

# The impact of the 2020 global sulfur cap on maritime CO<sub>2</sub> emissions

Sulfur cap vs  
CO<sub>2</sub> emissions

Vasiliki Zisi, Harilaos N. Psaraftis and Thalys Zis  
*Danmarks Tekniske Universitet, 2800 Kongens Lyngby, Denmark*

339

Received 5 December 2020  
Revised 7 January 2021  
9 January 2021  
Accepted 11 January 2021

## Abstract

**Purpose** – As of January 1, 2020, the upper limit of sulfur emissions outside emission control areas decreased from 3.5% to 0.5%. This paper aims to present some of the challenges associated with the implementation of the sulfur cap and investigates its possible side effects as regard the drive of the International Maritime Organization (IMO) to reduce carbon dioxide (CO<sub>2</sub>) emissions. Even though it would appear that the two issues (desulfurization and decarbonization) are unrelated, it turns out that there are important cross-linkages between them, which have not been examined, at least by the regulators.

**Design/methodology/approach** – A literature review and a qualitative risk assessment of possible CO<sub>2</sub> contributors are presented first. A cost-benefit analysis is then conducted on a specific case study, so as to assess the financial, as well as the environmental impact of two main compliance choices, in terms of CO<sub>2</sub> and sulfur oxide.

**Findings** – From a financial perspective, the choice of a scrubber ranks better comparing to a marine gas oil (MGO) choice because of the price difference between MGO and heavy fuel oil. However, and under different price scenarios, the scrubber choice remains sustainable only for big vessels. It is noticed that small containerships cannot outweigh the capital cost of a scrubber investment and are more sensitive in different fuel price scenarios. From an environmental perspective, scrubber ranks better than MGO in the assessment of overall emissions.

**Research limitations/implications** – Fuel price data in this paper was based on 2019 data. As this paper was being written, the COVID-19 pandemic created a significant upheaval in global trade flows, cargo demand and fuel prices. This made any attempt to perform even a rudimentary ex-post evaluation of the 2020 sulfur cap virtually impossible. Due to limited data, such an evaluation would be extremely difficult even under normal circumstances. This paper nevertheless made a brief analysis to investigate possible COVID-19 impacts.

**Practical implications** – The main implication is that the global sulfur cap will increase CO<sub>2</sub> emissions. In that sense, this should be factored in the IMO greenhouse gas discussion.

**Originality/value** – According to the knowledge of the authors, no analysis examining the impact of the 2020 sulfur cap on CO<sub>2</sub> emissions has yet been conducted in the scientific literature.

**Keywords** Sulfur legislation, Global sulfur cap, Cost benefit analysis, CO<sub>2</sub> emissions, Carbon emissions, Covid-19, Initial IMO strategy, Sulfur emissions

**Paper type** Research paper

## 1. Introduction

### 1.1 Preamble

The environmental urgency brought about by climate change created a shift toward ecological sustainability among societies, companies and policymakers. The shipping



sector, as one of the key contributors to climate change, has to deal with green measures for the reduction of marine and atmospheric pollution (UNCTAD, 2018).

The global sulfur cap (MARPOL Annex VI) that entered into force in 2020 tightens the limits of sulfur emissions both close to the coast and in the high seas. As of January 1, 2020, the limit in the sulfur content of the fuel used for vessel propulsion changed from 3.5% m/m to 0.5% m/m. IMO (2016) estimates a 77% drop in sulfur oxide (SOx) emissions from ships between 2020–2025. A main benefit of this reduction concerns human health, and a corresponding aversion of some 570,000 premature deaths is estimated.

A parallel development concerns greenhouse gas (GHG) emissions: until 2030, the International Maritime Organization (IMO) targets an at least 40% reduction of carbon dioxide (CO<sub>2</sub>) emissions per transport work, with the reduction target moving toward 70% by 2050 in comparison to 2008 levels. The IMO also has adopted an absolute target for GHG emissions; reduce them by at least 50% vis-a-vis 2008 levels (IMO, 2018).

Even though it would appear that the two issues, desulfurization and decarbonization, are unrelated, and indeed in the regulatory context they have been treated separately, it turns out that there are important cross-linkages between them, which have not been examined, at least by the regulators. For instance, ships using scrubbers have a higher fuel consumption, hence emit more CO<sub>2</sub> and distillate low sulfur fuels have a higher carbon coefficient, hence produce more CO<sub>2</sub>. Also, producing these low sulfur fuels would require more energy hence, would emit more CO<sub>2</sub>, plus there are some other side-effects that impact on CO<sub>2</sub> and which will be described later. The purpose of this paper is to shed some light into these cross-linkages and specifically to investigate and assess the impact of the 2020 sulfur cap on CO<sub>2</sub> emissions.

There are at least two sets of challenges associated with the implementation of the 2020 global sulfur cap. The first challenge concerns the fuel market. The most significant uncertainty related to the 2020 sulfur cap implementation has been related to the availability, cost and quality of the compliant fuels. The instability of the oil market and the vast differentiation in the fuel prices among the years made difficult accurate predictions of the oil market after January 1, 2020. BIMCO (2019) stressed that the increase in fuel prices would automatically lead to a rise in freight rates, as ship-owners cannot absorb this high cost. Indeed, the first months after sulfur cap implementation confirmed the scenarios of an increase in marine gas oil (MGO) and ultra-low sulfur fuel oil prices and a decrease in heavy fuel oil (HFO) prices. However, new market challenges such as the clash between Iran and the US in December 2019 and the parallel outbreak of the COVID-19 pandemic in early 2020, which, among other things, resulted in an unprecedented drop of fuel prices, increased again the uncertainty of the fuel market. Even though it is not the scope of this paper to examine issues related to COVID-19, one cannot neglect the almost simultaneous occurrence of the pandemic with the start of implementation of the global cap. We shall comment more on COVID-19 in Section 6.1 of this paper.

The second challenge is environmental. The main compliance options for meeting the 2020 global cap are a choice between scrubbers or distillate fuels, with liquid natural gas (LNG) also being another fuel option. Clarksons Research (2019) projected that 15% of the world fleet by tonnage capacity would be fitted with scrubbers by the end of 2020. According to Tzannatos and Nikitakos (2013), the use of LNG reduces SOx emissions and particulates by almost 100% while a reduction of 20%–23% and 85% in CO<sub>2</sub> and nitrogen oxides (NO<sub>x</sub>), respectively, is reported, as compared to HFO. However, LNG can increase GHG emissions due to the unburnt methane, also known as methane slip. Ushakov *et al.* (2019) reported that the global warming potential of methane is 86 times higher than that of CO<sub>2</sub> emissions in a 20-year time frame. Gilbert *et al.* (2018) argued that LNG is a solution to

meet the 2020 IMO regulation, but it could not be considered as a GHG-friendly fuel, mainly due to the methane slip issue.

According to [the Danish Ecological Council \(2018\)](#), the use of scrubbers can reduce SO<sub>x</sub> emissions by more than 95%, while the reduction of the particulate matter (PM) is around 50% to 60%. However, the increased fuel consumption and the possible increase of ship speed in high seas could lead to a rise in CO<sub>2</sub> emissions, thus questioning the sustainability of this solution in the long run. At the same time, the sustainability of ultra-low sulfur fuels is also questionable. Figures from Germany and Finland reported an increase between 10% and 80% in black carbon emissions because of low-sulfur fuels (very low sulfur fuel oil) – as compared to HFO ([IMO, 2019b](#)).

