Comparison of CO_2 emissions of MARPOL Annex VI compliance options in 2020

CE Delft

Committed to the Environment

Comparison of CO_2 emissions of MARPOL Annex VI compliance options in 2020

This report was prepared by:
Jasper Faber, Anne Kleijn, Diederik Jaspers

Delft, CE Delft, August 2020

Publication code: 20.190191E.091

Client: Alfa Laval, in cooperation with Yara Marine and Wärtsilä

Publications of CE Delft are available from www.cedelft.eu

Further information on this study can be obtained from the contact person Jasper Faber (CE Delft)

CE Delft
Committed to the Environment

Through its independent research and consultancy work CE Delft is helping build a sustainable world. In the fields of energy, transport and resources our expertise is leading-edge. With our wealth of know-how on technologies, policies and economic issues we support government agencies, NGOs and industries in pursuit of structural change. For 40 years now, the skills and enthusiasm of CE Delft's staff have been devoted to achieving this mission.

Content

Summary

MARPOL Annex VI regulation 14 sets limits for the sulphur content of fuel oil.
As of January 1st, 2020, the sulphur content of fuel oils used outside Emissions Control Areas (ECAs) is 0.50% m/m. inside ECAs, the limit has been 0.10% m/m since 2015.

Apart from using compliant fuels, MARPOL Annex VI allows ships to comply by using alternative compliance options, as long as those options are at least as effective in terms of emission reductions as the sulphur content limits.

In practice, there are two options to comply with the MARPOL Annex VI Regulation 14:
- using an exhaust gas cleaning system (EGCS) in combination with fuel oils with a sulphur content that is higher than 0.50% or 0.10%; and;
- using fuel oil with a sulphur content of 0.50%, respectively 0.10% or less.

Both options result in an increase of well-to-wake CO_2 emissions:
- an EGCS requires energy which is generated by engines running on fuel oil and thus generate CO_2;
- desulphurisation in a refinery requires hydrogen which is generally produced from methane, emitting CO_2 in the process, as well as energy.

This report quantifies and compares the CO_2 footprint of both options.

The analysis is carried out for five reference ships, which collectively provide a good reflection of the ship types which currently have installed scrubbers or which have a large demand for scrubbers:
- cruise ship (100,000 GT);
- small container ship (4,000 TEU);
- large container ship (18,000 TEU);
- bulk carrier (80,000 dwt);
- oil tanker (200,000 dwt).

The CO_2 footprint of using an EGCS depends on the sulphur content of the fuel and the amount of fuel a ship uses in an ECA. The higher the difference between the sulphur content of the fuel and the allowed emissions of sulphur oxides, the more energy an EGCS requires. CO_2 emissions associated with producing and installing the EGCS are small compared to the operational emissions. In contrast, by discharging acidic washwater into the ocean, an EGCS results in CO_2 emissions from the ocean, which are of a similar order of magnitude as the CO_2 emissions from operating the EGCS. In total, CO_2 emissions increase typically by 1.5-3%.

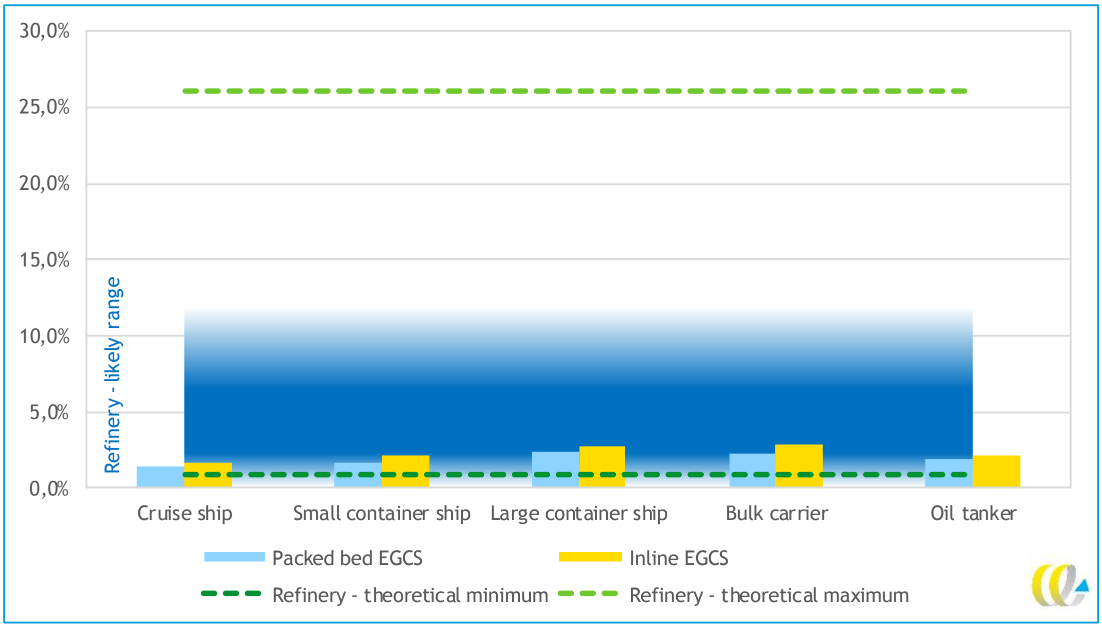
The CO_2 footprint of desulphurising fuel oil in the refinery depends on the crude oil used and the layout of the refinery. Using a generic refinery model, this report analyses the CO_2 impact of two options: hydrotreatment of residual fuel and hydrocracking in combination with hydrotreatment.

In both cases, the fuel quality inevitably improves. This is consistent with earlier studies that show that low-sulphur fuels will have a lower viscosity and a lower aromatics content than traditional residual fuels.

This report finds that the CO_2 footprint depends on the extent by which the fuel quality is improved. A theoretical calculation of the amount of CO_2 emitted only to remove a sufficient amount of sulphur from fuel oil shows that the footprint increases by around 1%. This method ignores the inevitable fuel quality improvement. A theoretical calculation of amount of CO_2 required to treat fuel until all the fuel products have the required sulphur content shows that the footprint increases by around 20-25%. This calculation ignores the fact that many of the resulting products meet quality standards of road or aviation fuels and will therefore unlikely be used as marine fuels. Therefore, the former is not physically possible, while the quality of the latter fuel is too good to be sold as a marine fuel.
In reality, the CO_2 emissions associated with desulphurising fuels will be between these extreme values.

The additional CO_2 emissions of both compliance options are compared with each other. The results for a petroleum-based fuel with a sulphur content of 3.5% m/m is shown in Figure 1.

Figure 1 - Additional CO_2 emissions (in %) for the reference ships for the different MARPOL Annex VI compliance options when using fuel with a sulphur content of 3.5% m/m



1 Introduction

1.1 Background of the study

Since its adoption in 1997, MARPOL Annex VI has included a 4.50% m/m limit to the sulphur content of marine fuel. In October 2008, MEPC 58 agreed to reduce the maximum sulphur content to 3.5% m/m from 2012 and to 0.5% m/m from 2020 onwards (in emission control areas, stricter limits apply) by prohibiting the use of any fuel oil that exceeds this limit. The 2020 implementation state has been reaffirmed in 2016 after a fuel oil availability assessment concluded the refinery sector has sufficient capacity to meet the demand of the shipping sector for compliant fuels.

Apart from using compliant fuels, MARPOL Annex VI allows ships to comply by using alternative compliance options, as long as those options are at least as effective in terms of emission reductions as the sulphur content limits. In the case of sulphur, alternative compliance options comprise the use of exhaust gas cleaning systems that remove sulphur oxides from the exhaust (commonly called EGCSs).

The number of ships with EGCSs installed or on order was about 1,000 in May 2018 (EGSCA, 2018) and is expected to be set at around 4,000 in January 2020 (EGSCA, 2019). At the same time, discussions continue about the environmental impacts of the use of EGCSs. Both Japan and Panama have submitted studies to MEPC 74 on the environmental impacts of EGCSs, which reach different conclusions.

The Japanese research study concludes that risks of discharge water from scrubbers to the marine environment and marine aquatic organism are in the acceptable range or negligible from both short-term and long-term perspectives (MEPC , 2019). The Panamanian literature study concludes that there is cause for concern about the impacts of EGCSs on marine life and that PM emissions of ships with an EGCS may be higher than emissions of ships using low-sulphur fuels.

Other studies have analysed the environmental impacts of EGCSs on water quality in ports and coastal waters (CE Delft, 2019) or the impact of difference MARPOL Annex VI Compliance options on air and water emissions, based on a case study (IVL, 2019).

From the different submissions and other studies, it is clear that there is uncertainty about the environmental impacts of the use of EGCSs, both about which environmental impacts are relevant, how large the impacts are and about how they should be judged.

In order to provide factual input to the debate, this report analyses the environmental impact of EGCSs and compare the results with the environmental impact of using compliant fuels. In order to compare like-with-like, the impact is assessed from well-to-wake for five different reference ships.

1.2 Objective of the study

The objective of the study is to compare the CO_2 emissions of two ways to comply with the MARPOL Annex VI sulphur regulation: using EGCSs in combination with high-sulphur fuels or using low-sulphur fuels.

This comparison will be conducted on a well-to-wake basis, implying that all GHG emissions over the lifecycle of both compliance options are considered. In this way, a full-integrated comparison of the CO_2 emissions of both options has been carried out.

1.3 Scope of the study

In this study, the following basic principles are applied:

- As mentioned in Section 1.2, the well-to-wake GHG emissions of using low-sulphur fuels and using EGCSs are compared in this study. In this assessment, we will focus on the main elements contributing to these GHG emissions. Elements that have a negligible impact on the comparison between both compliance options and processes that are the same for both options (e.g. the extraction of crude oil or its transport to refineries) is excluded from the analyses. This implies that this study is not a formal life cycle analysis (LCA). However, as all major elements are covered, the results of this study will provide a good indication of the GHG emissions that are caused by both compliance options.
- The comparative analysis of using low-sulphur fuel and using an EGCS is carried out for five reference ships:
  - a 100,000 GT cruise ship;
  - a 4,000 TEU container ship;
  - a 18,000 TEU container ship;
  - a 80,000 dwt bulk carrier;
  - a 200,000 dwt oil tanker.

  These five ships provide a good reflection of the main ship types that currently have installed scrubbers or which have a large demand for scrubbers. More detailed information on these five reference ships can be found in Section 2.3.
- In this study, we assume that all ships comply with MARPOL Annex VI. In other words, the impact of non-compliance on emissions is not assessed.
- The study will be confined to ships using petroleum-based fuels. In principle, LNG, methanol or other low-sulphur fuels can also be used to comply with MARPOL Annex VI. However, in practice LNG is only an option for new ships since the costs of retrofitting existing ships are prohibitive. Methanol and other alternative fuels are only used by a very small number of ships so these are currently not really viable options.

1.4 Outline of the report

The methodology applied in this study is discussed in detail in Chapter 2. In Chapter 3 all results of the study are presented. Finally, the conclusions of the study can be found in Chapter 4.

