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ABSTRACT

In 2016, the International Maritime Organization (IMO) decided on global regulations to reduce sulphur emissions to air from maritime shipping starting 2020. The regulation implies that ships can continue to use residual fuels with a high sulphur content, such as heavy fuel oil (HFO), if they employ scrubbers to desulphurise the exhaust gases. Alternatively, they can use fuels with less than 0.5% sulphur, such as desulphurised HFO, distillates (diesel) or liquefied natural gas (LNG). The options of lighter fuels and desulphurisation entail costs, including higher energy consumption at refineries, and the present study identifies and compares compliance options as a function of ship type and operational patterns.

The results indicate distillates as an attractive option for smaller vessels, while scrubbers will be an attractive option for larger vessels. For all vessels, apart from the largest fuel consumers, residual fuels desulphurised to less than 0.5 % sulphur are also a competing abatement option. Moreover, we analyse the interaction between global SO_X reductions and CO_2 (and fuel consumption), and the results indicate that the higher fuel cost for distillates will motivate shippers to lower speeds, which will offset the increased CO_2 emissions at the refineries. Scrubbers, in contrast, will raise speeds and CO_2 emissions.

Key words: Shipping and the environment; Abatement cost and options; CO_2; Marine fuels; MARPOL; IMO

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1. INTRODUCTION

The International Maritime Organization (IMO) decided at its 70th session of the Marine Environmental Protection Committee (MEPC) in October 2016 to reduce the maximum sulphur content in the exhaust gas to air from 3.5% to 0.5% from 2020. It can be viewed as an extension – a globalization – of the regionally motivated Emissions Control Areas (ECAs) already in place, though these impose a 0.1 % sulphur cap for areas near the coasts of North America and Northern Europe (North Sea and Baltic Sea).

Large seagoing vessels currently use heavy fuel oil (HFO) with a sulphur content of up to 3.5 %, while smaller vessels use distillates with sulphur content less than 1.0 %. Heavy fuel oil, i.e. residual fuel, consists of the fractions of crude that remains in the refinery process after its extraction of lighter and more valuable fractions, such as naphtha, petrol, diesel, and jet fuel. In 2012, the seagoing fleet consumed 7 – 8 % of the output from the world's oil refineries, i.e. nearly 300 million metric tons out of 4 000 million metric tons in total (Smith et al., 2014). Moreover, 75 % of the consumed maritime fuel was residual (HFO), nearly 25 % was distillates (diesel) and 2 % was liquefied natural gas (LNG) (Smith et al., 2014; BP 2015). Maritime shipping consumes nearly 50 % of residual fuel oils globally (Faber et al., 2016).

The advantage of HFO for the ship-owners is its low price compared to distillates. For the refineries, selling residual fuel has been an alternative to making large investments in process equipment, to convert more of the residual fuel to distillates. The typical output from a conventional refinery is around 2/3 of refined products including distillates and 1/3 of residual including HFO (Concawe, 2012; Cooper, 2013; πMath*Pro*, 2011). Increased demand for distillates, in combination with global crude becoming heavier and with increased sulphur content, has created a need for converting residual fuel to distillates independently of the IMO decision (Concawe, 2012). Newer refineries are therefore 'conversion' or 'deep conversion' refineries, representing both a higher investment cost and higher energy consumption in the refinery process (Mukherjee, 2011; Forman et al., 2014; Han et al., 2015). A conversion refinery transforms a large share of the residual fuel into jet fuel, diesel, and petrochemical feedstocks, while a deep conversion refinery goes one step further, by converting the remaining residual fuel and asphalt into distillates and pet coke. While removing sulphur from distillates are common technology for all refineries, removing sulphur from residual oil implies cost and complexity similar to conversion from residual to distillate (Concawe: 2006, 2009, 2012; Shell, 2017).

The IMO 2020 regulation implies that ships can continue to use sulphur-rich fuels if exhaust gas cleaning systems (scrubbers) are added. The function of a scrubber on a seagoing vessel is to use seawater to wash out the sulphur in the exhaust gas. Alternatively, they must use fuels with less than 0.5% sulphur, such as desulphurised residual fuel oils (HFO < 0.5 % S), diesel, liquefied natural gas (LNG) or methanol. The two major studies on fuel availability performed prior to the MEPC decision (Faber et al., 2016; EnSys Energy and Navigistics Consulting, 2016) agreed on the need for increasing the desulphurisation and conversion capacity at the refineries, to ensure sufficient availability of low-sulphur fuels for the shipping sector by 2020.

Previous studies of maritime fuel emission regulations have mainly focused on alternative fuels and technical options (Brynjolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015a, Lindstad et al., 2015b; Lindstad and Eskeland 2016). Fuels considered are typically HFO, LNG, diesel, biofuels and methanol. Lindstad and Eskeland (2016) show that the "HFO and scrubbers" option gives lowest cost for large vessels. LNG is an option for new-buildings, if the LNG price is equal to, or lower than, the HFO price (Lindstad et al., 2015b), while it tends to be too costly for retrofitting (Acciaro, 2014; Lindstad et al., 2015b). Moreover, present usage of LNG and methanol in ECA's is typically linked to incentives like the Norwegian NO_X fund, direct state aid, EU funding or national incentives through measures such as fairway and port rebates. While the above-mentioned studies have had the perspective of the shipping industry, the actors in the refining industry have focused on their challenges and opportunities (Concawe: 2006, 2009, 2012, 2014, 2016; Shell, 2017), such as whether to desulphurise residue to less than 0.5 % sulphur (HFO < 0.5 % S), convert residue to distillates, or continue production of HFO. Here, the first two options come at capital and energy cost.

The focus of the present study is to identify the best compliance options as a function of ship type and operational patterns. The employed model is described in section 2; its application and data are presented in section 3; the analysis and results in section 4; and the conclusions in the final section

2. MODEL DESCRIPITION

We need assessment of fuel consumption, costs and emissions as a function of vessel operation, abatement option and crude oil price, and we limit our attention to the vessels and their use, see Lindstad et al. (2011, 2014, 2015a). Moreover, we make a simplification and assess best options for the sailing fleet excluding the effects of future price differences between emission control areas (ECA) and global compliant fuels.