With this basic background, this paper attempts to investigate possible cross-linkages between desulfurization and decarbonization. To that effect, the rest of the paper is organized as follows: Section 2 provides a literature review on the main factors linked to the sulfur cap that may contribute to global warming, including a qualitative risk assessment of these factors. Section 3 presents a qualitative risk assessment of CO<sub>2</sub> side-effects. Section 4 describes the methodology followed for the estimation of the carbon impacts of the sulfur cap. Section 5 presents an illustrative case study to illustrate the impacts of the policy. Finally, Section 6 presents the limitations and conclusions of the paper, including a brief discussion of issues related to COVID-19.

## 2. Sulfur-related factors that may contribute to global warming: a literature review

The implementation of the 2020 sulfur cap entails a number of cross-linkages as regard the target of reduction of CO<sub>2</sub> (and by extension GHG) emissions and the associated mitigation of global warming. Below we present a related literature survey, which is focused and broken down into a list of factors connected to the sulfur cap and which at the same time represent risks as regard global warming. For more general analyzes of SO<sub>x</sub>-related issues, we refer to the issue of enforcement policies presented by [Topali and Psaraftis \(2019\)](#) and to the survey conducted by [Zis and Cullinane \(2020\)](#) on desulfurization challenges in shipping.

### 2.1 Reduction of radiative cooling

The reduction of sulfur emissions is directly connected with an associated decrease of the cooling effect caused by such emissions. As documented in various studies, anthropogenic sulfates cause a reflection of sunlight in the troposphere and as a result, cause a reduction of the sunlight that reaches the earth's surface. [Gratsos \(2018\)](#) reports on various studies that support the loss of cooling effect due to the decrease in sulfur coming from the ships. [Fuglestedt et al. \(2009\)](#) argue that the sulfur regulation can double the size of the global warming due to both the reduction of SO<sub>x</sub> and the increase in CO<sub>2</sub> emissions, reporting a switch to net temperature from cooling to warming in 70 instead of 350 years. [Partanen et al. \(2013\)](#) calculate a reduction of 83% of the cooling effect due to sulfur cap regulation. Last but not least, [Kontovas \(2020\)](#) estimates that the loss of radiative cooling would amount to an equivalent increase of CO<sub>2</sub> shipping emissions by 30%.

### 2.2 Impact on ship speeds

Two speed scenarios seem to be connected with the 2020 sulfur cap and have opposite effects:

- (1) A slow steaming scenario due to anticipated higher fuel prices.
- (2) Higher speeds from ships fitted with scrubbers that can burn cheaper HFO.

According to the first scenario, if the 2020 global sulfur cap would lead to higher fuel prices, as this would be expected under normal circumstances, these would induce lower ship speeds. [Psaraftis \(2019\)](#) describes slow steaming as a solution being practiced during periods of higher fuel prices and/or depressed markets and compares speed reduction achieved via a bunker levy versus that achieved via a speed limit. [Cariou \(2011\)](#) reports an 11% reduction throughout 2009–2011 due to slow steaming. [Psaraftis and Kontovas \(2010\)](#) examine the balancing of a ship's economic and environmental performances mainly as regard possible modal shifts that may be caused by speed reduction. [Chatzinikolaou and Ventikos \(2016\)](#), analyzing the emissions from a lifecycle perspective, estimate an increase in emissions with the replacement of one vessel with two, also considering the shipbuilding and recycling processes.

The second scenario is related to vessels fitted with a scrubber. According to the IMO, vessels fitted with scrubbers allow the burning of cheaper HFO. By burning the cheaper HFO fuel (as compared to MGO), ship operators would be able to take advantage and sail at higher speeds versus ships that burn MGO, thus emitting more CO<sub>2</sub>.

Again, the outbreak of the COVID-19 pandemic has masked, to a significant extent, how either of the above two scenarios would play out. However, it is fair to say that both scenarios would manifest themselves under normal circumstances.

### *2.3 Possible modal shifts*

Modal shift scenarios may emerge as a result of the fuel market uncertainty because of the imposition of sulfur cap regulation. From one side, ship operators should strike a balance between the fuel cost and the need for profit maximization. On the other hand, the choice for both shippers and passengers is equilibrium between the price they are willing to pay and the time that they are willing to sacrifice. The increase in freight rates, as well as passenger fares because of a fuel price increase, could lead in a shift toward rail and truck, to the extent the modal choice is available. According to [Zis and Psaraftis \(2017\)](#), modal shift scenarios could occur for ships sailing within sulfur emission control areas (SECAs), as a result of the 0.1% sulfur limit as of January 1, 2015. However, these shifts were not realized due to the significant drop in fuel prices in 2014, a drop that significantly camouflaged the impact of the new regulations. [Panagakos et al. \(2014\)](#) estimated a 5% shift in favor of road transport under the scenario of the designation of the Mediterranean Sea as a SECA.

In terms of environmental risk, a modal shift toward road (and secondarily toward rail) transport can increase CO<sub>2</sub> emissions significantly. [Fenham \(2017\)](#) estimated that for 1 tonne of freight a ship emits 3 gr of CO<sub>2</sub>/km while for rail the emissions are 18 gr of CO<sub>2</sub>/km and for a truck, they are 45 gr of CO<sub>2</sub>/km. According to [Zis et al. \(2019\)](#), the disincentivization of road transport, combined with the additional support of shippers through policy measures could avert possible modal shift scenarios. The proposed measures include:

- The internalization of external costs of transport as a way the environmental cost of the mode choice be transferred to the shipper.
- The increase in road costs through additional taxes.
- The provision of extra subsidies to cover the extra costs of freight rates imposed by ship operators because of high fuel prices.
- The subsidizing of new technological investments to ship operators.

A list of operational measures has also been proposed by Zis and Psaraftis (2019), to mitigate the modal shift risk due to the sulfur cap regulation. Speed reduction can lead to a significant decrease in fuel costs. In the case of Ro-Ro ships, the authors propose a trade-off between the cut-off times to cover the price difference due to lower speed. Finally, they propose the increase of utilization rate of vessels through the change in sailing frequency or the switch of similar vessels among the routes.

The most recent paper of Notteboom (2020) found that the use of low sulfur fuel has only a moderate impact on the cost competitiveness of shortsea routes. Only in a few cases do we see the cost balance in modal competition tilting toward the “truck only” option. The paper further demonstrated that lower vessel utilization degrees can seriously affect the cost competitiveness of routing alternates involving long and shorter roro sections and increase the risk of a modal back shift from sea to road.

2.4 Oil refineries

Based on Nelson (2018), 4% of the total CO<sub>2</sub> emissions are coming from the global refinery sector, while in 2015 it was estimated that the CO<sub>2</sub> emitted by refineries was 970 million tonnes per year globally. Low sulfur fuel oil (LSFO) seems to be the most dominant compliant solution. However, the increase in the production of low sulfur fuel could lead to a rise in CO<sub>2</sub> emissions due to the desulfurization processes. According to International Petroleum Industry Environmental Conservation Association, submission to IMO, the current net CO<sub>2</sub> refinery emissions would increase by 15% due to the production of low sulfur fuels (Gratsos, 2018). Schuller et al. (2019), reported 6% higher emissions for the production of MGO, as compared to HFO.

Conceivable compliance scenarios bring into surface a variety of compliance fuels requiring different energy levels of desulfurization and blending rates. Figure 1 presents a possible scenario developed by Schuller et al. (2019) for the estimation of CO<sub>2</sub> emissions after 2020. This estimation could significantly vary by different blending ratios and various desulfurization processes in a regional scale.