2 Methodology

2.1 Introduction

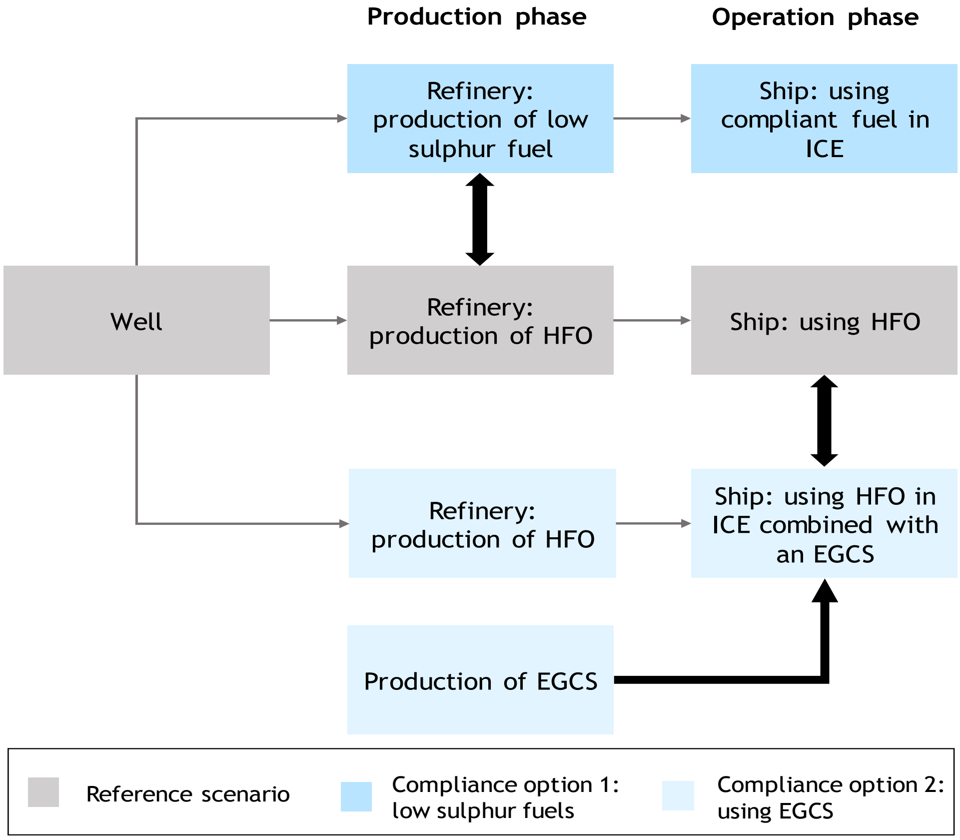
In this chapter we present the methodology applied in this study to assess the well-to-wake GHG emissions of applying low-sulphur fuels and using EGCSs. In Section 2.2 we first briefly describe the general approach of the study. The reference scenario applied in the assessments is discussed in Section 2.3, while both compliance options are defined in Section 2.4. Finally, the specific methodology to assess the GHG emissions of both options are discussed in Section 2.5.

2.2 General approach

To compare the well-to-wake GHG emissions (expressed in CO_2-equivalents, i.e. CO_2-eq.) of the appliance of low-sulphur fuels and the use of heavy fuel oil (HFO) in combination with a EGCS, the additional CO_2-eq. emissions of both compliance options compared to the reference scenario of using HFO (without any exhaust gas cleaning technology) are estimated. This is explained in more detail for both compliance options in Figure 2:

- The low-sulphur fuel pathway (top) requires desulphurisation of fuels in the refinery. The additional CO_2 emissions of the production of low-sulphur fuels are estimated. We have not been able to find studies into the energy density of low-sulphur fuels. The available evidence suggests that the energy density varies between different types of fuels and is very similar to the range of energy densities of HFO (CIMAC, 2018). Therefore, we do not assume a change in CO_2 emissions in the operation phase.
- The EGCS pathway (bottom) uses the same fuel as the reference scenario. In the operation phase, the energy required to operate the EGCS results in additional CO_2 emissions, while the emissions associated with the production and installation of the EGCS also are accounted for.

Figure 2 - Framework for comparison of environmental impacts



The CO_2-eq. emissions of transport of fuels or materials are not included in our estimations. As for the transport of fuels, no difference exist between the reference scenario and both compliance options. In all scenarios, crude oil have to be transported from the well to the refinery and from the refinery to the ship. Therefore, these transport emissions will be the same in all scenarios. There may be a difference in the transport emissions associated to the production and installation of the EGCSs (material to the production facility, EGCS units from the production facility to the ship) between the reference scenario and the scenario considering the use of an EGCS. However, based on IVL (2019) it was concluded that these emissions are negligible compared to the other CO_2-eq. emissions associated to the production and operation of the EGCSs. Additional CO_2-eq. emissions because of possible refinery expansions to produce compliant fuel for 2020 and additional transport of fuel products are not taken into account because they cannot be quantified.

The estimation of additional CO_2-eq. emissions for both compliance options compared to the reference scenario is carried out for five different reference ships (see Section 1.3). For each reference ship the difference in annual emissions is estimated, based on assumptions made on the annual fuel consumption of these ships. This is discussed in more detail in Section 2.3.

2.3 Reference scenario's

In this section, we briefly discuss the main issues with respect to the reference scenario. This includes among others the reference ships, the type of fuel used by the ships and the extent to which these ships sail in emission control areas.

2.3.1 Reference ships

The calculations carried out in this study are performed for five different types of reference ships. These ships are selected because they are known to have installed EGCSs. The key characteristics such as engine power and total fuel consumption was based on the average power/fuel consumption of similar ships in 2012, according to IMO (2014). These ships and their main characteristics are presented in more detail in Table 1 and their sources/ assumptions mentioned hereafter.

Table 1 - Overview reference ships and their technical and design characteristics

Characteristics	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Ship size					
Gross tonnage, TEU or DWT:	100,000 GT	4,000 TEU	18,000 TEU	80,000 DWT	200,000 DWT
Type and number of engines/boilers					
Type of power generation (1)	Diesel - Electric propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion
Main engine type (2)	N/A	Medium speed 4 stroke engine	Slow speed 2 stroke engine	Slow speed 2 stroke engine	Slow speed 2 stroke engine
No. of main engines	N/A	1	2(2)	1	1
No. of auxiliary engines	6	3(3)	6(3)	3	3
No. of boilers(4)	2	1	2	2	2
Installed power and engine load					
Average installed power (MW) (5)	76,1	34,6	60,2	9,7	27,2
Average installed main engine power (MW) (7)	N/A	24,7	43,0	8,2	21,4
Average installed auxiliary engine power (MW) (7)	N/A	9,9	17,2	1,5	5,7
Average main engine load (%MCR)(8)	N/A	33	56	54	47
Average aux engine load (%MCR) (5)	N/A	60	60	60	50
Average required power (MW)	55,5	14,1	34,4	5,4	12,9
Average required total engine load (%)	73	41	57	55	48

Characteristics	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Fuel consumption					
Average annual main engine fuel consumption (tonnes) (8)	47,200	13,900	25,300	5,400	15,300
Average annual auxiliary engine fuel consumption (tonnes) (8)	25,500	3,900	6,100	1,100	3,600
Average annual boiler fuel consumption (tonnes) (8)	500	600	1,100	300	1,100
Average total annual fuel consumptions (tonnes) (8)	73,200	18,400	32,500	6,800	20,000
SFOC (g/kWh) of main engine at average load (9)	210.8	202,6	179,4	180,1	183,2
SFOC (g/kWh) of auxiliary engine at average load (9)	226.3	229.0	229.0	229.0	233.7
Scrubbers and pumps (Packed bed technology)					
Number of scrubber(s) (10)	2	1	2	1	1
Number of pump(s) (10)	4	2	3	2	2
Scrubbers and pumps (Inline technology)					
Number of scrubber(s) (10)	5	2	2	1	2
Number of pump(s) (10)	5	2	3	1	2

Sources: IMO (2014) and CE Delft.

(1) Assumption made by CE Delft based on generic propulsion trend based on the ship size.
(2) Assumption made by CE Delft based on technical expertise and for bulk carrier, propulsion trends from (The Motorship, 2014) is used for the assumption.
(3) Assumption made by CE Delft based on bulk carrier configuration due to lack of data.
(4) Assumption made by CE Delft based on operational profile/technical expertise.
(5) Data derived from 4th IMO GHG Study 2018.
(6) Data derived from Clarkson. Container ships selected which are built between 2015 and 2020 and which has corresponding ship size as the reference container ships.
(7) Data derived from the main engine to auxiliary engine power ratio which is given in the IMO 3rd GHG study 2014.
(8) Data derived from IMO 3rd GHG study 2014 (IMO, 2014) and a range has been provided that takes into consideration all the operation modes (at berth, manoeuvring, anchorage and at sea).
(9) SFOC has been calculated based using the Eq.(3) of IMO 3rd GHG study.
(10) Average data provided by Alfa Laval, Wärtsilä and Yara Marine.

2.3.2 Reference maritime fuels

Prior to the introduction of the global sulphur cap of 0.50% m/m, the mean sulphur content of heavy fuel oil was: 2.6% m/m, with over 80% of the samples between 2.0 to 3.5% (MEPC, 2018).

For this study, we have chosen two reference maritime fuels that reflect choices made by shipping companies that install scrubbers:
- a fuel with a sulphur content of 2.2% m/m; and
- a fuel with a sulphur content of 3.5% m/m.

2.3.3 Emission control areas

Emission Control Areas (ECAs), or sulphur Emission Control Areas (SECAs), are sea areas in which stricter requirements with respect to air pollutant emissions are imposed on vessels. Areas covered by such requirements are, for example, the Baltic Sea, the North Sea, the North American ECA (including most of the US and Canadian coast) and the US Caribbean ECA. In the MARPOL regulations, a distinction is made between the sulphur limits inside and outside SECAs/ECAs. The current SECA/ECA limit is 0.1% m/m sulphur in the fuel. The global limit was up to and including 2019 equal to 3.5% m/m, but is reduced to 0.5% m/m since the 1st of January 2020.

The reference ships considered in this study sail both within and outside SECAs/ECAs. To take this into account in estimating the CO_2-eq. emissions of both compliance options, we have made a distinction in our calculations between the fuel consumed inside and outside these areas. Heavy fuel oil with a sulphur content equal to 3.5% m/m and heavy fuel oil with a sulphur content equal to 2.2% are considered to be representative for the maritime fuel market. Therefore, for the fuel consumed inside the SECA/ECA, the CO_2-eq. emissions of reducing the sulphur emissions from 3.5% m/m and 2.2% m/m to 0.1% m/m is estimated for both compliance options, while for fuel consumed outside the SECA/ECA, this approach has been replicated for a reduction of sulphur emission from 3.5% m/m and 2.2% m/m to 0.5% m/m.

The average annual fuel consumption within and outside SECAs/ECAs is shown for the various reference ships in Table 2.

Table 2 – Annual fuel consumption (%) within and outside SECAs/ECAs

	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Annual fuel consumption within SECAs/ECAs (%)	15	10	5	5	5
Annual fuel consumption outside SECAs/ECAs (%)	85	90	95	95	95

Source: Assumptions CE Delft.

2.4 Definition compliance routes

This report shows the differences in CO_2-eq. emissions of both compliance options: the use of low-sulphur fuels and the use of high-sulphur fuels in combination with an EGCS. Section 2.4.1 shows the definition of the first option and Section 2.4.2 shows the definition of the second option.