A vessel's annual fuel consumption F comprises the fuel used on cargo voyages F_c and that used on repositioning voyages F_b, as expressed by Equation (1):

$$F = F_c + F_b = \sum_{i=1}^{N_c} \left(K_{fp} \cdot \left(\frac{P_i^{Mv} \cdot D_i^c}{v} \right) + T_{lwd} \cdot P_i^{lwd} \cdot K_{fp} \right) + \sum_{i=1}^{N_b} \left(K_{fp} \cdot \left(\frac{P_i^{Mv} \cdot D_i^b}{v} \right) + T_{lwd} \cdot P_i^{lwd} \cdot K_{fp} . N\pi \right) \quad (1)$$

D_i divides each voyage N into sailing sections for different sea conditions. P_i^{Mv} is the required power as a function of the sea conditions, M is the total cargo carried and v the speed. K_{fp} is the fuel required per produced kWh as a function of engine load. T_{lwd} is time spent in port and P_i^{lwd} is average power required in port per voyage as function operational mode, i.e. loading, discharge and waiting.

The cost per ton-mile (all tons are metric, miles are nautical: 1852 meter) comprises the cost of fuel and the daily financial and operational costs of the cargo carrier, as expressed by Equation (2):

$$\mathrm{C}_{D \cdot M} = \frac{1}{\sum_{i=1}^{N_c} D_i^c \cdot M_i} \cdot \left((F \cdot C_{Fuel}) + TC \cdot T + C_v^{capex} \right) \quad (2)$$

The first factor transforms costs to USD per ton-mile (a measure of transportation work, or output). Inside the main bracket, we multiply quantity of fuel consumed per year F by price C_{Fuel}. TC is the vessel's other daily operational and financial costs, T is days per year and C_v^{capex} denotes the annual costs of the annualized capital and depreciation costs of the vessel and the abatement technology used.

Emissions ε, per pollutant per ton-mile is given by Equation (3):

$$\varepsilon = \frac{F}{\sum_{i=1}^{N_c}(D_i^c \cdot M_i)} \cdot K_e \quad (3)$$

F is the annual fuel usage in tons, N_c is the number of cargo voyages, K_e is the emitted pollutant per unit of fuel burnt, D_i^c is the distance per cargo voyage and M_i is the net cargo weight transported on a voyage.

3. APPLICATION AND DATA SET

Historically, about 75 % of maritime shipping's global fuel consumption has been HFO. HFO is mainly used by the largest ships, corresponding to 25 % of the approximately 120 000 vessels in the global fleet (Lindstad and Eskeland, 2016). The remaining 25 % of the fuel is consumed by a range of different vessels, generally smaller in size, representing 75 % of the vessels in numbers. Nearly all these smaller vessels currently use diesel, and the only change in 2020 will be that the sulphur content must be lower than 0.5 % globally. For these reasons, the focus in this study is on the existing fleet of vessels currently using HFO. Compared to new-buildings, retrofit on existing vessels implies that the abatement technology has to be paid back within a shorter time frame. Moreover, while LNG is an option for new-buildings, it tends to become too costly for retrofitting due to the need for new fuel tanks and engine modifications or replacements (Acciaro, 2014; Lindstad et al., 2015b). For these reasons, the present study focuses on three abatement options: 1) Retrofitting of scrubbers in ships to allow continued use of HFO, 2) switch to desulphurised residual fuel oils (HFO < 0.5 % S) or 3) switch to diesel. In the analysis, we focus on 2020 global compliance, i.e. on the 0.5 % sulphur cap.

An important aspect of the analysis is the fixed costs of scrubbers relative to higher costs of low-sulphur fuels. Figure 1 shows the average annual prices per ton of oil equivalent

(TOE) for diesel for marine applications, crude oil (Brent blend), HFO, coal and the price differential between diesel and HFO for the period from 2006 to 2015.

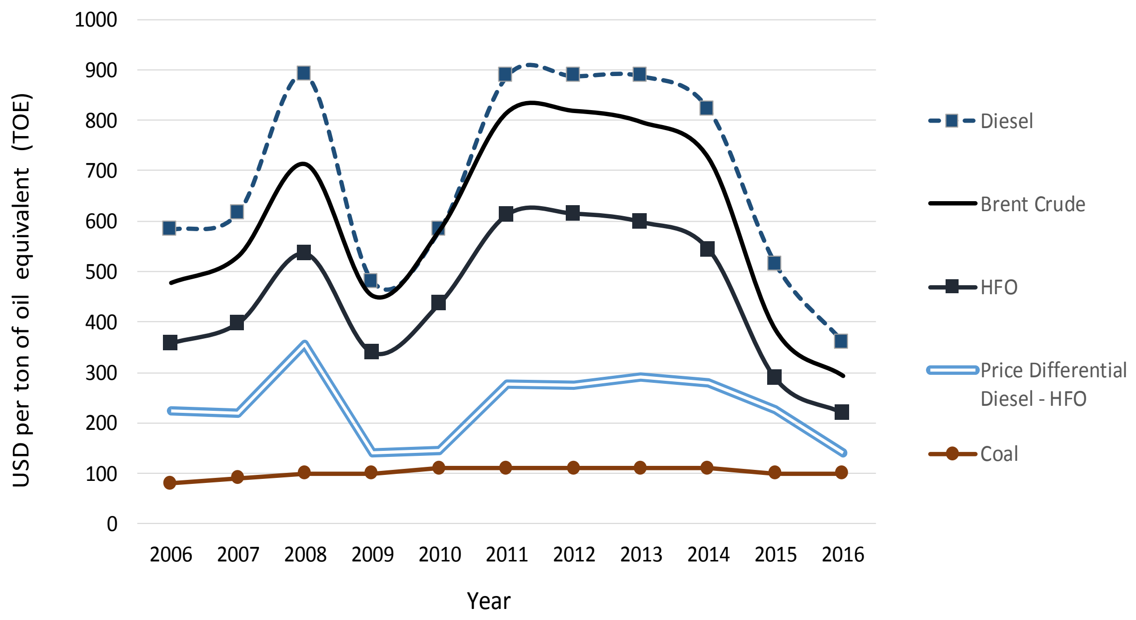


Figure 1: Development of fuel prices per ton of oil equivalents (TOE) from 2006 to 2016. Data Source: Bunker World; EIA – US Energy Information Administration; BP Statistical Review of World Energy (2016); all figures are yearly averages.