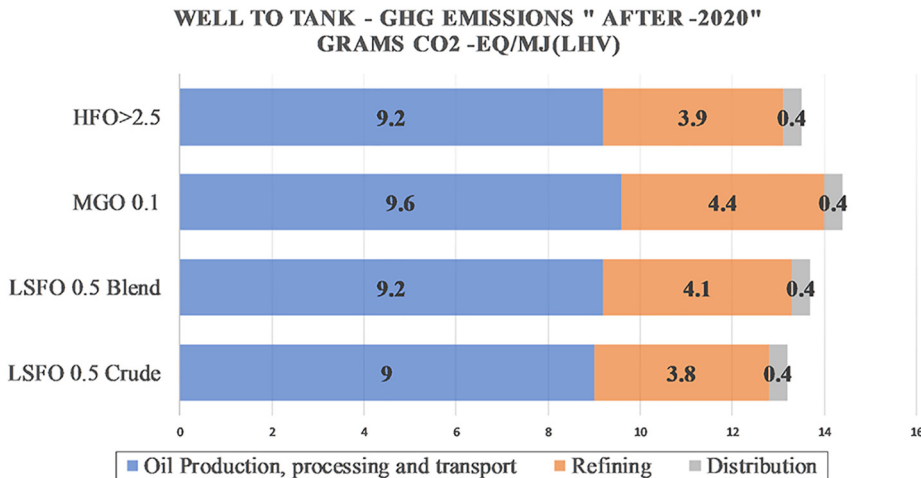


Figure 1. Well to tank – GHG emissions globally – post-2020 scenario breakdown by main processes steps

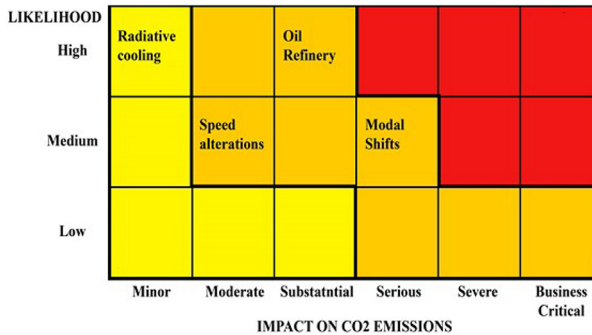
Source: Adapted from Schuller et al. (2019).

### 3. Qualitative risk assessment of carbon dioxide side-effects

Based on the literature analysis of the previous section, we next present a *qualitative* risk assessment, as an effort to make a preliminary evaluation of the severity of risks and possibly guide the actions required to reduce CO<sub>2</sub> emissions. This is shown in Figure 2, which depicts a risk matrix according to the likelihood of occurrence of these actions and their possible impact on CO<sub>2</sub> increase. Three levels of threats are defined, with the yellow area reflecting a low threat (deemed acceptable), the red area reflecting the highest threat (to be avoided) and the orange area corresponding to an intermediate threat (to be reduced). It should be emphasized that this assessment is qualitative and entails a degree of subjectivity.

We further explain Figure 2 as follows.

- *Radiative Cooling*: The probability of occurrence is considered high, as the reduction of sulfur in the atmosphere is proven to lead to radiative cooling, and thus, reduce global warming. Despite the gradient loss of cooling declared by Kontovas (2020), the current study characterizes this impact as minor comparing to the benefits that the sulfur cap will bring to human health.
- *Impact on Ship Speeds*: Given the market uncertainty and the forecasts for an increase in future fuel prices, speed alterations and specifically slow steaming are likely to occur. However, the severity of the impact seems moderate. Slow steaming can cause a reduction in CO<sub>2</sub> emissions in the short term but ships with scrubbers may sail faster.
- *Oil Refineries*: As described by different studies, the desulfurization of fuels requires intensive energy processes, which increase CO<sub>2</sub> emissions. The risk seems to be substantial and may be turned into a severe one in the future if other types of blends demand more energy than the current ones. However, this existing problem could be prevented with possible improvements in refinery processes.
- *Possible Modal Shifts*: The scenario of modal shifts seems to be the most critical regarding the increase of CO<sub>2</sub> emissions. Turning to a road solution will increase CO<sub>2</sub> emissions directly, creating a significant environmental danger. An increase in maritime freight rates could also lead to modal shifts to the road. However, the probability of a modal shift is considered to range from low to medium.



**Figure 2.** Qualitative risk/threats assessment matrix. Major threats to the increase of CO<sub>2</sub> emissions are mapped based on likelihood and impact

#### 4. Methodology: assessment of sulfur cap impact

This section examines the impact of the global sulfur cap in both financial and environmental terms. To that effect, a scrubber scenario and an MGO scenario are compared with a baseline HFO scenario in a specific case study.

##### 4.1 Calculation of fuel emissions

The emission factors and the assumptions suggested by the third IMO GHG Study (IMO, 2014) are used for the calculation of the bottom-up emissions  $E_P$  (tonnes/year) of a specific pollutant:

$$E_P = FC_k \times EF_p \quad (1)$$

where  $FC_k$  is the fuel consumption of the specific fuel type  $k$  and  $EF_p$  the emission factor for the type of pollutant  $p$ .

Based on the third IMO GHG study (IMO, 2014), CO<sub>2</sub> factors are not sulfur dependent and are presented in Table 1.

The calculation of SO<sub>x</sub> is proportional to the content of sulfur in the fuel and is calculated based on equation (2) under the assumption that 97.753% of the fuel is converted to SO<sub>x</sub> while the rest is converted to sulfites. The sulfur content in the fuel for this study is HFO 3.5% and MGO 0.5%, as listed in the case study assumptions in Section 5.

$$EF_{sox} = 2 \times 0.97753 \times S\% \quad (2)$$

##### 4.2 Estimation of cost elements

The following cost elements are important:

4.2.1 *Cost of switching to marine gas oil.* The lower price of HFO as compared to MGO creates a benefit in favor of HFO users. This price differential between the two fuels is to be contrasted with the high investment cost of a scrubber.

The next formula expresses the cost differential  $C_{MGO}$  because of fuel change:

$$C_{MGO} = FC_{HFO} \times P_{HFO} - FC_{MGO} \times P_{MGO} \quad (3)$$

where  $FC_{MGO}$  and  $FC_{HFO}$  are the fuel consumptions of MGO and HFO (respectively) for a number of calls per year and  $P_{MGO}$  and  $P_{HFO}$  are the corresponding fuel prices.

The fuel prices used here are in Table 2 and are given by Bunkerworld (2019) for the port of Rotterdam on the 2nd of April 2019. The HFO price used corresponds to the IFO 380 fuel price.

4.2.2 *Scrubber capital costs.* Unlike MGO, a scrubber has a high capital cost (CAPEX) depending on the size of the ship and the engine. This is considered as an initial investment cost. Additional scrubber costs are related to the scrubber's maintenance (OPEX) during its

Fuel type/emission factor (g/g fuel)	CO <sub>2</sub>	SO <sub>x</sub>
HFO	3.114	0.0684
MGO	3.206	0.0098

Source: IMO (2014)

**Table 1.**  
Emission factors g/g  
fuel by fuel and  
emission type

lifespan. Given that the variations of scrubber costs are high among the different ship sizes, [Table 3](#) presents the prices used for the current study based on the scrubber costs estimation provided by the SECA Investment Tool developed in the Envisum Project in the Baltic Sea Region (Envisum, 2019).

*4.2.3 Refining costs.* There is an additional amount of CO<sub>2</sub> emissions coming from refineries because of the refining process of distillate fuels. The amount of CO<sub>2</sub> emissions is higher for the low sulfur fuel as compared to HFO due to the more energy – demanding desulfurization process.