2.4.1 Low-sulphur fuels

Ships using compliant fuels use fuels with a sulphur content of maximally 0.1% m/m in (S)ECAs and maximally 0.5% m/m outside (S)ECAs.

In general, various types of refineries exist with different footprints per unit of operation. For a first order estimate, we use a generic refinery model of Prelim, Versions 1.2 and 1.3 (Abella, et al., 2017-2019). Footprints based on specific other refinery types require process modelling of the hydrodesulphurisation unit or HDS of that specific refinery. Relevant for this study, the origin of the hydrogen feed of an HDS differs per refinery type. In the Prelim 2 model we assume hydrogen production by steam methane reforming (SMR). For the footprint of hydrogen production the CO_2-eq. value of the Prelim model was used plus the EU-ETS value for reference. More variation exists, while in practice an HDS will receive a blend of feeds and the products is again blended to meet various fuel specifications.

The actual rerouting of flows for obtaining reduced sulphur HFO or MGO is unknown. However, the desulphurisation reaction requires constant stoichiometric amounts of hydrogen per unit of sulphur removed. Additionally, the same amount of hydrogen is required to convert the removed sulphur into hydrogen sulphide, so it can be further processed in a Claus unit of the refinery.

The HDS also removes nitrogen, which requires very little extra feed of hydrogen. However, much larger amounts of hydrogen are fed to the HDS for processing the fuel to its hydrogen specification and for carbon displacement. So the desulphurisation is only a small part of the hydrogen footprint of an HDS. The working point of 0.14% initial sulphur in the Prelim model, was normalised to a value per 1 w% sulphur removal, please refer to Annex A for a schematic overview of input and output flows. Overall, a 5% hydrogen loss was accounted for in the model.

Other footprints of the HDS comprise natural gas feed, power and steam. These are about constant for a specific processing volume and independent of the degree of sulphur removal. We assume power to be produced on site by natural gas fed CHP and steam by natural gas fed steam boilers. Greenhouse gas emissions from these operations other than CO_2 were also included in the CO_2-eq. value i.e. methane slip of natural gas in the CHP and originated from the Prelim model.

These latter footprints have been allocated over the HDS linear to the level of hydrogen feed, resulting in a minor 1.4% contribution for the desulphurisation.
Finally, a correction was applied to convert the footprint from the input feed to a value per ton of diesel.

2.4.2 High-sulphur fuels in combination with EGCSs

Ships using EGCSs to comply with the sulphur regulations commonly use fuels with a sulphur content of 3.5% m/m or 2.2% m/m.

In principle, an exhaust gas cleaning system (EGCS) or a scrubber is an equipment that removes sulphur oxides from the exhaust gas of ship's engine(s) and boilers. By using this kind of equipment, ships can use fuels with a sulphur content above the allowed limit. During fuel combustion, the sulphur is oxidised to sulphur dioxide (SO_2). A small amount of SO_2 will be further oxidised to sulphur trioxide (SO_3) (IVL, 2019). The total amount of SO_2 and SO_3 is also called SO_x.

The exhaust gas stream (SO_x) will be mixed with seawater or fresh water in the EGCS. The SO_x dissolve in the water (along with other components of the exhaust gas). With the use of seawater, the natural chemical composition of the seawater is being used for the removal process. The ability to neutralise SO_x with seawater depends on the alkalinity of the seawater. While with respect to the use of freshwater, an alkaline chemical such as caustic soda (NaOH) is used for neutralisation and scrubbing.

Seawater scrubbers are known as open loop systems since the seawater that is being used for scrubbing is discharged back into the sea (with or without a washwater treatment system). Hence the washwater is not recirculated. Since the washwater is being discharged back into the sea, the emissions from the exhaust gases and especially SO_2 have been transferred from the gas phase into water phase, causing no sludge removal exists in the system.

Fresh water scrubbers, also called closed-loop scrubbers, recirculate the water in the exhaust tower after being cooled with the help of a cooling pump and cleaned with the help of a process tank. Closed loop systems are able to operate at no discharge mode for a limited period of time thus being more suitable for ships whose operational profile includes sailing at sensitive areas such as Baltic areas or to ports where the discharge of washwater in the sea is banned.

According to (Clarksons research, 2019a), a total of 3,371 scrubbers have been installed until March 2020. Most of these are open loop systems. Open loop systems are more attractive within the retrofit market segment since they require less space and modifications onboard. With respect to retrofits and new builds installations, most of the scrubbers (around 60% or 2,033) are installed as a retrofit on existing vessels (Clarksons research, 2019a). This number also includes retrofits that are still pending to be installed.

With the above data, which indicates that open loop systems currently are the most commonly installed EGCS, we have considered an 'Open loop' EGCS with a multi stream configuration that have been retrofitted on all the five reference ship types (See Table 1) as the preferred compliance route for sulphur regulations. A multi stream configuration (multiple main and auxiliary engines) means that multiple exhaust gas streams are connected and diverted into a single scrubber tower. In the context of this study, this means that multiple exhaust gas sources of both main and auxiliary engines are sent to a single scrubber tower for the scrubbing and neutralisation process.

Open loop system can be segregated based on their type of technology used for scrubbing/neutralising:

1. **Packed bed or venturi technology.**
2. **Inline technology.**

Packed bed or venturi technology: This technology removes sulphur by inertial or diffusional impaction, reaction with a sorbent or reagent slurry, or absorption into liquid solvent (EPA, 2015). This removal process is executed in a chamber which contains layers of variously shaped-packing material such as Raschig rings, spiral rings or Berl saddles that provides a large surface area for liquid-particle contact to happen. The packing is held in place by wire mesh retainers and supported by a plate near the bottom of the scrubber. The scrubbing liquid is evenly introduced above the packing to maximise the efficiency. The liquid coats the packing and establishes a thin film. The nominal water flow is approximately 45 m^3/MWh.

Inline technology: This technology is a longer and slimmer version compared to the traditional design of open loop scrubber. The reduction in size is enabled by having an open spray solution where the scrubbing water is being divided into six spray layers to ensure a good mix between gas and water. A water trap situated in the scrubber inlet prevents scrubbing water from entering the engine (Wärtsilä, 2017). An inline system has a smaller spatial footprint than a packed bed system but it requires a higher water flow. The system has no moving parts inside.

Both packed bed and inline are the well-established and commonly applied open loop technologies currently available in the market. To make sure we take into account all the open loop systems for our analysis, this study considers both packed bed and inline technology.

Table 3 – EGCS and their associated technical characteristics

Factors	Technical - Assumptions and Data points
EGCS type	Open loop.
EGCS technology	Packed bed or inline scrubber.
EGCS configuration	Multi stream (Multiple engines connected to a single scrubber).
EGCS installation	Open loop without washwater treatment system (A conservative case).
EGCS size	Engine sizes of the reference ships (Table 1) are derived from the (IMO, 2014). Based on the engine size (MW) corresponding scrubber size will be calculated by the manufacturers and that input data will be used for our calculations.
EGCS lifetime	25 years
EGCS capacity	For this study, we will assume two capacities of scrubbing, one for 3.5% S and one for 2.2% S as mentioned above. The below represents the four scenarios that will be taken into account for calculations. Outside ECA's: 3.5% S → 0.5% S m/m & 2.2% S → 0.5% S m/m Inside ECA's: 3.5% S → 0.1% S m/m & 2.2% S → 0.1% S m/m
EGCS installation type	As per (Clarksons, 2019b) & (EGSCA, 2018), the current fleet comprises more ships that are retrofitted with scrubbers than new buildings with scrubbers. Therefore, and because retrofits are likely to have a larger environmental footprint than new builds due to the energy consumption during the installation phase, we will assume that scrubbers are retrofitted to the below mentioned five reference ship types.
EGCS operating modes	It is assumed that scrubbers operate in all the following modes especially after 2020: At berth (Less than 1 knot) Anchored (1 knot – 3 knots) Maneuvering (Greater than 3 knots and less than 20% MCR) Slow-steaming (Between 20% MCR and 65% MCR) Normal cruising (Above 65% MCR) For simplicity reasons, we have considered the average load of each reference ship type based on (IMO, 2014) which takes into consideration all the above operating modes. We assume that the entire power for operating the scrubber is always provided by the auxiliary engines/generator sets.
Aux engine(s)/boiler integration:	It is assumed that the main engine, the auxiliary engines and the boiler is integrated in the EGCS.

Factors	Technical - Assumptions and Data points
Type of power cycle:	The power cycle of each reference ship type has been assumed based on the CE Delft expertise and propulsion trends for a particular ship category based on the size. In general, a 4 stroke engine has higher exhaust temperatures than a 2 stroke engine, which means that for the same volumetric flow of exhaust, more water is required for cooling and saturation. While a 2 stroke engine has higher volumetric flow of exhaust than a 4 stroke engine, which means that for the same power of engines volumetric flow of exhaust more power of scrubber is required (Panasiuk, et al., 2018).
Feed or washwater pump(s) + electromotor(s):	The feed or the washwater pumps has been segregated based on the scrubber technology. Packed bed: A feed water pump has a flow rate of 400 m^3/h. Inline: A feed water pump has a flow rate of 720 m^3/h. Note: the weight of both the pump and the electromotor has been taken into account in the calculations.

Seawater alkalinity: When ships operate in low alkaline environments such as the Baltic sea, great lakes and Mississippi, the need for additional water required for the scrubber process will increase compared to operation in conventional sea areas. This scenario will increase the feed water pump flow rate, causing an increase in energy demand and consequently an increase in the discharge of washwater. This ‘operational scenario’ is not included in the calculations.

2.5 Methodology to estimate CO_2 impact

Section 2.5.1 describes the methodology to estimate the CO_2 impact of low-sulphur fuels. Section 2.5.2 describes the methodology to estimate the CO_2 impact of high-sulphur fuels in combination with the use of EGCSs.

2.5.1 Methodology to estimate the CO_2 impact of low-sulphur fuels

In general, refineries differ in their set-up. However, we use a conventional hydro-refinery set-up with diesel hydro-treatment as defined in the Prelim model, see the process flow diagram in the Annex A.

To produce the alternative low-sulphur marine fuels different pathways and blending strategies may be applied. The current flow of vacuum residue for today marine HFO fuels is to be replaced by a compliant low-sulphur product. In practice, this will be achieved by rerouting and blending depending on the specific refinery and crude oil assays.