As we can see, the crude price has varied between 300 and 850 USD per ton, diesel between 350 and 900 USD per ton and HFO between 200 and 650 USD per ton. The HFO price has been 100 to 350 USD per ton less than the diesel price, and in the magnitude of 75 % of the crude oil price. The price differential between diesel and crude oil is in the magnitude of 100 USD per ton, reflecting that the refineries have huge fixed costs, which has to be carried by the refined products independently of the crude price. For these reasons, we use the crude oil price plus 100 USD per ton as an estimate for the diesel price, and 75% of the crude oil price as an estimate for the HFO price in this study. Additionally, we may observe that the coal prise has been lower and comparatively stable, around 100 USD per TOE, i.e. 15 – 50 % of the HFO price. This explains why it is more economically attractive for refineries to sell residual oils as marine fuel, rather than competing with the coal producers for supplying energy to the power stations for electricity production.

Regarding on-board abatement options, we may distinguish between three types of scrubbers: Open loop, closed loop and hybrid. An open loop scrubber discharges the sulphur-rich wash-water directly into ocean. With a closed loop scrubber, the wash-water is treated with chemicals and particles are filtered out before it is reused many times. A hybrid scrubber combines the two modes and can run in open mode at sea and in closed mode in ports and sensitive areas. Today, the cost of scrubber starts at around 1.5 million USD, with an additional cost per kW of engine installed. This is lower than a few years back in time (Lindstad et al., 2015b), which indicates that the technology is becoming more mature. The starting cost for a hybrid scrubber is 50 % higher than for an open loop scrubber, while the additional cost per kW installed is of the same magnitude as an open loop (Lindstad and Eskeland, 2016; Faber 2016; Wärtsilä, 2017). With increased use of scrubbers, there will be ports where open loop will be banned from being used, while hybrid scrubbers running in closed loop mode will be allowed. For these reasons, we use the cost estimate for hybrid scrubbers, i.e. 2.25 million USD, adding 70 000 USD per additional 1000 kW of installed engine power on the vessel.

Desulphurising residual fuel oils implies cost and complexity similar to conversion from residual to distillate – this in comparison to sulphur removals from distillates which are common technology for all refineries. Shell, the major oil company, and Concave, the association of oil refineries (Concawe, 2006, 2009, 2012; Shell, 2016) have published figures that conversion or desulphurisation consumes around 10 % of the energy content in the residual fuel input. The bi-products from the processes, such as pet-coke from conversion and sulphur from both, will achieve a lower sales price per ton than HFO, and this gap increases with higher crude oil prices. Both conversion and desulphurisation require substantial capital expenditures. The cost of desulphurisation can thus be expressed as a percentage of the crude cost plus a fixed amount, i.e. 10 – 15 % of the crude plus a fixed cost to be distributed over output. For these reasons, we use 12.5 % of the crude cost plus 25 USD per ton as an estimate for the desulphurisation cost in this study.

Annual fuel consumption for a seagoing vessel is a function of operational pattern, sea conditions and parameters characterizing the vessel (Equations 1 and 2). In 2007, with booming shipping markets, average speeds and days at sea where higher than in 2012 (Smith et al., 2014). In those five years, total freight capacity in ton-miles increased by 50 % due to new-buildings that raised vessel numbers and average sizes. Since larger and slower vessels produce more ton-miles per ton of fuel consumed, total fuel consumption in maritime transport was reduced from 2007 to 2012, despite 20 % higher output in ton-miles. We have chosen to use the operational patterns of 2012 as published by Smith et al., (2014) as low case estimates for fuel consumption, and speeds corresponding to 95% of the design speed (with the same days at sea) for high case estimates, the latter with results more in line with the situation in 2007. Table 1 shows annual fuel consumption per vessel type. The first column shows vessel type, then follows: Number of vessel per vessel type; installed power; design speed; low case speed as a percentage of design speed; day's at sea; low case fuel per vessel; high case fuel per vessel.

Table 1: Vessel type characteristics with fuel consumption range per vessel

Ship type	Average per Vessel in 2012					Fuel per vessel	
	No. of vessels	Installed Power (kW)	Design speed (knots)	Speed in % of Design speed	Days at sea 2012	Low case estimate (ton)	High case estimate (ton)
General Cargo 7' dwt	2 900	3 300	13.6	74%	166	1 800	2 900
Tanker 9' dwt	900	3 200	12.8	69%	148	2 400	4 600
LNG & LPG 7' dwt	1 100	3 800	14.2	84%	180	3 200	4 300
Chemical Tanker 15' dwt	1 050	5 100	14.1	83%	181	3 700	4 800
Container 9' dwt	1 100	6 000	16.5	75%	190	3 700	5 900
Dry Bulk 42' dwt	5 400	10 100	15.1	77%	170	4 000	6 000
General Cargo 22' dwt	2 000	7 400	15.8	76%	174	4 400	6 900
Reefer 6' dwt	1 100	5 000	16.8	80%	173	5 100	7 200
Tanker 44' dwt	650	8 600	14.8	79%	164	6 100	8 800
Dry Bulk 80' dwt	2 300	10 900	15.3	78%	191	6 200	9 200
Ferry - RoPax > 2' GT	1 200	15 500	21.6	65%	215	7 000	15 000
Container 20' dwt	1 300	12 600	19.5	71%	200	7 500	13 300
Tanker 70' dwt	400	12 100	15.1	81%	183	7 800	10 800
Chemical 43' dwt	1 200	9 300	15.0	82%	183	7 900	10 600
Tanker 110' dwt	900	13 800	15.3	76%	186	9 000	14 100
Ro-Ro & Vehicle 12' dwt	1 300	10 100	19.2	77%	243	9 200	14 200
Dry Bulk 180' dwt	1 200	17 300	15.3	76%	202	9 600	14 800
Tanker 160' dwt	500	18 800	16.0	73%	206	10 900	18 400
Dry Bulk 270' dwt	300	22 200	15.7	78%	202	11 400	17 000
Container 47' dwt	1 700	30 500	23.3	67%	224	14 600	29 800
LNG 70' dwt	500	22 600	18.5	81%	254	18 500	27 100
Tanker 310' dwt	600	27 700	16.0	78%	233	19 100	28 200
Container 90' dwt	900	59 500	25.3	64%	250	25 600	55 700
Container 180' dwt	100	83 000	25.0	59%	242	30 200	77 800
LNG 120' dwt	50	37 400	19.3	88%	277	34 100	40 100
Cruise > 10' GT	250	42 600	21.3	73%	261	42 000	71 600
Totals	31 000	12 950	16.5	74%	190	7 400	12 400

The main observations are that low case speeds vary from 59 % of design speed for the large container vessels up to 88 % for the large LNG carriers. This is indicative of a general tendency that more valuable cargos and vessels travel at higher speeds, although the variation being less pronounced in high-demand situations. Average annual fuel consumption per vessel for the fleet as a whole is 7 400 tons in low case conditions and 12 400 tons based on the high-case assumptions.

