60%	20-90%	0-85%	+ 0-2%	11-44	33-271 k€/year[6]
- Switch to biodiesel and biofuels	-	-	12-37%	38-75%	+ 8-11%	-	-
- Switch to methanol	100%[3]	55%	99%	97%[4]	+ 9%	150-450	10-15 €/MWh for fuel and 3-4 €/MWh for other O&M
- Slow steaming	13-50[5]%	21-64%	18-69%	0-30%	- 15-50%	71	- 42-77% (fuel savings)[7]
- Slide valves	-	20%	10-50%	25-50%	+ 2%	0.33-1.43	(assumed to be null)
Secondary measures:							
- Exhaust Gas Recirculation (EGR)	-	25-80%	-	0-20%	+ 0-4%	36-60	17-25€/kW, so 2-3 €/MWh assuming 8,000 hours/year
- Selective Catalytic Reduction (SCR)	-	70-95%	10-40%	-	0-2%	19-100	3-10 €/MWh
- PM filters (DPFs)	-	-	45-92%	70-90%	+ 1-4%	30-130	+1-4% in fuel penalties
- Scrubbers	90-98%	-	0-90% (median: 14-45%)	0-70% (median: 16-37%)	+ 0.5-3%	100-433	0,6[8]-12 €/MWh (~2% of capital investments)

[1]: theoretical conversion from a 3.5 wt% fuel to a 0.1 wt% fuel

[2]: only valid for distillate fuels

[3]: methanol does not contain sulphur

[4]: expected achieved reduction (based on drop in particle number)

[5]: not directly reported but proportional to fuel savings

[6]: based on a lifetime of 12 years for all equipment but injectors, which are supposed to have a lifetime of 4 years

[7]: do not consider the eventual needs of additional ships in the fleet

[8]: the lower end of the range corresponds to open-loop scrubber where the only operational costs are due to fuel penalty of 1-3%

Diesel vessels and engines constitute some of the longest-lived transport equipment, which can last for more than 30 years [26]. In early 2019, the average age of the world merchant fleet was 21 years, which is in slight increase compared to previous years [8] although the age repartition is not uniform across the different types of vessel: 71% of carrying capacity below 10 years old for bulk carriers, 56% for container ships, 54% for oil tankers, 41% for "other types" of ships and 35% for cargo ships (see Figure 30) [8]. Hence, if only a few vessels are being replaced every year, this conducts to a slow implementation rate of the reduction techniques. Therefore, reduction techniques which are suitable for retrofitting, measures which concern fuel specification limitations and speed reduction are preferable in order to speed-up the efficiency of the policies [26].

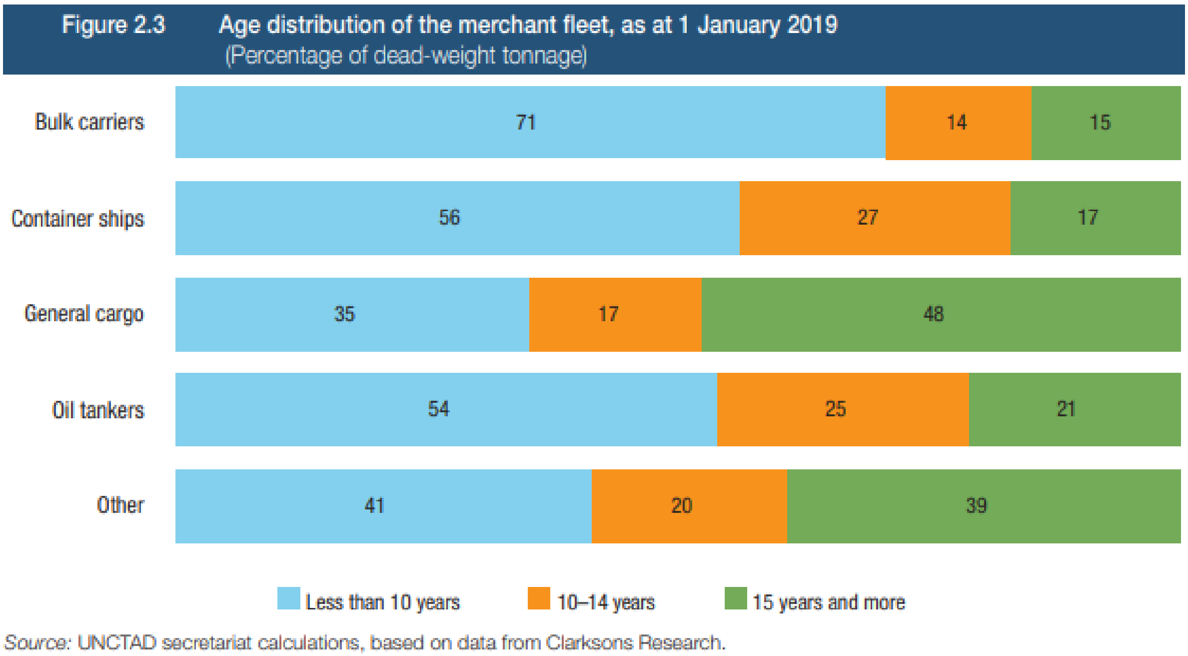


Figure 30: Age distribution of the merchant fleet in January 2019, as the percentage of dead-weight tonnages (source: [8])

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