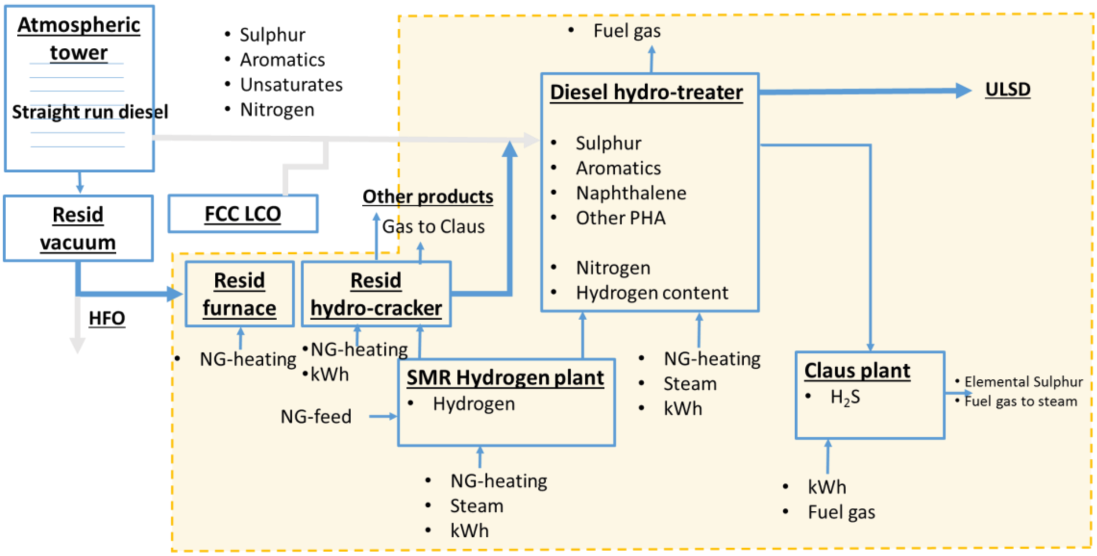
With respect to the scope of this study the impact of additional desulphurisation for two generic cases are considered to meet the final specifications of the compliant fuel:

1. Feeding 100% HFO to a reside hydro-cracker resulting in different products. Followed by additional hydro-treatment of the diesel fraction in an HDS.
2. Hydro-treatment of straight-run diesel in an HDS.

Case 1

The first case assumes that HFO currently brought to the market is now processed in a residue furnace and residue hydro-cracker. Impact is derived from a 100% HFO feed.
Apart from diesel and gasoil, the hydro-cracker gives multiple other products like naphtha and residue HFO. In the Prelim model, the hydro-cracker removes 40% of the sulphur, which is not sufficient to produce compliant fuels. Therefore, further processing of diesel product is required in a diesel HDS. Please refer to Figure 3.

Figure 3 - Process to remove sulphur from residue HFO in hydro-cracker and diesel hydro-treater



In general, for these process routes to remove additional sulphur, nitrogen, unsaturation and aromatics consists following process steps are considered:

- Hydrogen production; as input for the hydro-treatment additional hydrogen is required. The most common method to produce hydrogen is by steam methane reforming (SMR). In this method high-temperature steam (700 to 1,000°C) is used to produce hydrogen from a methane source, such as natural gas (NG). Under pressure, the methane reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide and carbon dioxide. In a next step, the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final step, carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.

- Residue hydro-cracker furnace; vacuum residue/HFO with about 3.5 m% sulphur obtained from a crude assay matching this sulphur content (Arab Light-Stratiev, 3.35 m% S) is fed to a residue furnace for thermal pre-treatment. Herein natural gas is consumed.
  In order to start with 3.5 and 2.2 m% of sulphur, the impact is scaled linearly based on the actual sulphur reduction percentage.

- Residue hydro-cracking; under hydrogen feed the vacuum residue is cracked to a mix of lighter components like cracking gas, naphtha, diesel, gas oil plus a residue/HFO.

- Hydro-treatment; the diesel fraction is fed to the diesel hydro-treater. Here in unwanted impurities/inorganic components (including sulphur, nitrogen, unsaturation and aromatics) are removed by processing at high temperature and pressure in the presence of hydrogen and a catalyst. In this process, hydrogen reacts with the sulphur in the fuel to form gaseous hydrogen sulphide, which is then separated from the fuel. Also for naphthalene and aromatics hydro-treating is considered the most common method for removal. In an industrial refinery, hydro-treatment takes place in a fixed bed reactor at elevated temperatures ranging from 300 to 400°C and elevated pressures ranging from 30 to 100 kPa, in the presence of a catalyst consisting of an alumina base impregnated with cobalt and molybdenum.

- Claus process; the product gas rich in hydrogen sulphide resulting from the hydro-treatment process is further processed in the Claus plant. The Claus process consists of a thermal stage (combustion chamber, waste heat boiler) and some catalytic reaction stages (reheater, reactor and condenser). The main products of this process are elemental sulphur and fuel gas. This fuel gas is used elsewhere in the refinery and replaces the impact of the consumption of natural gas.

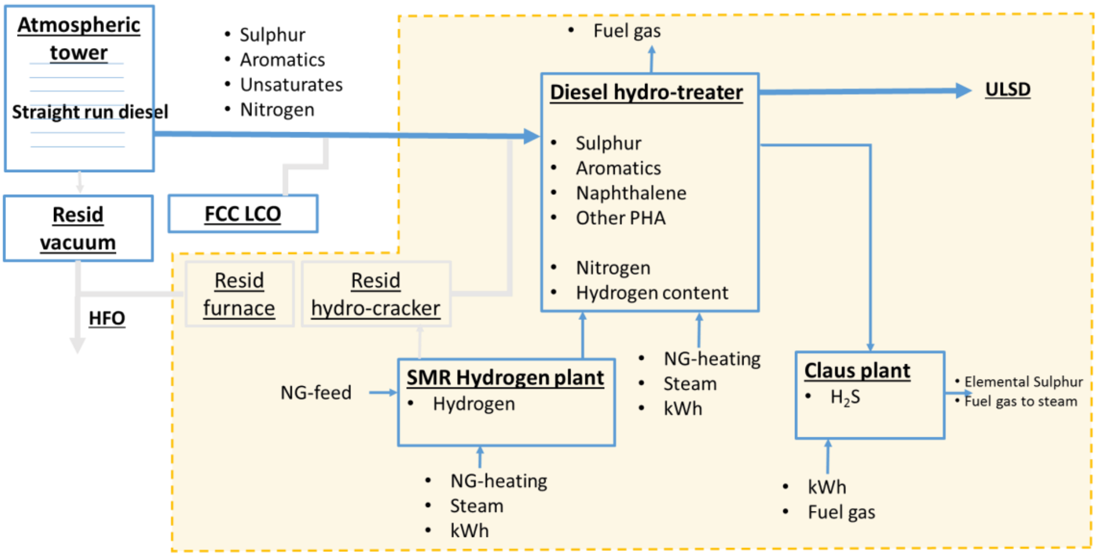
- Utilities steam and power. Steam is considered to be produced by natural gas and refinery gas. Power is assumed to be produced by natural gas fed power plants.

As indicated in Figure 3, specific inputs (e.g. natural gas, electricity) and intermediate products (H2) are required in each of these process steps. The use of these inputs and intermediate products result in additional production footprint. The amounts of natural gas, electricity, steam and hydrogen that are required in each step of sulphur, aromatics, and naphthalene removal are taken from the detailed refinery model Prelim Versions 1.2 and 1.3. The following assumptions are used in this respect:
- We consider the marginal increase of primary resources for additional hydro-treatment (compared to the conventional sulphur level in HFO) in an existing refinery assuming linearity versus removal.
- As indicated in Section 1.3, we assume that no new refinery capacity will be developed and hence no additional process steps are included in the assessment. This also implies that the hydrogen used is coming from existing Steam Methane Reformers (SMR).
- Cost increase exclusively by extra primary energy sources: natural gas and grid power
- Steam of SMR is used elsewhere in the refinery and equivalent distracted from the natural gas consumption.
- Hydrogen consumption for H_2S to enable processing in Claus is included in the assessment.
- Claus process with its input and output energy streams is included.
- Of The Claus process produces hydrogen as a by-product which is used elsewhere in the refinery. It replaces natural gas and thus leads to lower CO_2 emissions.
- Heat, steam and power consumption of hydro-treatment is allocated by the amount of hydrogen consumed per component (sulphur, Claus H_2S and aromatics).
- The footprint effect of the yield and sale of additional elemental sulphur production is neglected.

Case 2

In this case it is assumed that blending with diesel distillates is applied in reaching sulphur compliance for marine fuels. Therefore, the impact is exclusively determined by additional hydro-processing in the HDS including allocated utilities required to produce ultralowsulphur feedstock for marine fuel blends with compliant sulphur levels. An overview of the diesel hydro-treatment processes involved in the Prelim model used are shown in Figure 4.

Figure 4 - Process to remove sulphur from straight run diesel



Based on these assumptions, the amounts of inputs and intermediate products have been estimated by using the Prelim 1.2 and 1.3 refinery model.

2.5.2 Methodology to estimate the CO_2 impact when using EGCSs

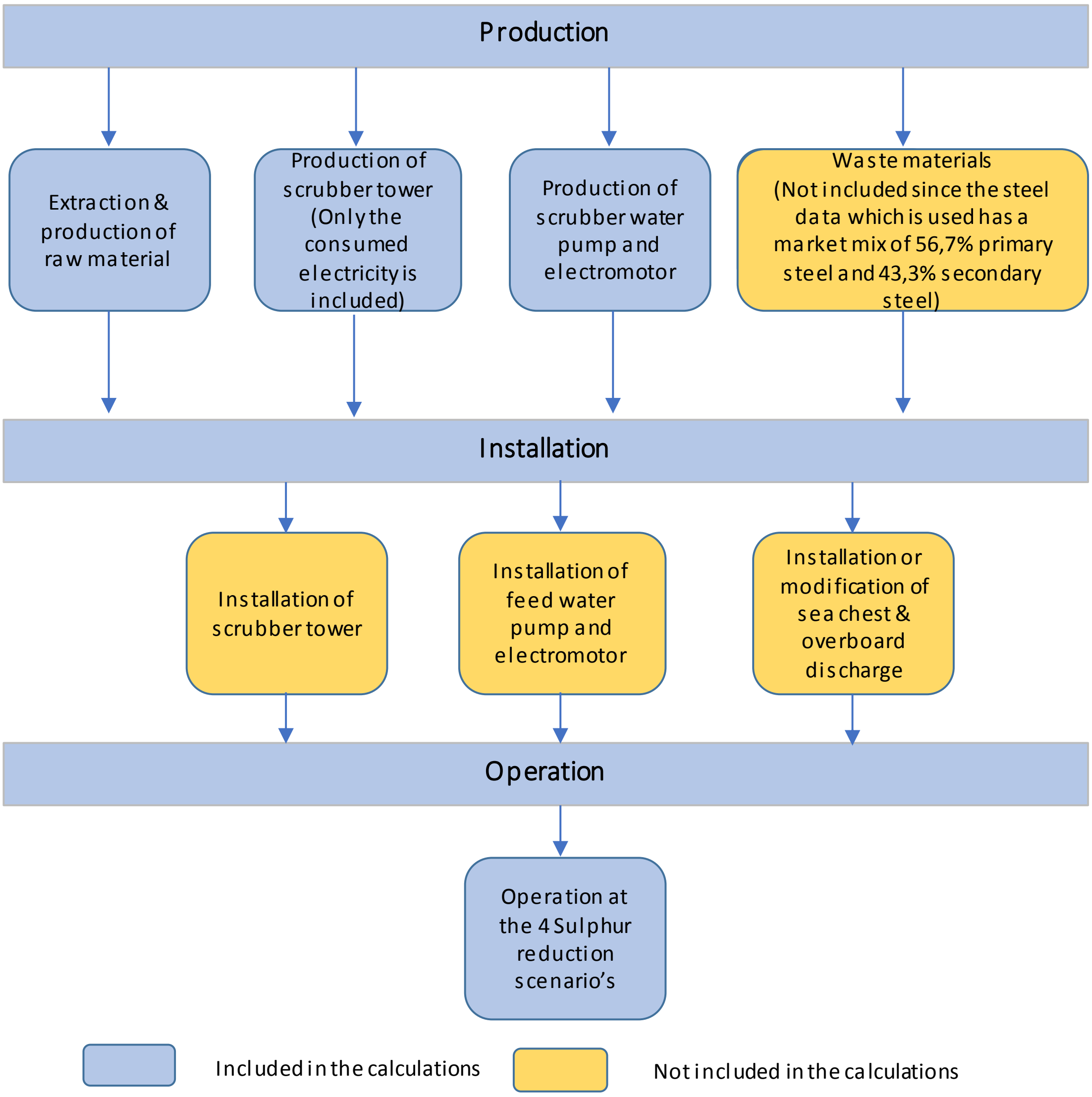
When effective as an alternative compliance mechanism to the MARPOL Annex VI sulphur requirements, an EGCS achieves the goal of reaching a maximum limit of 0.5% S m/m outside ECA's and reaching a maximum limit of 0.1% S m/m inside ECA's. Heavy fuel oil with a sulphur content equal to 3.5% m/m and heavy fuel oil with a sulphur content equal to 2.2% are considered to be representative for the maritime fuel market. Therefore, for the fuel consumed inside the SECA/ECA, the CO_2-eq. emissions of reducing the sulphur emissions from 3.5% m/m and 2.2% m/m to 0.1% m/m is estimated for both compliance options, while for fuel consumed outside the SECA/ECA, this approach has been replicated for a reduction of sulphur emission from 3.5% m/m and 2.2% m/m to 0.5% m/m. This is shown in Table 4.