4. ANALYSIS

We investigate abatement options in terms of costs per ton of fuel as a function of crude oil price and annual fuel consumption. First, we use tankers of three different sizes to illustrate basic relationships. The smallest of these is a 15 000 dwt chemical tanker with a design speed of 14 knots and annual fuel consumption in the range of 3 700 to 4 800 tons. The 110 000 dwt tanker is an Aframax crude oil carrier with a design speed of 15 knots and 9 000 to 14 000 tons in annual fuel consumption. The largest is a very large crude oil carrier (VLCC) of 310 000 dwt, with a design speed of 16 knots, consuming between and 19 000 and 28 000 tons annually. Fitting these vessels with scrubbers, the acquisition costs will be 2.6, 3.3 and 4.2 million USD respectively, thus increasing less than proportionally with vessel capacity – illustrating the declining marginal cost of scrubbers in size due to economies of scale. For new-buildings, the required annual time charter cost to operate the vessel and earn back the scrubber investment over 15 to 20 years is typically about 12 – 15 % (8 % - 11 % for the capital and 4 % for the operational cost (Lindstad et al., 2011, 2014, 2016)). In comparison, for retrofits on existing vessels the investments typically have to be earned back within 3 – 10 years, which gives 20 % of the capital expenditures even without interest for 5 years payback time, and 24 % annually when including 4% operational cost. In Figure 2, the horizontal shaded fields show abatement cost per ton of fuel consumed for the three classes of ships retrofitted with scrubbers, and the upwardly sloped curves show abatement costs for the alternatives of avoiding the scrubber investments by using desulphurised residual fuel oil (HFO < 0.5 % S) or diesel.

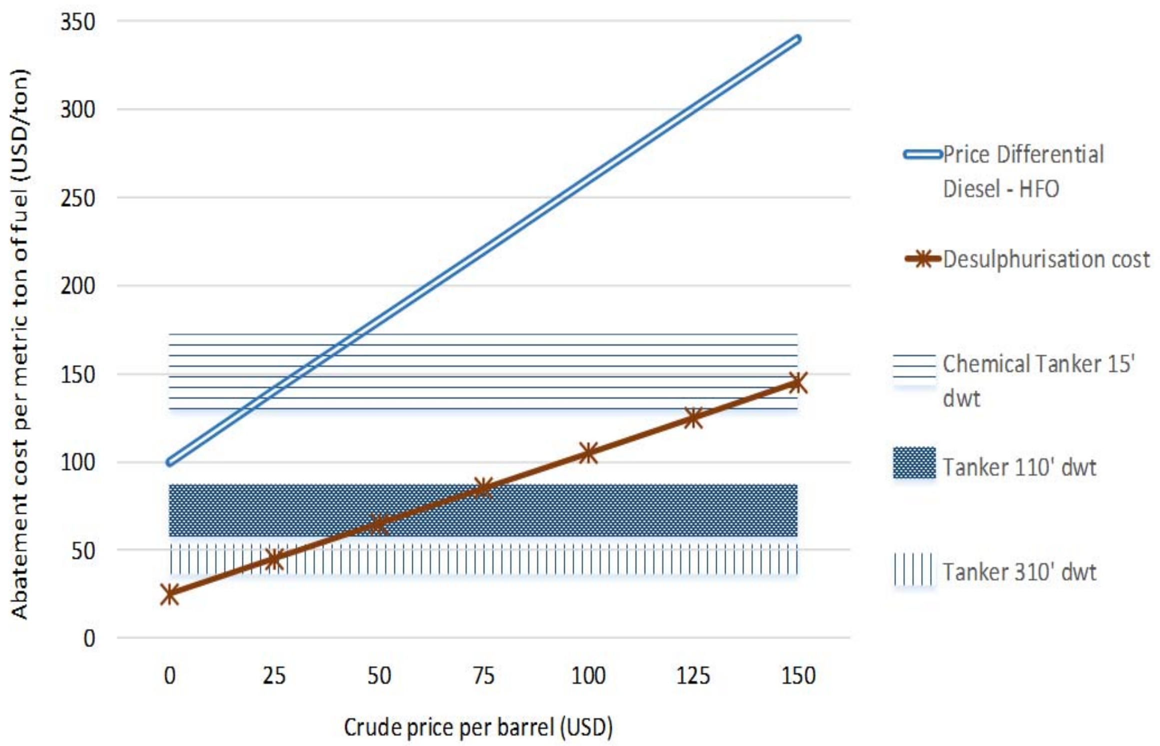


Figure 2: Abatement cost per ton of fuel with scrubbers retrofitted versus compliant fuels (‘representing thousand).

We may first observe that the scrubber options give highest abatement costs per ton of fuel for the smallest tanker, i.e. 130 – 170 USD per ton, and lowest for the largest tanker, i.e. 35 – 55 USD per ton. This is mainly due to the fixed cost element in the scrubber installation process. As a result, the cost curve indicates that diesel is a competitive option for the 15 000 dwt tanker for crude oil prices up to approximately 40 USD per barrel, but for the larger vessels diesel is not competitive at all.

Second, the cost curve for desulphurised residual fuel (HFO < 0.5 % S) indicates that this fuel is competitive versus scrubbers for a crude oil price up to approximately 40 USD per barrel for the largest tanker, up to approximately 75 USD per barrel of crude for the medium tanker and up to above 150 USD per barrel of crude for the smallest tanker. The dependence on the crude oil price for low-sulphur fuel oil reflects that the low-sulphur premium in fuel prices is greater at high oil prices (due mostly to energy inputs in the refinery desulphurisation), so that scrubbing on board gains an advantage in high-oil price environments. Thus, the fuel options benefit from low crude prices, but are punished at high oil prices due to their energy requirements. It should be noted that the diesel curve reflects the average historical price difference between diesel and HFO, and that if we had plotted daily differentials there would have been a spread with lower and higher plots along the line (reflecting variations in supply and demand and the volatility of the oil markets). It can be expected that for the desulphurised fuels (HFO < 0.5 % S) we will see similar spreads in the future spot prices.