The following formula describes the refining emissions  $E_k^{RF}$  for the MGO and HFO:

$$E_k^{RF} = FC_k \times CF_k \tag{4}$$

for the different fuel types  $k$ ,  $FC_k$  (tonne) is the fuel consumption and  $CF_k$  (tonne CO<sub>2</sub>/tonne of oil equivalent) the refining emission factor.

Based on [Figure 1](#), a refinery emission factor of CO<sub>2</sub> per tonne of oil equivalent is calculated both for an HFO and MGO fuel and used for the current study. The calculation of the refining emission factor is based on the following transformation: 1 MJ = 0.0000238 tonnes of oil equivalent. According to this, the values presented in [Figure 1](#) are converted into refining emission factors as these are presented in [Table 4](#).

The calculated values are based on a post-January 1, 2020 GHG refining emission scenario presented by [Schuller et al. \(2019\)](#). Different studies present higher or lower values. The cost of CO<sub>2</sub> emissions  $C_k^{RF}$  emitted from refineries for the production of MGO and HFO is calculated as:

$$C_k^{RF} = E_k^{RF} \times C_{CO2} \tag{5}$$

Based on different approximations as they were presented in Section 2.3, where the cost  $C_{CO2}$  is based on the global value of 42 €/tonne of CO<sub>2</sub> emissions presented in [Table 5](#). The value is conservative as the real cost of global warming is unknown, and its effects could be quite higher than the proposed value. Given that in many countries refineries are still not charged for the extra CO<sub>2</sub> they produce, this cost is directly transferred to society.

*4.2.4 External costs of carbon dioxide emissions.* Shipping activities entail important externalities. The monetary translation of these adverse effects on society can considerably

**Table 2.**  
Fuel prices in  
Rotterdam port 2019  
in €/tonne

Fuel costs 2019	
MGO	518.29 €/tonne
HFO	368.17 €/tonne

**Source:** [Bunkerworld \(2019\)](#)

**Table 3.**  
Scrubber costs

Engine output	CAPEX	OPEX
11,060 KW	3 541 480 €	7 936 €/year
12,600 KW	3 630 800 €	8 860 €/year
18,900 KW	3 996 200 €	12,640 €/year

**Source:** Envisum (2019)



change the way that ship-owners make environmental decisions. If ship-owners had to pay for the health damage caused by shipping activity, then both the price of compliance and the compliant choices because of environmental regulations might be different. However, the external costs that are not internalized are still paid for by society. Undoubtedly, this creates market instability where the ships pollute more than in the hypothetical case that external costs were internalized.

Zis *et al.* (2017) suggested a generalized formula for the conversion of the external costs into a monetary value with the use of a cost factor per unit of emission. Jiang *et al.* (2014), used the marginal external costs of air emissions as they are presented in the CAFE (for Clean Air For Europe) and HEATCO (for Developing Harmonised European Approaches for Transport Costing and Project Assessment) projects. Also, the cleaner shipping study presented by The Danish Ecological Council (2018) provided a conservative estimation on the cost of the health damage due to shipping activities in and out of the North European SECA, based on an estimation for CO<sub>2</sub>, SO<sub>x</sub>, PM and NO<sub>x</sub> emissions.

Given that the climate change caused by GHG emissions (CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>) has a global effect, a global external cost factor of CO<sub>2</sub> is suggested for the monetization of the global warming effect. However, it remains unclear, which is the most suitable method for the internalization of external costs in shipping activities. Table 5 presents different values as they are suggested by different studies.

4.2.5 *Environmental benefits of emission reduction measures.* According to Jiang *et al.* (2014), the emission reductions  $\Delta E_p^{scrubber}$  and  $\Delta E_p^{MGO}$  after switching to scrubber and MGO (respectively), could be described as follows (all emissions are in tonnes/year):

$$\Delta E_p^{scrubber} = E_p - E_p^{scrubber} \quad (6)$$

$$\Delta E_p^{MGO} = E_p - E_p^{MGO} \quad (7)$$

CO <sub>2</sub> emissions from refining	
MGO	0.18 tonne CO <sub>2</sub> /tonne of MGO equivalent
HFO	0.16 tonne CO <sub>2</sub> /tonne of HFO equivalent

**Table 4.**  
Emission factor of CO<sub>2</sub> because of the refining process for HFO and MGO fuels

Source: Estimation based on Figure 1 provided by Schuller *et al.* (2019)

Suggested value of CO <sub>2</sub> cost factor	Source
0.025 €/kg	Maibach <i>et al.</i> (2008)
0.090 €/kg	Korzhenevych <i>et al.</i> (2014)
0.011 €/kg	Zis <i>et al.</i> (2017)
0.07 (low values) €/kg	Zis <i>et al.</i> (2019)
0.1104 (medium values) €/kg	
0.2061 (high values) €/kg	
0.1104 (Baltic Sea) €/kg	
0.026 €/kg–0.042 €/kg	The Danish Ecological Council (2018)

**Table 5.**  
Cost of CO<sub>2</sub> equivalent in different studies

where  $E_p$  are the emissions because of a specific type of emission  $p$  with the use of HFO, and  $E_p^{scrubber}$  and  $E_p^{MGO}$  are the corresponding emissions if a scrubber or MGO is used (respectively).

These equations can express the possible environmental benefits or costs because of a switch in the compliance choice.

The next formula describes the monetization of the benefits and costs because of the use of a scrubber or MGO:

$$B_p^{scrubber} = C_p \times \Delta E_p^{scrubber} \tag{8}$$

$$B_p^{MGO} = C_p \times \Delta E_p^{MGO} \tag{9}$$

where  $C_p$  is the (external) cost factor for each emissions type  $p$ :  $SO_x$ ,  $CO_2$ .

The external cost factors used in this paper are based on the most recent values representing health damage provided by the Danish Ecological Council (2018), as per the previous section. All values are converted in €/kg of emissions according to 2019 prices and they constitute in our opinion a conservative estimation (Table 6).

#### 4.3 Cost-benefit analysis

The cost-benefit equations are used for the calculation of the attractiveness of the two compliance choices, scrubber and MGO. The two different options are ranked, and the one with a higher net present value (NPV) is considered as the most attractive. Given that the decision of the ship operators lies on the financial attractiveness of a project, two different types of NPV are calculated for this study. First, a financial analysis is conducted based on the costs and profits of the investment. However, both choices are having positive and negative impacts on the environment. Thus, the second analysis is taking into consideration the environmental impacts associated with both the shipping activities and the refineries.

In our calculations, any cost has a negative value while all the environmental benefits because of the reduction measures have positive values. All costs and benefits are measured in monetary units. The analysis period is considered to be 12 years, the same as the lifespan of a scrubber in a retrofit vessel (Jiang *et al.*, 2014). The cash flows are discounted in the present value with a discount rate of 5% as in relevant studies (Jiang *et al.*, 2014). Lower discount rates would tilt the results more in favor of the scrubber option.

The next formulas describe the  $NPV_{financial}^{scrubber}$ :

$$NPV_{financial}^{scrubber} = CAPEX + \sum_{t=0}^{12} \frac{OPEX + C_{HFO}}{(1+r)^t} \tag{10}$$

**Table 6.**

External cost factors

Emissions type:	SOx	CO <sub>2</sub>
€/kg	15.8	0.042

where  $CAPEX$  is the capital cost of a scrubber investment,  $OPEX$  is the operational and maintenance cost of a scrubber,  $C_{HFO}$  the extra HFO fuel cost as compared to the baseline HFO scenario and  $r$  is the discount rate.