Table 4 - Sulphur reduction scenario's

	Sulphur reduction scenario's
Inside ECA	3.5 - 0.1 % S m/m
	2.2 - 0.1 % S m/m
Outside ECA	3.5 - 0.5 % S m/m
	2.2 - 0.5 % S m/m

Figure 5 shows all the elements included in the calculation of the CO_2 emissions during the lifetime of an EGCS. The diagram also provides insight in the elements for which data was available and for which data was not available. As earlier discussed, the transportation is not included in the calculations for both compliance options and is therefore not included in the diagram.

Figure 5 - Calculation model for the entire lifecycle for EGCS compliance route



Production process

The initial phase is the production phase, where the focus is on all the raw materials acquired and the energy consumed to produce a fully functioning EGCS for the five different reference ship types. An EGCS, both packed bed and inline technology, mainly consists of the scrubber tower, pump(s) with the electric motor(s) to supply the required water and piping, fitting, valves and sample lines, which are necessary to integrate the EGCS unit (scrubber tower and pumps) with multiple exhaust streams. The size of the scrubber tower and the amount of required pumps are directly dependant on the fuel quality (content sulphur), engine sizes and the corresponding amount of exhaust streams, which need to scrubbed.

CO_2 emissions are caused during the extraction of the raw materials for the production and the production of the scrubber tower, the feed or washwater pump, the necessary piping to feed the scrubber with seawater from the sea chest and to discharge the washwater overboard. All the above mentioned elements covers the scope of the production phase, which are needed to calculate the (kg) CO_2-eq. footprint. An overview is shown in Table 5.

Table 5 - Different elements of EGCS during the production phase

Phases	Data availability
Raw materials for the production of scrubber tower	Yes, included in the calculations
Raw materials for the production of scrubber pump and electromotor	Yes, included in the calculations
Raw materials for the production of the sealing fan	No, assumed that this is negligible
Raw materials for the production of piping, valves, sample lines and fitting	No, assumed that this is negligible
Energy needed to manufacture the scrubber tower from the extracted raw materials	Yes, but only electricity included in the calculations. Data about required heat, steam or gas not possible to estimate.
Energy needed to manufacture the scrubber pump and electromotors	No, not included in the calculations

EGCSs are exposed to seawater, exhaust gases and a high concentration of chlorine. For this reason, EGCSs are made from materials, which are high resistant to corrosion. Table 6 shows an overview of the typical materials used for the production of an EGCS and the associated equipment.

Table 6 - Raw materials required for the production of an EGCS and associated equipment's

Open loop technology	Scrubber tower	Feed or washwater pump	Piping	Valves/Sample lines and fitting
Packed bed technology	254SMO (SS alloy), Carbon steel, Stainless steel with duplex materials	Pump: NiAlbz*, Stainless steel Electromotor: Aluminium, Stainless steel	GRE, GRP, GRVE, Carbon steel, Super duplex steel	Negligible
Inline technology	Alloy 59 (Nickel chromium-molybdenum) 6 MO grades (Stainless steel alloy), Duplex, 254SMO	Housing: Bronze/NiAlBz*/ Super duplex Impeller: Bronze/ Superduple Electromotor: 90% Aluminium 10% Ss	GRE, GRP, GRVE, Carbon steel, Super duplex steel	Negligible

*NiAlBr = Nickel aluminium and bronze alloy.

As shown in Table 6, the scrubber tower for packed bed technology is predominated by steel and its variants. The scrubber tower for inline technology, on the other hand, is dominated by both alloys of nickel chromium molybdenum and stainless steel variants. Since no distinction is made in the data of alloy which is received from Ecoinvent (a database used by LCA experts to derive environmental footprint data for various products and activities), the data for world steel which possess a market mix of primary steel (56.7%) and secondary/recycled steel (43.3%) is used. The use of this market mix does not take into account the eventual benefits at end of life because of the extra recycled steel in the market.

The composition of the pump(s) and electromotor(s) for both packed bed and inline technology slightly differ, mainly due to the fact that the pump used for inline technology contains a bronze impeller.

There is a lack of information regarding the amount and size of the materials, which are necessary for the production of the piping, valves, sample lines and fittings of an EGCS. In addition, pipe lengths are case specific, depending on factors such as ship size, engine size and flow rate (m^3/h). Furthermore, most manufactures of EGCSs are not involved in the installation process on board. This does not make it possible to make a realistic assumption. It can be assumed that the required materials for piping, valves, sample lines and fittings are almost equal for both packed bed and inline technology. Due to lack of reliable information is has been assumed that the required materials for piping, valves, sample lines and fittings are negligible compared to the production of the scrubber tower(s) and the pump(s). This is not included in the calculations and the comparison with the ‘low-sulphur fuel’ compliance option.

Energy consumption

Electricity necessary for the production of the scrubber tower is taking into account, but the electricity necessary for the production of the pump(s) and electromotor(s) is not taken into account since this is unknown. It is expected that corresponding CO_2-eq. is negligible in the overall picture. More research can be done in this area in a potential next in-depth investigation.

Calculations

The CO_2 footprint of extraction and production of scrubber tower and feed or washwater pump (including electromotor) is used to derive the kg CO_2-eq. per year, by dividing this value by the life time of the scrubber (25 years) (IVL, 2019). To provide the reader an example, Table 7 shows for a large container ship (18,000 TEU) the kg CO_2-eq. for these two important production elements and the total production impact.

Table 7 – kg CO_2-eq./year for the production process of an EGCS for a large container ship

Open loop technology	kg CO_2-eq./year for the production of scrubber tower(s)	kg CO_2-eq./year for the production of feed or washwater pump(s) & electromotor(s)	Total kg CO_2-eq./year for the production process
Packed bed	5,736.4	2,028.9	7,765.3
Inline	4,371.3	2,727.6	7,098.9

Installation process

The second element within the life cycle of an EGCS is the installation process.
This includes the following steps:

1. Modification of the exhaust funnel.
2. Installation of the scrubber tower(s) (Inline technology has only one tower while packed bed has the venturi tower as well).
3. Installation of feed or washwater pump(s) and electromotor.
4. Installation of the sealing fan.
5. Installation or modification of the sea chest (adjustment to the water intake demand of the EGCS).
6. Installation or modification of the overboard discharge.

The steps are based on the similar ideology that all the five reference ship types are fitted with an open loop EGCS without a discharge cleaning system. The installation of a scrubber takes approximately 16 to 20 days. Installation of the scrubber tower and modification of the sea chest are the activities, which have to be carried out while the ship is in dry dock. It is assumed that the rest of the installation work does not require the ship to be in dry dock. Due to a lack of information and complexity in building scenarios such as geographical location of the installation and the electricity mix in the concerned country, there is decided not to include this phase in the CO_2 footprint calculations.

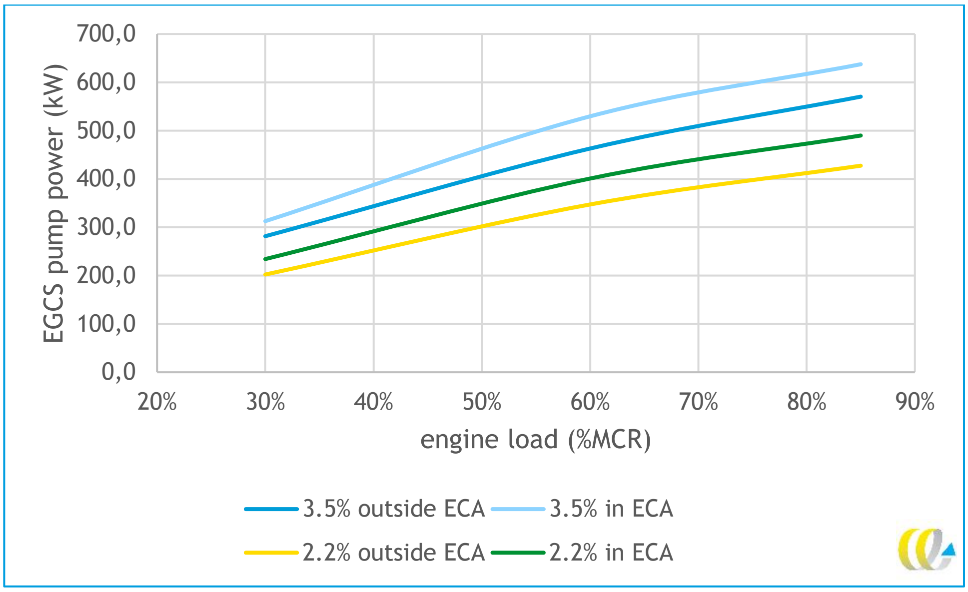
It is assumed that the five reference ships are existing vessels which will be retrofitted, which means that a certain amount of CO_2 is being emitted to the installation phase of EGCSs. However, in 25 years it is expected that the CO_2 emissions corresponding to the installation process will become negligible since the installation of the vessel is included in the new building process.

Operation

The power (and thus fuel) needed to operate the EGCS is commonly referred to as the fuel penalty. This fuel penalty is usually predominated by the power required for the pump(s). The pump(s) ensure a safe operation of the scrubber such as maintaining the spray patterns and eventually maintaining the efficiency of the scrubber.

The power required by the pumps depends on the engine load, the sulphur content of the fuel oil and on the applicable sulphur limit. Figure 6 shows the relation for the cruise reference ship.

Figure 6 - Relation between engine load and pump power for various fuel contents and sulphur limits



Besides the fuel penalty, one of the other main concerns among ship owners is the increase in backpressure. An increase in back pressure can increase the engine load, which consequently increase the SFOC of the engine. According to the manufacturers of EGCSs, in general the increase of SFOC due to back pressure is held below 1%. This correlates with the information from marine engine manufacturers who indicate a maximum allowable back pressure threshold for an EGCS. Furthermore, engine manufacturers evaluate the scrubber impact on engine performance/load and recommend possible counter measures to ensure safe and reliable operation of the engine in combination with the EGCS, which further reduce any possibility of increase in SFOC. Since the fuel penalty caused due to back pressure is below 1%, we assume that this is negligible and is therefore not been included in the operational CO_2 footprint calculations.