Figure 3 shows scrubber abatement costs in USD per ton of fuel as a function of engine size and annual fuel consumption for a selection of vessels types currently using HFO, based on Table 1. In the figure, the x-axis represents the annual fuel consumption and the y-axis installed power. Abatement costs per ton of fuel (and also per ton of emissions avoided) are lower in the lower-right of the figure than in the upper-left. The cruise, container, LNG and VLCC vessels with the lowest abatement costs per ton for scrubbers have in common a high fuel consumption, reflecting a combination of size and typical speed. The three dotted lines in the figure going from the x-axis upwards to the right represent level-curves for the abatement costs or price differentials, i.e. cost increase of 200, 100 and 50 USD per ton of fuel respectively. The grey bars represent the typical ranges for annual fuel consumption by vessel type, so an average ship in the LNG 70 000 dwt segment typically consumes between 18 000 and 27 000 ton of fuel, and has an abatement cost of approximately 50 USD per ton.

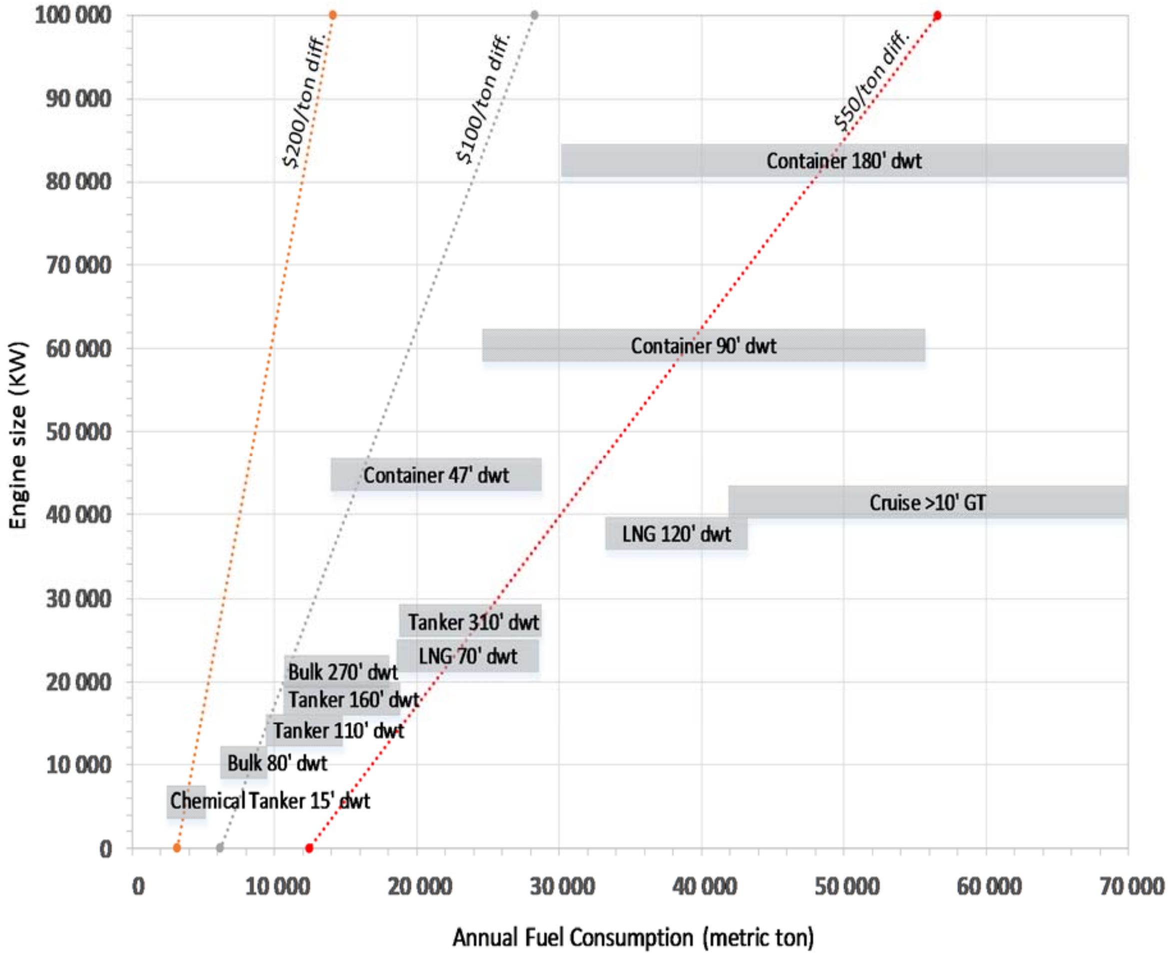


Figure 3: Scrubber abatement cost per vessel as a function of engine size and annual fuel consumption (‘representing thousand).

Main observations from Figure 3 are that for a higher installed power, a higher annual fuel consumption is required to keep abatement costs for scrubbers down, or to reduce them. As an example, with an installed power of 10 000 kW, an annual fuel consumption of 8 000 tons or more are needed to achieve an abatement cost of less than 100 USD per ton. Doubling engine size to 20 000 kW, the required fuel consumption is 11 000 tons or more.

To discuss implications, let us use the comparison between market conditions in 2007 to 2012. Speeds at sea and days at sea in 2012 were reduced due to greater capacity relative to transport demand, and higher fuel prices. In 2007 fuel consumption per vessel was higher, due to more days at sea and higher speeds. When a ship raises its speed, its fuel consumption per day increases approximately with the power of three (and per ton-mile, with the power of two), and hence fuel cost per ton-mile of freight work increases (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al., 2011; Jonkeren et al., 2012). For these reasons, it becomes relevant to investigate how the alternative abatement options influence the cost-minimising speeds of the vessels.

We use the well-known Aframax crude oil tanker (110 000 dwt) as an example in the rest of the analysis. It has the 12th highest consumption out of the 27 types currently using HFO, as listed in Table 1, and its ratio between annual fuel consumption and installed power is quite close to the average of all the 27 vessels. Assumed newbuilding price is 50 million USD. Our calculations are based on one-way voyages of 2 500 nautical miles, carrying 100 000 tons of crude oil, and returning in ballast. When the vessel sails in ballast, the power to achieve a desired speed will be around 70 % of the power required in laden. Therefore, we investigate the ballast leg and the laden leg separately, to arrive at cost per ton transported as a function of speed and abatement option. We exclude loading and discharging costs since these have no impact on the abatement options. See Lindstad and Eskeland (2015) for more extensive discussions of speed in crude oil transportation.