For the MGO, the financial estimation  $NPV_{financial}^{MGO}$  is given by the following formula:

$$NPV_{financial}^{MGO} = \sum_{t=0}^{12} \frac{C_{MGO}}{(1+r)^t} \quad (11)$$

For our analysis, the financial cost of MGO is calculated in the lifespan of a scrubber.

These formulas are different when the socio-economic dimension  $NPV_{environmental}$  is considered for both alternatives.

$$NPV_{environmental}^{scrubber} = CAPEX + \sum_{t=0}^{12} \frac{B^{scrubber} - (OPEX + C_{HFO} + C_{hfo}^{RF})}{(1+r)^t} \quad (12)$$

$$NPV_{environmental}^{MGO} = \sum_{t=0}^{12} \frac{B^{MGO} - (C_{MGO} + C_{mgo}^{RF})}{(1+r)^t} \quad (13)$$

where  $B^{MGO}$  and  $B^{scrubber}$  represent the annual environmental benefits/costs compared to the base case as they are described in Subsection 3.2.3 and  $C_{hfo}^{RF}$ ,  $C_{mgo}^{RF}$  are the refining costs for the production of HFO and MGO, respectively.

#### 4.4 Profitability of investment

Given that the environmental costs and benefits are not paid for by the ship operators, the post-January 1, 2020 compliance choice is related to the time that the investment will pay back and starts being profitable.

For our analysis, the profitability calculation is based on the comparison between scrubber and MGO. MGO can be considered as a “do-nothing” scenario. The NPV estimation is conducted for different price scenarios to test the profitability of these two choices under various market conditions.

The next formula describes the calculation of NPV for post-January 1, 2020 implementation:

$$NPV = CAPEX + \sum_{t=0}^{12} \frac{OPEX + C_{MGO}}{(1+r)^t} \quad (14)$$

The profitability lies in the price difference between HFO and MGO. Based on the current fuel prices and the average fuel price fluctuations from 2015 to 2019, three different price scenarios are developed as they presented in the table. The first scenario is based on April 2019 prices while the other two scenarios are based on the scenarios in price differentiation presented by Meech (2017) (Table 7).

Due to the uncertainty of the fuel market conditions and the lack of accurate fuel price predictions, these prices consist of a subjective estimation of the possible market trends and can vary a lot from future prices. No effects of COVID-19 have been assessed (Section 6.1).

## 5. Analysis and results

### 5.1 Case studies

Three real cases have been used to examine the financial and environmental impact in terms of SO<sub>x</sub> and CO<sub>2</sub> emissions of the sulfur cap regulation. The examined routes are in the Mediterranean Sea because of the extensive discussion about its possible designation as a SECA in the future (Panagakos *et al.*, 2014). Both Ro-Ro and container vessels of different sizes are examined. The required data for the study are based on the information provided by the companies operating the vessels as described in Table 8. The names of the shipping companies are not disclosed.

The assumptions used for our analysis can be summarized as follows:

- The free sailing phase is considered as the most critical contributor to emissions. The berthing and maneuvering phases are not taken into consideration in this study, as they are connected mostly to environmental costs within the specific port areas and because they are substantially lower. Including them would be a straightforward extension, which we speculate would not change the main thrust of the results.
- The fuel consumption during free sailing is based on average data as they were provided by the ship operators.
- In the basis scenario, the vessels use HFO 3.5% for the main engine and MGO 0.5% for the auxiliary engine and the boiler.
- The vessels with scrubbers have an increase of 2% in their fuel consumption while they use the cheaper HFO (DNV GL, 2019).
- The calculation of emissions and the cost-benefit analysis are conducted separately for each case. All emissions are converted into monetary terms. All prices are expressed in € while all masses are calculated in tonnes per year.
- For each of the cases, the cost-benefit analysis was conducted in two stages. First, including only financial values. Second, taking into consideration also the

**Table 7.**  
Post-2020 fuel price  
scenarios in €

Scenarios	HFO	MGO	Difference
1. April 2019	368 €	518 €	150 €
2. HFO stable – MGO increase	380 €	593 €	213 €
3. HFO drop – MGO increase	280 €	700 €	420 €

**Table 8.**  
Description of the  
technical vessel  
characteristics, the  
route characteristics  
and the fuel  
consumption

Route/vessel data	Marseille – Tunis	Trieste – Yalova	Said – Aliaga
Vessel type	Ro – Ro cargo	Ro – Ro cargo	Container
Year of built	2000	2009	2002
Engine output (kW)	12,600	18,900	11,060
Deadweight (tonnes)	8,702	11,235	12,123
Main fuel	IFO 380	IFO 380	IFO 380
Speed (knots)	15	19	14
Distance (nm)	499	1,202	964
Time at sea (hrs)	35	65	70
Voyages per year	148	72	88
Main engine consumption (tonnes/year)	6,299	13,376	3,810
Auxiliary engine consumption (tonnes/year)	191.3	229.6	76.6

environmental impacts of CO<sub>2</sub> and SO<sub>x</sub> emissions of shipping activities, as well as the refining costs for the production of the fuels. PM and NO<sub>x</sub> emissions are not taking into consideration for the specific study.

## 5.2 Results

The results of the three case studies are based on the methodology presented in Section 4.

**5.2.1 Calculation of emissions.** The emissions of SO<sub>x</sub> and CO<sub>2</sub> are calculated for the three cases, based on the fuel consumption of each vessel for the whole year and the corresponding emission factors as provided by the IMO.

**Table 9** presents the annual tonnes of emissions for each route. As expected, compliance with the sulfur regulation entails a significant decrease in SO<sub>x</sub> emissions with both MGO and scrubber. MGO decreases sulfur at 85.7% while scrubber almost at 98.7% in comparison with HFO. **Table 9** presents the emissions in tonnes as they calculated for the three cases.

Even though compliance with sulfur regulation entails a reduction in SO<sub>x</sub> emissions, concerning the shipping activity, the use of MGO increases the CO<sub>2</sub> emissions by 3% as compared to the current HFO case. Moreover, the use of a scrubber entails an increase of 2% as compared to the HFO case, corresponding to the higher amount of HFO that is burned.

In addition to this, there is an increase in CO<sub>2</sub> emissions coming from the refinery level. The refining of MGO causes an increase of 13% in CO<sub>2</sub> comparing to the CO<sub>2</sub> released for the refining of the same amount of HFO. **Figure 3** presents the overall yearly CO<sub>2</sub> emissions, defined as emissions from shipping activity plus emissions from refinery, for each of three cases.

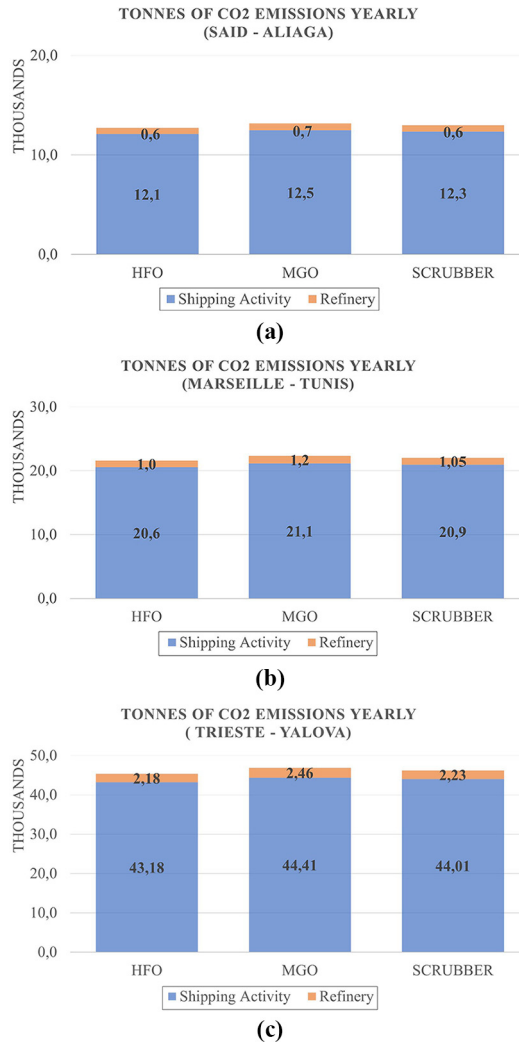
From the comparison of the emission volumes, it can be noticed that the amount of CO<sub>2</sub> released during the shipping activity consists of 95% of the whole CO<sub>2</sub> emissions, with refinery responsible only for 5%.