Calculations

The average installed power and average engine load for both main and auxiliary engines are derived from the 3rd IMO GHG Study 2014 (IMO, 2014). The required pump power at the average required total engine load is based on input from the EGCS manufactures who based the values on the installed power and average load. The required pump power is multiplied by the SFOC (g/kWh) of the auxiliary engines and divided by the total annual fuel consumption to calculate the additional required fuel to scrub one ton of fuel. Subsequently, the operational CO_2 footprint per reference ship per year is calculated with the use of the CO_2 emission factor of HFO (3,114 kg CO_2/ton of HFO) (IMO, 2014) and the total annual fuel consumption. This methodology is used to calculate the CO_2 footprint of each reference ship per year for all the four 'sulphur reduction scenarios' mentioned in Table 4.

The calculated CO_2 footprint per year of the reference ships based on the above mentioned methodology does not take into account the operational profile of the ship in terms of sailing inside or outside ECAs. To include this and place the results into perspective, the amount of fuel (%) necessary inside ECAs (Table 2) is multiplied by the CO_2 footprint caused by scrubbing the total annual fuel consumption from respectively 3.5% S or 2.2% S to

0.1% S m/m. The amount of fuel (%) necessary outside ECAs is multiplied by the CO_2 footprint caused by scrubbing the total annual fuel consumption from respectively 3.5% S or 2.2% S to 0.5% S m/m.

Ships using EGCS wash the exhaust gases in order to meet the sulphur regulations which restrict the release of SO_2 emissions. The resulting acid washwater, which contains SO_2 is released into the sea. This leads to the acidification of the water. Researchers have looked into the effect of the release of acid washwater by ships using scrubbers in the North Sea and compared the results with the impact of CO_2 emissions on ocean acidification.
This study, conducted by European commission (EU Science Hub , 2016), concluded that in overall terms CO_2 emissions are the leading cause of ocean acidification in the North sea.

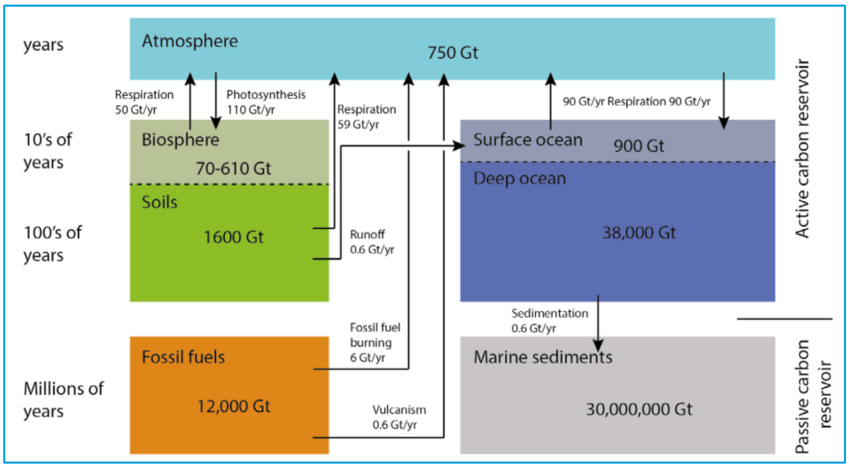
CO_2 emissions from the ocean

Release of acidic washwater can cause CO_2 emissions, which can in turn cause the acidification of seawater. The chemical reaction of the process is:

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2(g)$$

Dutch institute NIOZ published about ocean acidification. The amount of carbon present is ocean waters is considerably large, see Figure 7 of carbon presence and distribution:

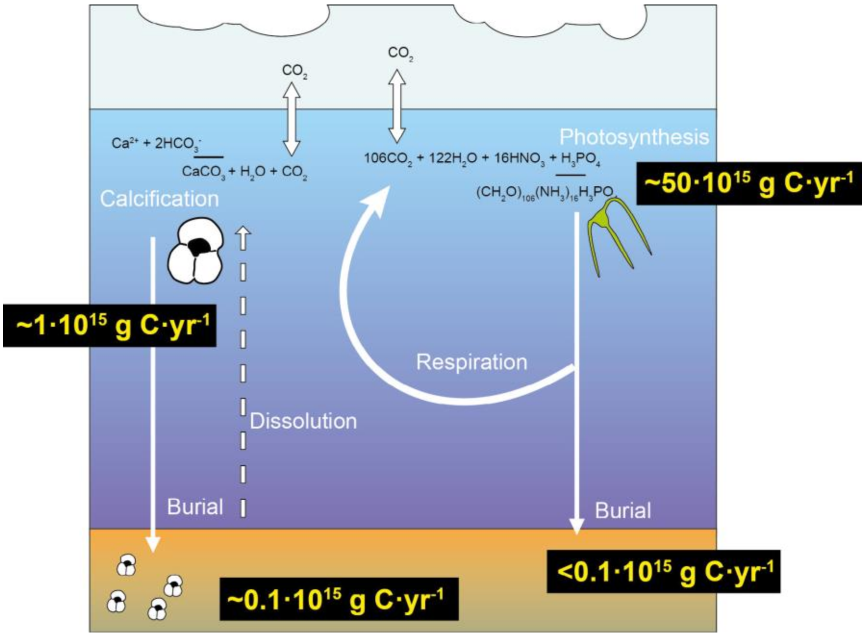
Figure 7 - Carbon presence and distribution in ocean waters.



Source: NIOZ Ocean Acification

For inorganic carbon the equilibrium is controlled by the so called ‘carbonate pump’ (left) and ‘biological pump’ (right) as described in Figure 8:

Figure 8 – Carbon equilibrium by carbonate pump in ocean waters

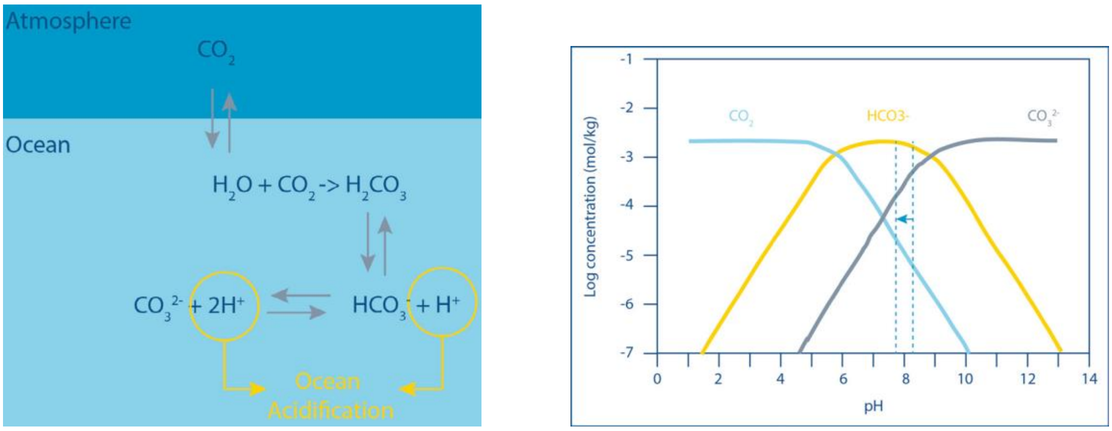


Source: NIOZ Ocean Acification

From this it can be concluded that biological uptake of CO_2 by calcification and algae can be neglected compared and most carbon is released to the atmosphere.

The inorganic equilibrium at specific pH is depicted in Figure 9.

Figure 9 - The inorganic carbon equilibrium and pH



Source: NIOZ Ocean Acification

Under current seawater pH conditions seawater is supersaturated with respect to $CaCO_3$ in most surface waters. Calcium concentration varies little in the open ocean, but the ocean acidification decreases CO_3^{2-} concentration and thereby degree of supersaturation.

In the reaction of SO_x with water the strong sulphuric acid is produced. Per mole SO_2 or SO_3 this results in 2 moles H_3O^+:

$$SO_2 + H_2O \text{ ---> } 2\ H_3O^+ + SO_3^{2-}$$

$$SO_3 + H_2O \text{ ---> } 2\ H_3O^+ + SO_4^{2-}$$

When taking into account Figure 9 and the supersaturation of carbonate in most surface waters in 'worst case' we assume that discharge can locally decrease supersaturation, shift the pH at the point of discharge to a significantly lower value. This releases two moles by reaction of all H_3O^+ with bicarbonate by:

$$HCO_3\text{-} + H_3O^+ \text{ <-> } H_2CO_3 + H_2O$$

and

$$H_2CO_3 \text{ <-> } H_2O + CO_2\ (g)$$

Because of the large quantities of sulphur removed, the CO_2 emissions from the seawater are significant.

3 GHG emissions of compliance options

3.1 Introduction

This chapter presents the results of the calculations on the increase in CO_2 emissions of the two main options to comply with MARPOL Annex VI sulphur regulations: the use of an EGCS (Section 3.2) and the use of low-sulphur fuels (Section 3.3). Section 3.4 presents a comparison of both options.

3.2 CO_2-eq. emissions when using an EGCS

The use of an EGCS in combination with high-sulphur fuels does not generate additional emissions in the fuel production but does result in higher emissions due to the choice of using a scrubber, see Figure 2. The related emissions comprise emissions associated with the production of an EGCS, emissions generated during the installation of an EGCS on a ship, emissions generated to operate the EGCS and emissions due to the release of acidic discharge water. The emissions associated with the production and the operation of an EGCS can be quantified accurately; the emissions generated during the installation cannot be quantified without additional research; and only the upper bound of the emissions from the seawater can be quantified.

This section presents the results (ton CO_2-eq./year) for both packed-bed and inline EGCSs, for all five reference ships when using fuel which contains a sulphur content of respectively 3.5% m/m or 2.2% m/m. This is shown in Table 8 through Table 11.

The results show that more than 90% of the emissions arise during the operation phase. The reason for this is that the emissions associated with the production only occur once and are divided over the lifetime of a scrubber (25 years). If the EGCS were used for fewer years, the share of this share of the emissions would increase. However, even in case the EGCS is installed and used only for a few years, the operational emissions still dominate the total emissions. The operational emissions strongly corresponds to the required amount of pump power.

Only the worst-case scenario of the amount of CO_2 emissions from the discharge of washwater is shown, see Section 2.5.2.