Figure 4 shows costs and CO_2 emissions for the considered standard Aframax tanker. The common vertical axis represents costs in USD per ton of crude transported, as a function of vessel speed on the right-hand panel of the figure, and as a function of gram CO_2 emitted per ton-mile on the left-hand side. We can thus read reduction in CO_2 emissions as a function of speed reduction and CO_2 increase per ton transported as a function of speed increase. Of the right-hand panel, we can identify the speed which minimises ship owner’s cost, both for ballast and for laden voyage legs. The letter A is used to mark the cost-minimising speed in the right-hand panel of the figure and corresponding emission levels on the left-hand side when diesel is the selected abatement option, B marks cost minimising speeds when HFO & Scrubber is the selected, and C is used for HFO without scrubber, i.e. today’s conditions. The HFO price is 300 USD and the diesel price is 500 USD per ton of oil equivalent, i.e. approximately spring 2017 cost levels with a crude oil price level of 50 USD per barrel.

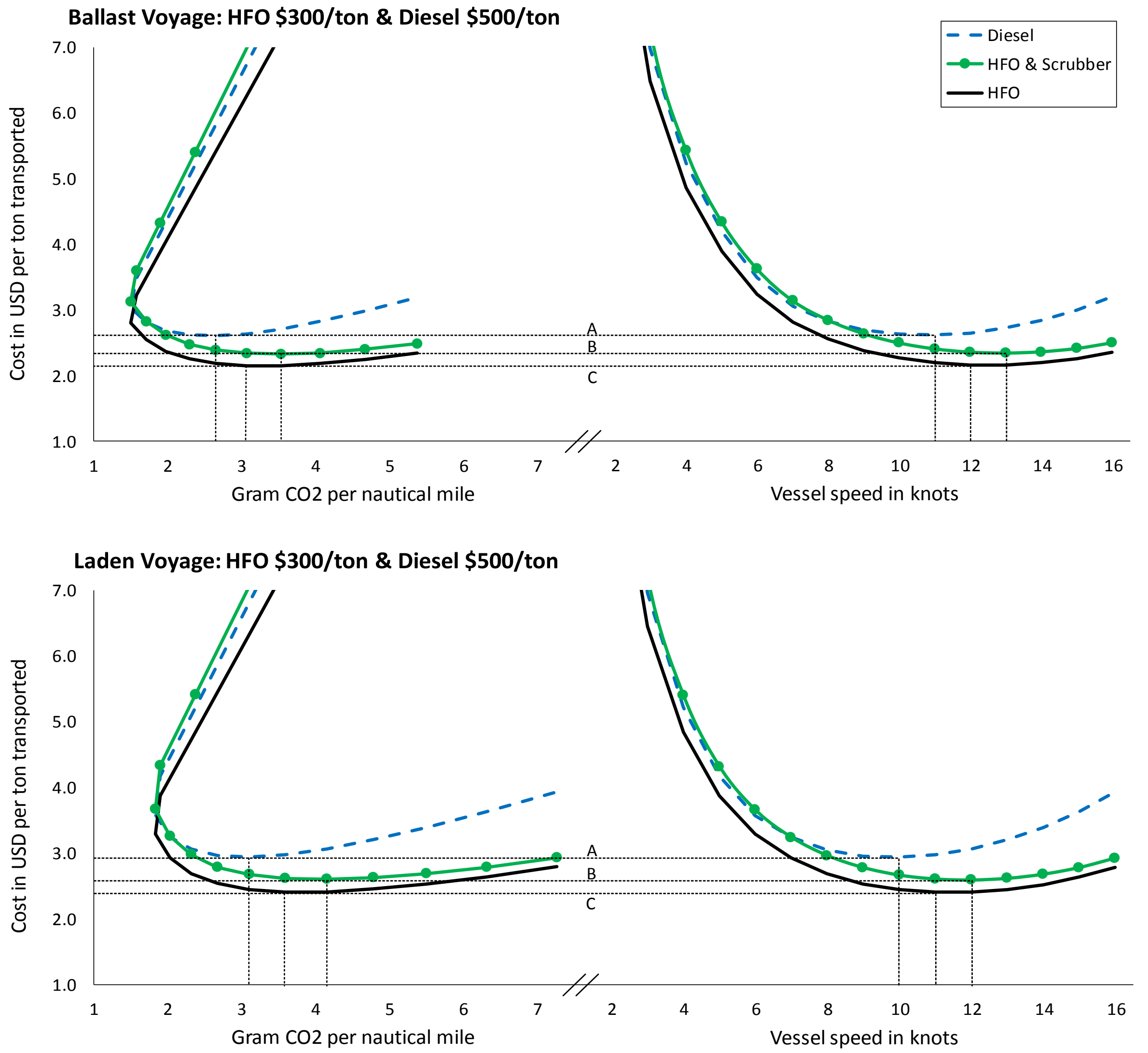


Figure 4: Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 50 USD per ton.

From Figure 4 we can see that using HFO alone, the speed which gives the lowest cost on the ballast leg is 12 knots, and on the loaded leg it is 11 knots, i.e. not far from the average of 12 – 13 knots corresponding to current speeds for Aframax tankers. Switching from HFO to the costlier diesel option reduces the speeds with one knot, to 11 knots in ballast and to 10 knots on the loaded leg. Compared to the status quo of HFO only, the introduction of scrubbers raises the speed with one knot, to a ballast speed of 13 knots and a loaded speed of 12 knots, i.e. owners are economically encouraged to operate at higher speeds with a scrubber than without.

For CO_2 emission levels, speed reductions of 1 knots for the diesel option compared to HFO gives CO_2 emission reductions in the range of 10 – 15 % due to the lower optimal speeds with higher fuel costs. If implemented, these emission reductions would offset the increased refinery emissions for the production of the diesel. In contrast, the speed increases resulting from scrubber installation of 1 knot *raises* CO_2 emissions 10 – 15 %.

To test the sensitivity of these results, we investigate the effects of alternative fuel prices and price differentials between diesel and HFO, as shown in Figure 5 and Figure 6, with 50 % higher and lower fuel prices, corresponding to crude oil prices around 75 USD per barrel in Figure 5 and 25 USD per barrel in Figure 6.