**5.2.2 Cost-benefit analysis.** The cost-benefit analysis is conducted to evaluate both MGO and scrubber choices in comparison with the base HFO case. Two different NPV indicators are calculated for each of the case studies. First,  $NPV_{financial}$  is calculated, taking into consideration the costs related to fuel, initial investment and maintenance. Second,  $NPV_{environmental}$  is calculated, including not only the costs but also the internalized CO<sub>2</sub> and SO<sub>x</sub> emissions because of shipping activity and the CO<sub>2</sub> emissions coming from the refineries for the production of fuels (**Table 10**).

From a financial perspective, it can be seen that compliance entails a substantial cost. The scrubber has a better ranking comparing to MGO as the lower HFO price overspreads the required scrubber investment cost.

Tonnes of emissions	HFO	MGO	Scrubber	Routes
SO <sub>x</sub>	261	38	3	Said-Aliaga
CO <sub>2</sub>	12,111	12,462	12,348	
SO <sub>x</sub>	434	64.4	7	Marseille –Tunis
CO <sub>2</sub>	20,556	21,136	20,949	
SO <sub>x</sub>	920	135.4	14	Trieste – Yalova
CO <sub>2</sub>	43,181	44,412	44,015	

**Table 9.**  
Tonnes of emissions  
per emission type per  
year



**Figure 3.** Shipping activity and refinery CO<sub>2</sub> emissions for the three routes (a) Said – Aliaga, (b) Marseille – Tunis and (c) Trieste – Yalova

From an environmental perspective, both the MGO and scrubber have a positive environmental impact compared to the previous HFO situation. Having a higher NPV, the scrubber choice ranks better than MGO when it comes to the environmental evaluation.

*5.2.3 Profitability of scrubber investment.* Table 11 describes the estimated payback period for different fuel price scenarios. Scrubber is a profitable investment as long as there is a significant price differential between HFO and MGO. If the spread between MGO and HFO narrows considerably, then the payback period of a scrubber investment becomes longer. The containership of Said – Aliaga has a long payback period with the 2019 fuel prices. Its payback period remains long also in different fuel scenarios comparing to the 12 years lifespan. On the other side, the larger Ro-Ro vessel of the Trieste – Yalova route seems to benefit a lot from the price difference between HFO and MGO, and the same is the

case with the Ro-Ro vessel of Marseille – Tunis. This can indicate that vessels with larger engines enjoy a benefit from a scrubber investment while smaller container ships may not undertake the risk of a scrubber, and hence, may prefer to comply via MGO.

In that sense, if the containership of the Said – Aliaga route complies via MGO, then a high increase in MGO prices can lead to an increase in freight rates. However, a modal shift scenario does not seem applicable in that case due to poor road infrastructure and the war that is going on in the Middle East. In a similar scenario, in which the vessel of the Trieste – Yalova route uses a scrubber as the most profitable investment and the fuel price of HFO decreases, there is an extra amount of CO<sub>2</sub> due to a possible increase of speed in the Mediterranean. This amount could be significant enough if we take into consideration the overall volume of CO<sub>2</sub> coming from Ro-Ro vessels as it was presented in the emission results. From all the examined scenarios, it can be noticed that only the route of Trieste-Yalova seems to be prone to a modal shift scenario because of adequate infrastructure connections in these areas.

Finally, with the smaller vessels being less resilient in a scrubber investment, a sudden narrowing of the price difference between MGO and HFO could weaken smaller ship operators. This raises the need for an early evaluation and development of risk frameworks by ship operators.

## 6. Final remarks

### 6.1 Limitations of analysis – the impact of COVID-19

Fuel price data in this paper was based on 2019 data. As this paper was being written, the COVID-19 pandemic created a significant upheaval in global trade flows, cargo demand and fuel prices. This made any attempt to perform even a rudimentary ex-post evaluation of the 2020 sulfur cap virtually impossible. Due to limited data, such an evaluation would be extremely difficult even under normal circumstances. However, the COVID-19 crisis created

NPV financial		Said – Aliaga	Marseille – Tunis	Trieste – Yalova
Scrubber NPV		-3.9	-4.2	-5
MGO NPV		-5.6	-9.3	-19.8
NPV environmental				
Scrubber environmental benefits/costs	SOx	40	66	141
	CO <sub>2</sub>	-0.113	-0.163	-0.345
	CO <sub>2</sub> refinery	-0.006	-0.010	-0.020
Scrubber NPV		42	62	136
MGO environmental benefits/costs	SOx	35	58	122
	CO <sub>2</sub>	-0.145	-0.27	-0.510
	CO <sub>2</sub> refinery	-0.033	-0.05	-0.116
MGO NPV		29	48	102

**Table 10.**  
Net present value of scrubber in million €, MGO in comparison with an HFO scenario

Route/scenario	Payback period for different price fuel scenarios		
	Said-Aliaga	Marseille-Tunis	Trieste-Yalova
1	6.5 years	3.5 years	1.5 years
2	2.5 years	1.5 years	1 year
3	1.5 years	1 year	9 months

**Table 11.**  
Payback period for different fuel price scenarios

a multitude of completely unforeseen circumstances that are relevant as regard both sulfur and carbon emissions. For instance, if ships burning MGO were expected to slow down in 2020 by virtue of using more expensive fuel than a year ago, the precipitous drop in fuel prices as a result of COVID-19 made such a slow steaming scenario highly unlikely. Containerships on the Far East to Europe route were observed sailing around Africa at higher speeds than before, as it was cheaper to do so than paying the Suez canal tolls. As a result, these ships emitted more CO<sub>2</sub>. In addition, the much lower than anticipated fuel price difference between MGO and HFO may very well render scrubber investments a posteriori questionable, even though when the relevant decisions were made, they were obviously justified by completely different fuel price forecasts. For instance, in April 2020 fuel price differences between MGO and HFO were recorded as low as 43 (143–100) €/tonne (Ship and Bunker, 2021). Such price differences, if sustained, would result in a significant increase of scrubber payback periods. In this case, the scrubber payback periods for the Marseille-Tunis and Said-Aliaga routes would exceed the scrubbers' economic life of 12 years and would increase to 7.5 years for the Trieste-Yalova route.

Yet, and to the extent that COVID-19 is only a transient phenomenon, and in spite of the above and other factors that are difficult or impossible to ascertain at this time, we believe that the analysis in this paper is still relevant, and will be even more so as soon as the shipping markets return to a more normal state. For an analysis of COVID-19 impacts on the shipping sector (see Hoffmann *et al.*, 2020).