Table 8 - Additional emissions for the reference ships when using a packed-bed EGCS in combination with 3.5% S fuel, ton CO_2-eq. per year

	Cruise	(Small) Container	(Large) Container	Bulk carrier	Oil tanker
Production (ton CO_2/year)	8	4	8	2	3
Installation (ton CO_2/year)	Negligible	Negligible	Negligible	Negligible	Negligible
Operation (ton CO_2/year)	3,261	832	2,612	420	1,029
Max. washwater (ton CO_2/year)	<<6,150	<<1,536	<<2,695	<<564	<<1,658
Max. total (ton CO_2/year)	***9,419***	***2,372***	***5,315***	***986***	***2,690***
Max additional emissions as a percentage of annual operational emissions	***1.5%***	***1.7%***	***2.3%***	***2.3%***	***1.8%***

Table 9 - Additional emissions for the reference ships when using a packed-bed EGCS in combination with 2.2% S fuel, ton CO_2-eq. per year

	Cruise	(Small) Container	(Large) Container	Bulk carrier	Oil tanker
Production (ton CO_2/year)	8	4	8	2	3
Installation (ton CO_2/year)	Negligible	Negligible	Negligible	Negligible	Negligible
Operation (ton CO_2/year)	2,453	591	1,957	294	732
Max. washwater (ton CO_2/year)	<<3,537	<<879	<<1,535	<<321	<<944
Total (ton CO_2/year)	***5,998***	***1,474***	***3,500***	***617***	***1,679***
Max additional emissions as a percentage of annual operational emissions	***1.1%***	***1.3%***	***1.8%***	***1.6%***	***1.3%***

Table 10 - Additional emissions for the reference ships when using an inline EGCS in combination with 3.5% S fuel, ton CO_2-eq. per year

	Cruise	(Small) Container	(Large) Container	Bulk carrier	Oil tanker
Production (ton CO_2/year)	10	5	7	2	4
Installation (ton CO_2/year)	Negligible	Negligible	Negligible	Negligible	Negligible
Operation (ton CO_2/year)	3,646	1,043	3,141	553	1,220
Max. washwater (ton CO_2/year)	<<6,150	<<1,536	<<2,695	<<564	<<1,658
Total (ton CO_2/year)	***9,806***	***2,584***	***5,843***	***111,9***	***2,882***
Max additional emissions as a percentage of annual operational emissions	***1.7%***	***2.1%***	***2.8%***	***2.9%***	***2.2%***

Table 11 - Additional emissions for the reference ships when using an inline EGCS in combination with 2.2% S fuel, ton CO_2-eq. per year

	Cruise	(Small) Container	(Large) Container	Bulk carrier	Oil tanker
Production (ton CO_2/year)	10	5	7	2	4
Installation (ton CO_2/year)	Negligible	Negligible	Negligible	Negligible	Negligible
Operation (ton CO_2/year)	2,641	730	2,187	380	844
Max. washwater (ton CO_2/year)	<<3,537	<<879	<<1,535	<<321	<<944
Total (ton CO_2/year)	***6,188***	***1,614***	***3,729***	***703***	***1,792***
Max additional emissions as a percentage of annual operational emissions	***1.2%***	***1.5%***	***1.9%***	***2.0%***	***1.5%***

3.3 CO_2-eq. emissions when using desulphurised fuel

Case 1: followed by hydro-treatment

While the hydro-cracker shows a multiple effect of sulphur removal, nitrogen removal, fuel quality improvement by saturation and carbon displacement we will report the impact of these effects separately. Additionally, the hydro-cracker produces multiple products plus sulphur rich cracking gas, which is brought to a Claus unit for desulphurisation. The impact effect of the resulting gas to the overall impact to marine fuel is to be subtracted, replacing the impact of natural gas consumption in the refinery.

In the Prelim model the hydro-cracker removes a constant overall percentage of 40% of sulphur from the residue feed-in. For the diesel fraction, this is approximately 50%. This removal is not sufficient to reach the compliant sulphur levels of 0.5 and 0.1 m% from neither 3.5 nor 2.2 m% in the feed respectively.

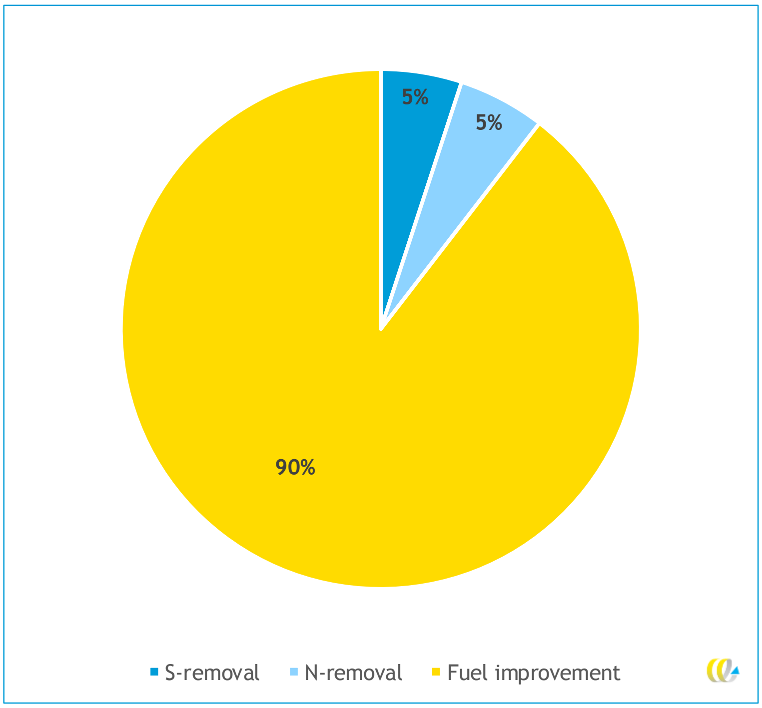
Table 13 presents the CO_2-equivalent emissions of the different inputs and gas output of the hydrocracking process. Separately reported is the impact related to desulphurisation showing its relative contribution to the total hydrogen consumption and thus impact.
As explained in Section 2.4.1, the hydro-cracker also uses H_2 for saturation and carbon displacement for quality improvement of fuels and removal of nitrogen, which are not directly required for MARPOL Annex VI compliance. The hydro-cracker produces different output streams of which diesel comprises 32 m% based on the residue feed.

Table 12 - Hydro-cracker hydrogen consumption

Hydrogen consumption **At vacuum residue HFO feed 3,274,128 kg/day, 3.35 m% S**				**Of which**	**From 2.2 to 1.1 m% S**	**From 3.5 to 1.7 m% S**
Incl. 5% H_2 loss factor	**Kg H_2/day**	**Fraction H_2 cons.**	**Kg H_2/ton feed per S wt% change**	**Sulphur/ Nitrogen/ Fuel spec.**		
S-removal	2,520.16	2.4%	0.68	1.4	1.5	2.5
S-saturation	2,520.16	2.4%	0.68			
H_2 for H_2S in gas	179.29	0.2%	0.05			
N-removal	5,616.96	5.4%	1.51	1.5	1.7	2.7
H_2 spec improvement	57,645.81	56%	15.50	25.0	27	45
H_2 for HC in gas	19,653.31	19%	5.28			
Carbon displacement	15,567.54	15%	4.19			
Total H_2 consumption	**103,703.23**	**100%**	**27.88**	**27.88**		

Figure 10 depicts the distribution of the hydrogen consumption over the effects:

Figure 10 – Hydro-cracker hydrogen consumption



With the EU ETS value of 8.85 ton CO_2/ton H_2 for SMR this results in the following CO_2-eq. footprint for the hydro-cracker, see Table 13.

Table 13 - Kg CO_2-eq. emissions from production of hydro desulphured fuels per tonne fuel

Desulphurisation footprint **kg CO_2-eq./ton product**	**2.2 to 1.1%**	**3.5 to 1.7%**
H_2 production for desulphurisation	14	22
H_2 production for Nitrogen removal	15	24
H_2 production for saturation and carbon displacement	243	400
Hydro-cracker utility emissions allocated to desulphurisation	0.6	1.0
Other hydro-cracker utility emissions	19	19
Refinery gas from Claus	-5.2	-7.0
Total sulphur only	**9.5**	**11.6**
Total including fuel quality improvement	**267**	**440**

Note: The Claus process produces refinery gas as a by-product, which is used elsewhere in the refinery. It replaces natural gas and thus this leads to lower CO_2 emissions.

Further removal of sulphur in a hydro-treater is required. The following additional impact is for the residual treatment in the hydro-treater in order to meet compliant fuel specification.

Table 14 - Kg CO_2-eq. emissions from production of hydro desulphured fuels per tonne fuel

Desulphurisation	1.1 to 0.1%	1.1 to 0.5%	1.7 to 0.1%	1.7 to 0.5%
H_2 production for desulphurisation	16	10	26	20
H_2 production for saturation and carbon displacement	350	350	350	350
Hydro-treater utility emissions allocated to desulphurisation	0.3	0.2	0.3	0.2
Other utility emissions	7.1	7.1	7.1	7.1
Refinery gas from Claus	-5	-3	-8	-6
Total sulphur only	**12**	**7.7**	**19**	**15**
Total including fuel quality improvement	**369**	**364**	**376**	**371**

Note: The Claus process produces refinery gas as a by-product, which is used elsewhere in the refinery. It replaces natural gas and thus this leads to lower CO_2 emissions.

This results in a total impact from the hydro-cracker plus the hydro-treater:

Table 15 - Kg CO_2-eq. emissions per tonne of fuel of combined hydro-cracker and hydro-treater

Desulphurisation	2.2 to 0.1%	2.2 to 0.5%	3.5 to 0.1%	3.5 to 0.5%
Total sulphur only	**22**	**17**	**31**	**27**
Total including fuel quality improvement	**636**	**632**	**816**	**811**

Clearly, the impact of sulphur removal shows a minor contribution compared to the fuel improvement.

Case 2: Hydro-treatment of distillates

Table 16 presents the CO_2-equivalent emissions of the inputs in the HDS process that are related to desulphurisation. As explained in Section 2.4.1, an HDS also uses H_2 for saturation of fuels and removal of nitrogen, but since these are not related to MARPOL Annex VI compliance, they are not included in this table.

Table 16 - Kg CO_2-eq. emissions from production of hydro desulphured fuels per tonne fuel

Desulphurisation	2.2 to 0.1%	2.2 to 0.5%	3.5 to 0.1%	3.5 to 0.5%
H_2 production for desulphurisation	34	28	56	49
Refinery utility emissions allocated to desulphurisation	0.6	0.6	0.6	0.6
Claus	-9.8	-8.0	-16	-14
Total	**24**	**19**	**40**	**36**

Note: The Claus process produces refinery gas as a by-product, which is used elsewhere in the refinery. It replaces natural gas and thus this leads to lower CO_2 emissions.

Table 17 presents the increase in CO_2 emissions from using desulphured fuels. Note that these emissions are not from the exhaust of the ship but from the refinery and from the hydrogen production in the refinery or in the hydrogen plant (Section 2.5.1).

Table 17 - Increase in CO_2 emissions from desulphured fuels

		Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Baseline	Annual fuel consumption (tonnes)	73,200	18,400	32,500	6,800	20,000
	Annual baseline CO_2 emissions (tonnes)	228,000	57,000	101,000	21,000	62,000
3.5% S scenario	Additional CO_2 emissions from fuel desulphurisation (tonnes)	2,700	700	1,200	200	700
	Increase in CO_2 emissions (%)	1.2%	1.2%	1.2%	1.2%	1.2%
2.2% S scenario	Additional CO_2 emissions from fuel desulphurisation (tonnes)	1,600	400	700	140	400
	Increase in CO_2 emissions (%)	0.7%	0.7%	0.7%	0.7%	0.7%

3.4 Conclusion

This section compares the additional CO_2 emissions associated with the two main options to comply with the sulphur regulations in MARPOL Annex VI: the use of desulphured fuels and the use of EGCSs.