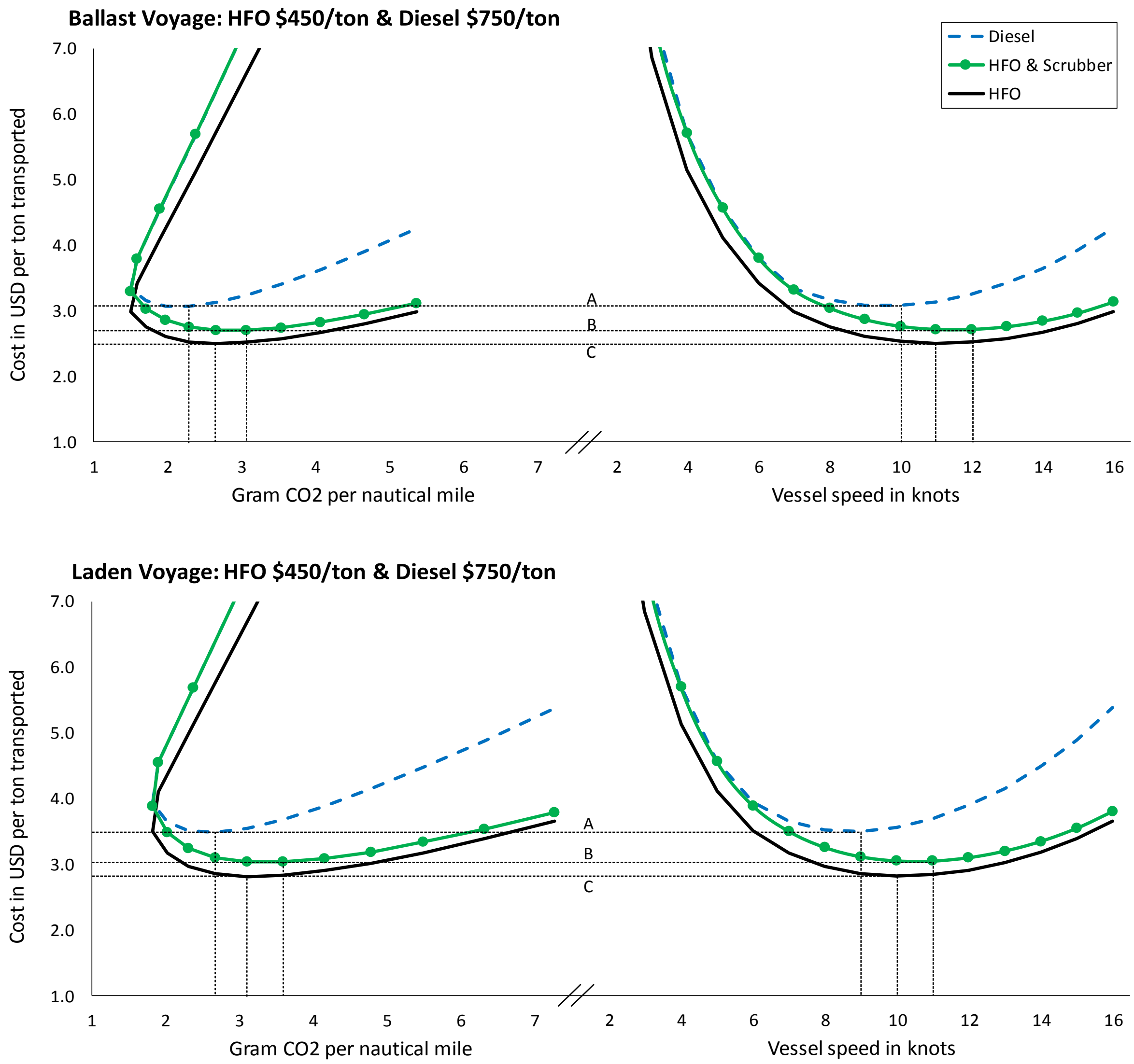
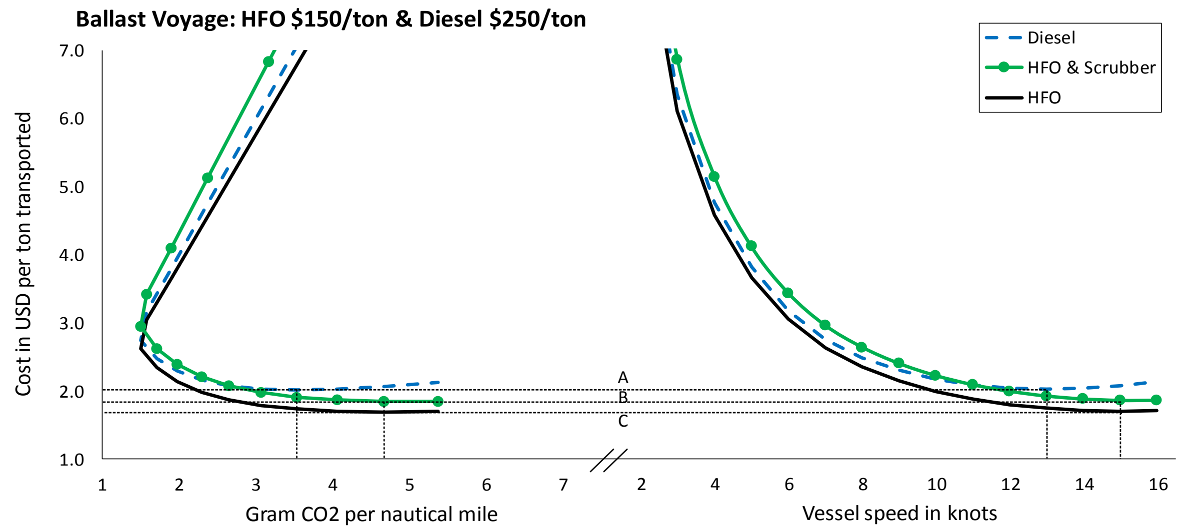


Figure 5: Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 75 USD per ton.