Moreover, as the case studies concern only a subset of the shipping sector and have a specific geographical coverage, their results are to be interpreted with caution. Even though we conjecture that similar results are relevant in other shipping sectors and in other geographical areas, this will need to be confirmed with relevant analysis.

As this paper was being finalized, the 4th IMO GHG study was released and approved by the IMO, covering emissions up to 2018 (IMO, 2020). A perhaps surprising result of the study was that SO<sub>x</sub> emissions have increased, even though as of January 1, 2015 a maximum 0.1% sulfur fuel has been mandated in the European, North American and US Caribbean SECAs. Indeed, the study shows a SO<sub>x</sub> increase from 10.1 million tonnes in 2014 (the year before the 0.1% SECA limit) to 11.4 million tonnes in 2018. This is a 13% increase. The explanation offered in the study is that the average sulfur content increase in HFO over the period exceeds the sulfur content reduction associated with the change in fuel use.

## 6.2 Conclusions

Through three case studies, the paper examined the impact of the compliant options in CO<sub>2</sub> emissions. The results enclosed in the study indicate the importance of the global sulfur cap for the improvement of human health. However, they also indicate a negative impact of both MGO and scrubber in terms of CO<sub>2</sub> emissions.

From a financial perspective, the choice of a scrubber ranks better comparing to an MGO choice because of the price difference between MGO and HFO. However, and under different price scenarios, the scrubber choice remains sustainable only for large vessels. It is noticed that small containerships cannot outweigh the capital cost of a scrubber investment and are more sensitive to different fuel price scenarios.

From an environmental perspective, scrubbers rank better than MGO in the assessment of overall emissions. In terms of CO<sub>2</sub> emissions, MGO contributes more than scrubbers. Besides, the amount of CO<sub>2</sub> is increasing more if the refinery emissions are considered. It is estimated that to produce MGO, the refineries emit 13% more CO<sub>2</sub> than for the production of HFO. However, this amount cannot be comparable in size with the significant amount of CO<sub>2</sub> released by the shipping



activity. Overall, this paper calculates a 3% increase in CO<sub>2</sub> emissions with the use of MGO as compared to HFO.

Moreover, further contributors to GHG emissions were also analyzed, and a qualitative risk assessment was conducted. The loss of radiative cooling was characterized by a high likelihood of occurrence, but it was considered acceptable because of the benefits to human health. Speed alterations were considered as a medium impact as it remains unknown under which conditions these would occur. As far as oil refineries are concerned, the desulfurization of fuels has a significant contribution to CO<sub>2</sub> emissions, which could be severe in the future if different blends require more energy. Finally, modal shift scenarios could have the highest impact on CO<sub>2</sub> emissions. However, poor road infrastructure and unstable geopolitical conditions in some routes are limiting factors.

## References

- BIMCO (2019) "December bulletin", BIMCO, available at: <http://portfolio.cpl.co.uk/portfolio/BIMCO/201912/cover/> (accessed 19 April 2019).
- Bunkerworld (2019) "Fuel prices in Rotterdam port", Bunkerworld, available at: [www.bunkerworld.com/prices/](http://www.bunkerworld.com/prices/) (accessed 19 April 2019).
- Cariou, P. (2011), "Is slow steaming a sustainable means of reducing CO<sub>2</sub> emissions from container shipping?", *Transportation Research Part D: Transport and Environment*, Vol. 16 No. 3, pp. 260-264, doi: [10.1016/j.trd.2010.12.005](https://doi.org/10.1016/j.trd.2010.12.005).
- Chatzinikolaou, S.D. and Ventikos, N.P. (2016), "Critical analysis of air emissions from ships: lifecycle thinking and results", in Psaraftis H.N. (Ed.), *Green Transport and Logistics Springer*, Springer, Cham, pp. 387-412, doi: [10.1007/978-3-319-17175-3\\_11](https://doi.org/10.1007/978-3-319-17175-3_11)
- Clarksons Research (2019), "Scrubber count update and Imo 2020 market impact assessment", Clarksons Research, July 2019 No.3, available at: [www.vda.org.tr/upload/duyuru/scrubber%20count%20report%20for%202020.pdf](http://www.vda.org.tr/upload/duyuru/scrubber%20count%20report%20for%202020.pdf) (accessed 19 April 2019).
- DNV GL (2019), "Global sulfur cap 2020. Compliance options and implications for shipping—focus on scrubbers", DNV GL, available at: [www.intercargo.org/wp-content/uploads/2019/06/DNV\\_Global\\_Sulfur\\_Cap\\_2020.pdf](http://www.intercargo.org/wp-content/uploads/2019/06/DNV_Global_Sulfur_Cap_2020.pdf) (accessed 19 April 2019)
- Envisum (2019), "Seca Investment Tool", Envisum, available at: <https://envisum.ttu.ee/index.php>. [accessed 19 April 2019]
- Fenham, J.V. (2017), "CO<sub>2</sub> emissions from international shipping", *UNEP DTU Partnership Working Paper Series 2017*, Vol. 4.
- Fuglestedt, J., Berntsen, T., Eyring, V., Isaksen, I., Lee, D.S. and Sausen, R. (2009), "Shipping emissions: from cooling to warming of climates – and reducing impacts on health", *Environmental Science and Technology*, Vol. 43 No. 24, pp. 9057-9062, doi: [10.1021/es901944r](https://doi.org/10.1021/es901944r).
- Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K. and Murphy, A. (2018), "Assessment of full life-cycle air emissions of alternative shipping fuels", *Journal of Cleaner Production*, Vol. 172, pp. 855-866, doi: [10.1016/j.jclepro.2017.10.165](https://doi.org/10.1016/j.jclepro.2017.10.165).
- Gratsos, G. (2018), "Global warming, mankind, the environment, transport, shipping and clear thinking", available at: [www.academia.edu/38936281/Global\\_Warming\\_Mankind\\_the\\_Environment\\_Transport\\_Shipping\\_and\\_Clear\\_Thinking\\_revised\\_April\\_25th\\_2019](http://www.academia.edu/38936281/Global_Warming_Mankind_the_Environment_Transport_Shipping_and_Clear_Thinking_revised_April_25th_2019)
- Hoffmann, J., Benamara, H., Hopp, D. and Rodriguez, L. (2020), "Navigating through the coronavirus crisis and uncertainty – how maritime transport data can help", Article No. 60 [UNCTAD Transport and Trade Facilitation Newsletter N°87 – Third Quarter 2020], available at: <https://unctad.org/news/navigating-through-coronavirus-crisis-and-uncertainty-how-maritime-transport-data-can-help> (accessed 25 December 2020)