As can be seen in Figure 11 and Figure 12, all compliance options result in higher CO_2 emissions since it costs energy to remove the sulphur from the fuel or the exhaust gas and since this required energy is generated from fossil fuels. In addition, the desulphurisation of fuels requires hydrogen, which is generated by steam-reforming methane, a process which also emits CO_2. Desulphurisation on board results in emissions of CO_2 from the seawater.

The additional CO_2 emissions related to the use of an EGCS are dependent on the ship type. The additional CO_2 emissions related to the use of desulphured fuel are not dependent on the ship type, but are dependent on the refinery. The amount of hydrogen and energy required to reduce the sulphur content of the fuel may vary from refinery to refinery. However, this study has used one representative refinery and one representative hydrogen plant. This means that the amount of hydrogen and energy per tonne of fuel is only dependent on the sulphur content of the fuel and not the ship type which use the fuel. The variation in additional CO_2 emissions related to the use of an EGCS is caused by the type of EGCS and the required electricity.

For all reference ships, the additional CO_2 emissions of removing the sulphur from the exhaust are higher than the additional CO_2 emissions of desulphured fuel, as can be seen from Figure 11 and Figure 12.

Figure 11 - Additional CO_2 emissions (in %) for the reference ships for the different MARPOL Annex VI compliance options when using fuel with a sulphur content of 3.5% m/m

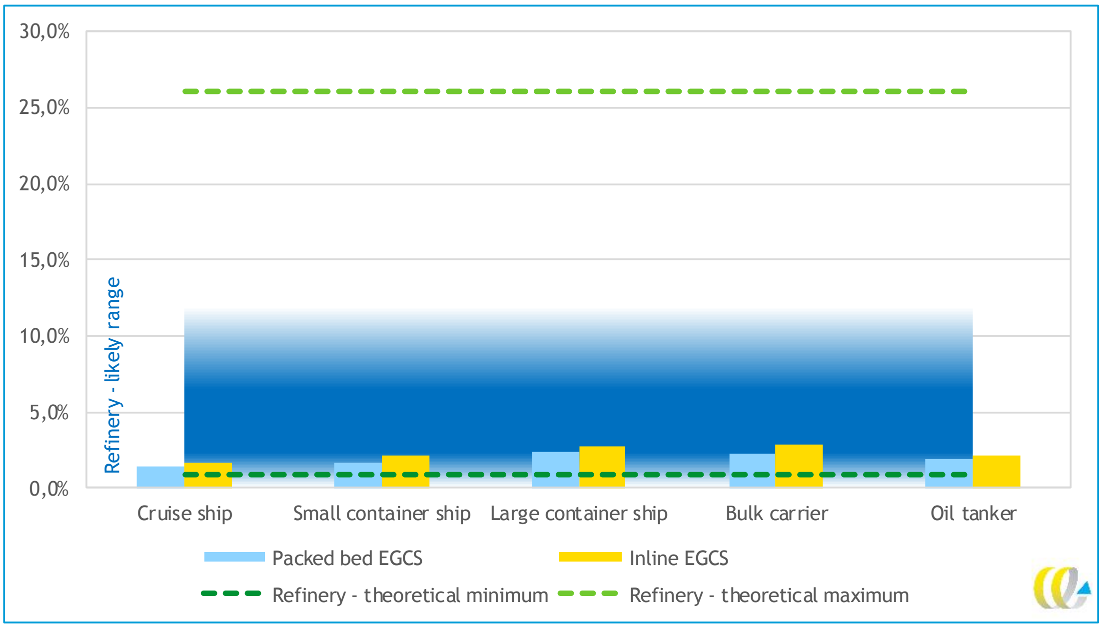
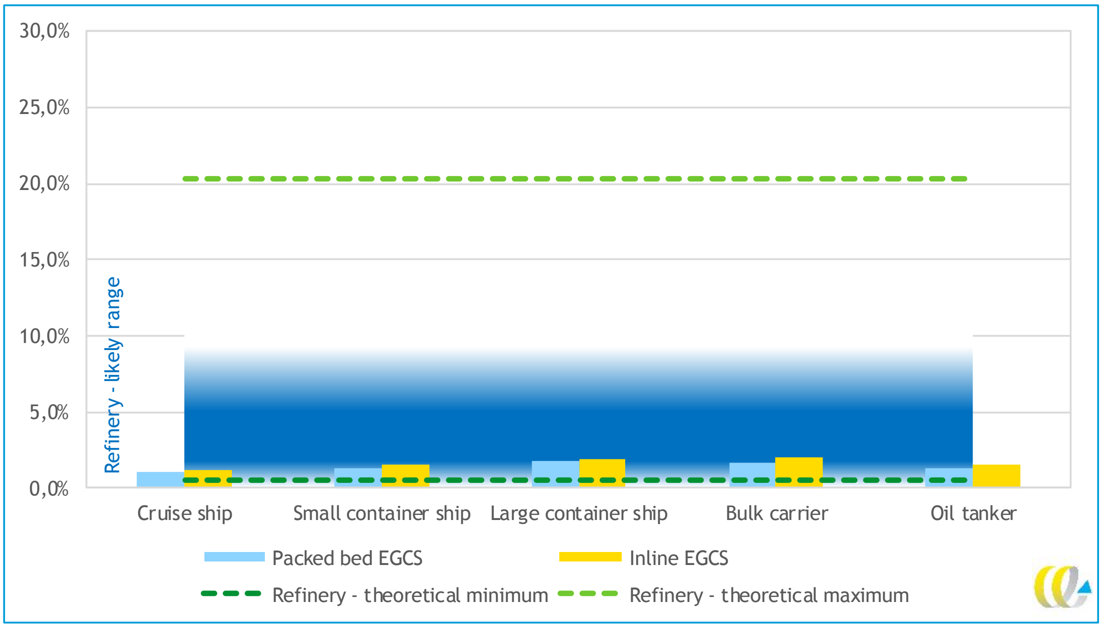


Figure 12 - Additional CO_2 emissions (in %) for the reference ships for the different MARPOL Annex VI compliance options when using fuel with a sulphur content of 2.2% m/m



4 Conclusion

This study has compared the additional CO_2 emissions of the two main options to comply with the MARPOL Annex VI sulphur requirements: using low-sulphur fuels or using high-sulphur fuels in combination with an EGCS.

Various processes can be used to produce low-sulphur fuels; the choice will depend on the refinery design and the crude oil slate the refinery uses. In most cases, sulphur removal coincides with an improvement of quality of the fuel, as unsaturated bonds and aromatics are saturated and the fuel becomes more paraffinic. Many low-sulphur fuels have better qualities in terms of viscosity and aromatics content than required by the applicable standards.

Whether or not removal of sulphur on board or removal of sulphur in the refinery generates lower CO_2 emissions depends on whether or not the inevitable fuel quality improvements are taken into account. The mere removal of sulphur generates less CO_2 emissions than the use of an EGCS, whereas sulphur removal plus fuel quality improvement has more CO_2 emissions than using an EGCS.

This finding is similar to other studies. For example, Winnes et al., (2018) found that the additional CO_2 emissions of the two compliance options are comparable. The main difference between this study and the study from IVL is the fact that this study has used multiple reference ships and data about the EGCSs received from manufacturers, which they would have installed on the selected reference ships, whereas the study from IVL has used generalised assumptions about the required power to operate an EGCS. IVL assumes an additional power use of 1.3%. (Bengtsson, et al., 2011) found that the CO_2 emissions of ships using an EGCS or using low-sulphur fuels are very close, but they assume a much lower power consumption by the EGCS: 1% of the fuel used.

5 References

Abella, J. P. et al., 2017-2019. *Petroleum Refinery Life Cycle Inventory Model (PRELIM), versions 1.2 (Oct 2017) and 1.3 (May 2019): HydroRefineryCalcs sheet.*, Calgery : University of Calgary, Department of Chemical and Petroleum Engineering.

Bengtsson, S., Andersson, K. & Fridell, E., 2011. *Life cycle assessment of marine fuels. A comparative study of four fossil fuels for marine propulsion*, Gothenburg: Chalmers University of Technology.

CE Delft, 2019. *The impacts of EGCS washwater discharges on port water and sediment*, Delft: CE Delft.

CIMAC, 2018. *Fuel 2020 presentation at Circle SMM Hamburg Sep. 2018.* [Online]
Available at:
https://www.cimac.com/cms/upload/events/circles/circle_2018_SMM/CIMAC_Circle_SMM_2018.pdf
[Accessed 2019].

Clarksons research, 2019a. *NOx/SOx - Emission abatement systems*, London: Clarksons Research.

Clarksons, 2019b. *NOx/SOx - Emission abatement systems (Installations by vessel)*, London: Clarksons.

EGSCA, 2018. *EGCSA Numbers Infographic.* [Online]
Available at: https://www.egcsa.com/wp-content/uploads/EGCSA-numbers-31-May-2018-7.pdf
[Accessed 2020].

EGSCA, 2019. *The facts about the environmental impact of exhaust gas cleaning systems.* [Online]
Available at: https://www.egcsa.com/category/all/
[Accessed 2020].

EPA, 2015. *Air pollution control technology fact sheet*, Washinton D.C: United States Environmental Protection Agency (US EPA).

EU Science Hub , 2016. *Ocean acidification exacerabated by emissions from ships on major shipping routes.*. [Online]
Available at: https://ec.europa.eu/jrc/en/news/ocean-acidification-exacerbated-emissions-ships-major-shipping-routes
[Geopend 11 November 2019].

ICCT, 2019. *Excel file: Marine black carbon emissions reduction strategies and technologies : Emissions Reductions Strategies and Technologies.* [Online]
Available at: https://theicct.org/sites/default/files/ICCT_Emissions_Control_Strategies.xlsx
[Accessed 11 11 2019].

IMO, 2014. *Third IMO GHG Study 2014,* London: IMO.

IVL, 2019. *Scrubbers: Closing the loop, Activity 3: Task 4,* Stockholm: Swedish Environmental Research Institute (IVL).

Llyods Register, 2012. *Understanding exhaust gas treatment systems,* London: Llyods Register.

MEPC , 2019. *Air pollution and energy efficiency - Report on the environmental impact assessment of discharge water from exhaust gas cleaning systems, MEPC 74/INF.24,* London: IMO, Marine Environment Protection Committee (MEPC).

MEPC, 2018. *Air pollution and energy efficiency - Consistent implementation of regulation 14.1.3 of MARPOL Annex VI - Consideration of the framework of ISO 8217, MEPC 72/5/3,* London: IMO, Marine Environment Protection Committee (MEPC).

Panasiuk, I., Lebedevas, S. & Cesnaukis, M., 2018. *Selection of exhaust scrubber: Concept for optimal solution,* Klaipeda: Klaipeda University.

The Motorship, 2014. *Propulsion Trends in Bulk Cariers.* [Online]
Available at: https://www.motorship.com/news101/engines-and-propulsion/propulsion-trends-in-bulk-carriers
[Accessed 21 November 2019].

Wärtsilä, 2017. *Wärtsilä I-SOx Scrubber system,* s.l.: Wärtsilä Corporation.

Winnes, H. et al., 2018. *Scrubbers: Closing the loop: Activity 3: Summary. Environmental analysis of marine exhaust gas scrubbers on two Stena Line ships,* Stockholm: Swedish Environmental Research Institute IVL.

A Prelim Hydrorefinery PFD