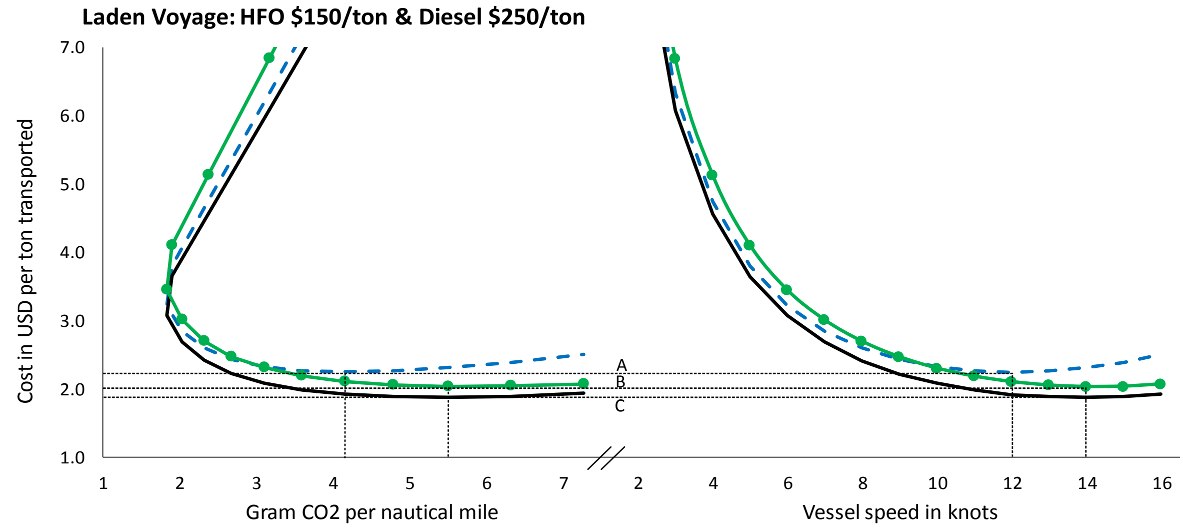


Figure 6: Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 25 USD per ton.

From Figure 5 we can see that with fuel prices of 450 USD per ton for HFO and 750 for diesel, the cost-minimising speeds are reduced with one knot compared to the 300/500 USD per ton scenario presented earlier. Figure 6 depicts a scenario with a 50 % reduction in fuel prices (150/250 USD per ton), and here we can see higher speeds for both abatement options compared to the 300/500 USD per ton base scenario.

If the curves for desulphurised residual oil (HFO<0.5% S) had been included in Figure 4, 5 and 6 they would have been plotted between the diesel and the HFO curves, displaying cost-minimising speeds and CO_2 emissions per ton mile higher than diesel and lower than for HFO.

To generalize the sensitivity analysis for cost-minimising speeds, we additionally investigate the effects of changing the new-building price of the ship, as indicated in Figure 7. Here we can more clearly see the interplay between the initial investments costs ("capex" in Figure 7) and the operating costs (affected by the fuel price), of which we get a triangle in the lower-right of Figure 7 (in grey) with increasing speeds. In general, with higher capital investments, the fuel costs play a relatively smaller role in the overall economics. The resulting pressures for higher outputs per vessel raises speeds, allowing energy (and emissions) to substitute for capital. Thus, for all initial measures driving investment costs, albeit particularly meant for reducing sulphur emissions, those that raise investment costs have the effect of raising speeds and CO_2 emissions, those raising fuel costs reduce speeds and CO_2 emissions.

Fuel price: +50% HFO \$450/ton Diesel \$750/ton	Lower speed	Lower speed	Constant speed
Fuel price: as is HFO \$300/ton Diesel \$500/ton	Lower speed	Constant speed	Higher speed
Fuel price: -50% HFO \$150/ton Diesel \$250/ton	Constant speed	Higher speed	Higher speed
	Capex: -50% \$25 million	**Capex: as is** \$50 million	**Capex: +50%** \$75 million

Figure 7: Sensitivity analysis: changes is cost-minimising speeds for a 110 000 dwt oil tanker, as a function of fuel price levels and newbuilding prices.

When testing on smaller or larger tankers or other vessels types, i.e. bulk, or container, similar results are obtained. It can therefore be concluded that for crude oil prices in the range which we have seen during the last decade, i.e. 25 – 150 USD per barrel, the diesel abatement option contributes to speed reductions and CO_2 emissions reductions compared to HFO. If these speed reductions are implemented, the associated emission reductions would offset the increased refinery emissions for the production of the diesel. In contrast, the scrubber option raises speeds and CO_2 emissions relative to HFO.

The Ballast Water Convention is likely to give similar effects in terms of higher speeds and emissions, since it comes at as an additional capex per vessel. By raising the costs both of new-buildings and of 'staying in business', these regulations will likely slow newbuilding, prolong the lifetime and intensify of use for younger existing vessels, while shortening that of some older ones.

5. CONCLUSIONS

This study has investigated cost efficiency of alternative abatement options for the 2020 IMO Sulphur regulations. The focus has been on identifying best compliance options for the sailing fleet, i.e. retrofit as a function of ship type, engine size, operational pattern and remaining use time.

Our findings are: First, continued use of HFO with exhaust gas scrubbing gives the lowest cost for the vessel with the largest consumption, consistent with Lindstad and Eskeland (2016) and Lindstad et al. (2015b). Second, in a case with crude oil prices less than 50 USD per barrel, diesel is an interesting abatement option for the smaller vessels that currently use

HFO. Third, desulphurised HFO (HFO < 0.5 % S) comes at a production cost which makes it a competitive abatement option for all vessels apart from the largest fuel consumers.

Furthermore, when scrubber is selected as the abatement option, it encourage to operate vessels at higher speeds. For fuel consumption and CO2 emissions per ton-mile produced, these are increasing with higher speed, since the power input required for propulsion rises with speed to the power of three. Still, for the scrubber option, the additional fuel consumption is less important than the reward for better utilization of the scrubber and the vessel, and speeds will increase. With diesel as an abatement option, the higher fuel cost reduces speeds in the range of 1 to 2 knots. For CO_2 emission levels, speed reductions of 1 knots for the diesel option compared to HFO gives CO_2 emission reductions in the range of 10 – 15 % per ton-mile. These emission reductions will offset the increased emissions at the refinery associated with producing diesel instead of HFO. In contrast, with the higher speeds for the scrubber option, CO_2 emissions increase by 10 – 15 % compared to pre-2020 levels.

In today's world, the need for reducing man made greenhouse gas emissions (and hence CO_2) is well documented by IPCC and acknowledged by the world leaders (Cop-21) and also by IMO policies through their energy efficiency design index (EEDI). It is therefore a surprise to find that new the IMO legislation rewards solutions likely resulting in increased CO_2 emissions. A lesson may be that environmental policy analysis integrating across both local and global problems will be rewarding.

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