- IMO (2014), "Greenhouse gas study 2014", Executive Summary and Final Report. International Maritime Organization (IMO), pp. 57-58.
- IMO (2016), *Study on Effects of the Entry into Force of the Global 0.5% Fuel Oil Sulfur Content Limit on Human Health*, International Maritime Organization (IMO).
- IMO (2018), "Initial Imo strategy on reduction of GHG emissions from ships", *MARPOL Annex IV Resolution MEPC*, Vol. 304 No. 72.
- IMO (2019b), *Reduction of the Impact on the Arctic of Black Carbon Emissions from International Shipping*, International Maritime Organization (IMO).
- IMO (2020), *Greenhouse Gas Study 2020, Executive Summary and Final Report*, International Maritime Organization (IMO).
- Jiang, L., Kronbak, J. and Christensen, L.P. (2014), "The costs and benefits of sulfur reduction measures: sulfur scrubbers versus marine gas oil", *Transportation Research Part D: Transport and Environment*, Vol. 28, pp. 19-27, doi: [10.1016/j.trd.2013.12.005](https://doi.org/10.1016/j.trd.2013.12.005).
- Kontovas, C.A. (2020), "Integration of air quality and climate change policies in shipping: the case of sulfur emissions regulation", *Maritime Policy*, Vol. 113, doi: [10.1016/j.marpol.2020.103815](https://doi.org/10.1016/j.marpol.2020.103815).
- Korzheneych, A., Dehnen, N., Bröcker, J., Holtkamp, M., Meier, H., Gibson, G., Varma, A. and Cox, V. (2014), "Update of the handbook on external costs of transport: final report for the European commission: DG-MOVE", Ricardo AEA, available at: <https://ec.europa.eu/transport/sites/transport/files/themes/sustainable/studies/doc/2014-handbook-external-costs-transport.pdf>
- Maibach, M., Schreyer, C., Sutter, D., Van Essen, H.P., Boon, B.H., Smokers, R., Schrotten, A., Doll, C., Pawlowska, B. and Bak, M. (2008), *Handbook on Estimation of External Costs in the Transport Sector*, Ce Delft.
- Meech, R. (2017), "6th bunkernet bunker conference industry trends and 2020", Marine and Energy Consulting Limited, available at: <https://bunkernet.com.cy/wp-content/uploads/2017/04/02-Robin-Meech-Bunkernet-6-April-2017-2-PRINT.pdf> (accessed 5 January 2020).
- Nelson, R. (2018), "The importance of carbon capture and storage technology in European refineries", *Concawe Review*, Vol. 27 No. 1, pp. 34-47.
- Notteboom, T. (2020), "Roro shipping vs. trucking: revisiting the impact of low-sulphur marine fuel use on cost competitiveness of routing options in North Europe", *WMU Journal of Maritime Affairs*, Vol. 19 No. 4, pp. 399-426.
- Panagakos, G.P., Stamatopoulou, E.V. and Psaraftis, H.N. (2014), "The possible designation of the Mediterranean sea as a SECA: a case study", *Transportation Research Part D: Transport and Environment*, Vol. 28, pp. 74-90, doi: [10.1016/j.trd.2013.12.010](https://doi.org/10.1016/j.trd.2013.12.010).
- Partanen, A.I., Laakso, A., Schmidt, A., Kokkola, H., Kuokkanen, T., Pietikäinen, J.P., Kerminen, V.M., Lehtinen, K.E.J., Laakso, L. and Korhonen, H. (2013), "Climate and air quality trade-offs in altering ship fuel sulfur content", *Atmospheric Chemistry and Physics*, Vol. 13 No. 23, pp. 12059-12071, doi: [10.5194/acp-13-12059-2013](https://doi.org/10.5194/acp-13-12059-2013).
- Psaraftis, H.N. (2019), "Speed optimization for sustainable shipping", in Psaraftis, H.N. (Ed.). *Sustainable Shipping*, Springer, Cham, pp. 339-374, doi: [10.1007/978-3-030-04330-8\\_10](https://doi.org/10.1007/978-3-030-04330-8_10).
- Psaraftis, H.N. and Kontovas, C.A. (2010), "Balancing the economic and environmental performance of Maritime transportation", *Transportation Research Part D: Transport and Environment*, Vol. 15 No. 8, pp. 458-462, doi: [10.1016/j.trd.2010.05.001](https://doi.org/10.1016/j.trd.2010.05.001).
- Schuller, O., Kupferschmid, S., Hengstler, S. and Whitehouse, S. (2019), "Life cycle GHG emission study on the use of LNG as marine fuel", Sphera, available at: <https://sphera.com/research/life-cycle-ghg-emission-study-on-the-use-of-lng-as-marine-fuel/> (accessed 5 January 2020).
- Ship and Bunker (2021), "Fuel prices in Rotterdam port", Ship and Bunker, available at: <https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#IFO380> (accessed 5 January 2021)

- 
- The Danish Ecological Council (2018) “Cleaner shipping-focus on air pollution, technology and regulation”, The Danish Ecological Council, available at: [www.dendanskemaritimefond.dk/wp-content/uploads/2017/03/Cleaner-Shipping\\_Ecological-Council.pdf](http://www.dendanskemaritimefond.dk/wp-content/uploads/2017/03/Cleaner-Shipping_Ecological-Council.pdf) (accessed 5 January 2020)
- Topali, D. and Psaraftis, H.N. (2019), “The enforcement of the global sulfur cap in Maritime transport”, *Maritime Business Review*, Vol. 4 No. 2, pp. 199-216, doi: [10.1108/MABR-12-2018-0050](https://doi.org/10.1108/MABR-12-2018-0050).
- Tzannatos, E. and Nikitakos, N. (2013), “Natural gas as a fuel alternative for sustainable domestic passenger shipping in Greece”, *International Journal of Sustainable Energy*, Vol. 32 No. 6, pp. 724-734, doi: [10.1080/14786451.2013.811414](https://doi.org/10.1080/14786451.2013.811414).
- UNCTAD (2018), “Review of Maritime transport”, *United Nations Conference on Trade and Development*, doi: [0.18356/a9b345e7-en](https://doi.org/0.18356/a9b345e7-en).
- Ushakov, S., Stenersen, D. and Einang, P.M. (2019), “Methane slip from gas fuelled ships: a comprehensive summary based on measurement data”, *Journal of Marine Science and Technology*, Vol. 24 No. 4, pp. 1-18, doi: [10.1007/s00773-018-00622-z](https://doi.org/10.1007/s00773-018-00622-z).
- Zis, T.P.V. and Cullinane, K. (2020), “The desulfurisation of shipping: past, present and the future under a global cap”, *Transportation Research Part D: Transport and Environment*, Vol. 82, doi: [10.1016/j.trd.2020.102316](https://doi.org/10.1016/j.trd.2020.102316).
- Zis, T., Panagakos, G., Kronbak, J. and Psaraftis, H.N. (2017), *Report on the Outcome of Task 3.2: Measures from Policy Makers*, Technical University of Denmark.
- Zis, T. and Psaraftis, H.N. (2019), “Operational measures to mitigate and reverse the potential modal shifts due to environmental legislation”, *Maritime Policy and Management*, Vol. 46 No. 1, pp. 117-132.
- Zis, T. and Psaraftis, H.N. (2017), “The implications of the new sulfur limits on the European Ro-Ro sector”, *Transportation Research Part D: Transport and Environment*, Vol. 52, pp. 185-201, doi: [10.1016/j.trd.2017.03.010](https://doi.org/10.1016/j.trd.2017.03.010).
- Zis, T.P.V., Psaraftis, H.N., Panagakos, G. and Kronbak, J. (2019), “Policy measures to avert possible modal shifts caused by sulfur regulation in the European Ro-Ro sector”, *Transportation Research Part D: Transport and Environment*, Vol. 70, pp. 1-17, doi: [10.1016/j.trd.2019.03.001](https://doi.org/10.1016/j.trd.2019.03.001).

### Further reading

IMO (2019a), *2020 Sulfur Limit Frequently Asked Questions*, International Maritime Organization (IMO).

### Corresponding author

Harilaos N. Psaraftis can be contacted at: [hnpсар@dtu.dk](mailto:hnpсар@dtu.dk)

---

For instructions on how to order reprints of this article, please visit our website:

[www.emeraldgrouppublishing.com/licensing/reprints.htm](http://www.emeraldgrouppublishing.com/licensing/reprints.htm)

Or contact us for further details: [permissions@emeraldinsight.com](mailto:permissions@emeraldinsight.com)