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Sulphur abatement globally in maritime shipping

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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.

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. 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 IMO 2020 regulation implies that ships can continue to use sulphur-rich fuels by vessels using exhaust gas cleaning systems (scrubbers). The function of a scrubber on a seagoing vessel is to use seawater to wash out the sulphur in the exhaust gas. Alternatively, vessels must use fuels with less than 0.5% sulphur, such as Light Sulphur Heavy Fuel Oil (LSHFO) with less than 0.5% S, distillate (diesel), liquefied natural gas (LNG) or methanol. The two major studies on fuel availability performed prior to the MEPC

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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 for the shipping sector by 2020.

Previous studies of the of abatement options to comply with stricter fuel emission regulations have mainly focused on existing emission control areas (ECA's) such as in North Sea and the Baltic, and potential extensions (Campling et al., 2013; Johansson et al., 2013; Brynolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015b). Less attention has been on the climate impact of the 2020 global sulphur cap and the stricter NOx regulations (Lindstad et al., 2015a). Fuels considered are typically HFO, LNG, diesel, biofuels and methanol. Jiang et al. (2014) and Zis et al. (2015) show that scrubbers increase their competitiveness relative to low-sulphur fuels at high fuel prices. Lindstad and Eskeland (2016) show that the “HFO and scrubbers” option gives lowest cost for large vessels even with low fuel prices. LNG is an option for new-buildings, if the LNG price is equal to or lower than the HFO price, while LNG tends to be too costly for retrofitting (Acciaro, 2014; Lindstad et al., 2015b). 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 (Plain et al., 2006; Concawe, 2009, 2012, 2016; Shell, 2017; Silva, 2017), such as whether to desulphurise residue to less than 0.5% sulphur (LSHFO), convert residue to distillates, or continue production of HFO. Here, the first two options come at capital and energy cost.

Under the present ECA regulations, the cost implication for a container vessels of using diesel when it serves ports like Aarhus, Gothenburg and Hamburg on its sailings to and from Asia is marginal. In contrast, costs of switching fuel on the whole voyage to comply with the 2020 regulation will give a major cost increase. Second, with a 20–30 years lifetime of vessels, only a small share of the fleet in 2020 will be vessels built after the global sulphur cap was confirmed in October 2016. Third, refineries will introduce new LSHFO fuels which will come at a lower cost than diesel and hence be a more competitive option versus on board abatement options. For these reasons the focus of the present study is to identify the best options, i.e. lowest abatement cost as a function of ship type, size and its operational pattern. The employed model is described in Section 2; abatement options are described in Section 3; the dataset for fuel consumption estimation is presented in Section 4; the analysis and results in Section 5; and the conclusions in the final section.

2. Model description

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, 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 fuel consumption F comprises fuel used during sailing, and fuel used in ports when loading, discharging and waiting as expressed by Eq. (1):

$$F = \sum_{i=1}^{n} \left(\frac{D_i}{v_i} \cdot P_i^{mv} \cdot K_{fp} + T_{lwd} \cdot P_{lwd} \cdot K_{fp} \right) \tag{1}$$

During a roundtrip voyage, the sea conditions will vary, and this is handled by dividing each voyage into sailing sections (i, here), with a distance D_i, speed v_i and power P_i^{mv} as a function of sea conditions, speed v and total weight carried m. Here total weight consists of: cargo, empty cargo units, ballast, fuel and supplies. Moreover, K_{fp} is the fuel required per produced kWh as a function of engine load, T_{lwd} is time spent in port loading, discharging and waiting and P_{lwd} is average power used in ports.

The cost per ton-mile transported per roundtrip voyage (all tons are metric, miles are nautical = 1852 m) comprises the cost of fuel and the daily financial and operational costs of the cargo carrier, as expressed by Eq. (2):

$$C = \frac{1}{D \cdot M} \cdot \left(\left(\sum_{i=1}^{n} \frac{D_i}{v_i} + T_{lwd} \right) \cdot (TC + C_{abatement}) + F \cdot C_{Fuel} \right) \tag{2}$$

The first factor transforms cost to cost per ton-mile. Here M is the average weight of the cargo transported on the roundtrip voyage and D is distance sailed. While large bulkers and tankers typically sail one way fully loaded and returns or a repositioned empty in ballast, container vessels will tend to have more cargo one way than the other and are usually neither empty nor completely full. Inside the main bracket the first term gives total days per voyage as a function of days sailing $\sum_{i=1}^{n} \frac{D_i}{v_i}$ and days in port T_{lwd}. The second term gives the vessel’s daily cost as a function of its operational and financial cost and the abatement technology used $C_{abatement}$. The last term gives fuel cost per voyage based on consumed fuel F multiplied by the fuel price C_{Fuel}.

For the emissions of interest in this paper, SOx and CO_2, strict proportionality to fuel consumption by fuel type is assumed, allowing for the use of scrubbers shifting down SOx emissions.

3. Abatement options

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 4000 million metric tons in total (Smith et al., 2014). Historically, about 75% of maritime shipping’s global fuel consumption has been heavy fuel oil (HFO), mainly used by the largest ships. The remaining 25% of the fuel are consumed by a range of different vessels, generally smaller in size, representing 75% of the vessels in the global fleet. Nearly all these smaller vessels currently use diesel, and the only change in 2020 for these vessels will be that the sulphur content in their fuel must be lower than 0.5% globally.

The focus in this study is on the existing fleet of vessels currently using HFO. Compared to new-buildings, for retrofit on existing vessels, the abatement technology has to be paid back within a shorter time frame. Also, while LNG is an option for new-buildings, it tends to become too costly for retrofitting existing vessels due to the need for new fuel tanks and engine modifications or replacements (Acciaro, 2014; Lindstad et al., 2015b). Consequently, 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 (LSHFO $<$ 0.5% S) or (3) switch to diesel.

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 (Lloyd's Register, 2012; Campling et al., 2013; 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 et al., 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, plus 70 000 USD per additional 1000 kW of installed engine power on the vessel. Moreover, running the scrubber increases energy consumption by 2% compared to using low sulphur fuels.

Desulphurising residual fuel oils implies cost and complexity similar to conversion from residual to distillate – this in comparison to sulphur removals from distillates which is common technology for all refineries. Shell, the major oil company, and Concave, the association of oil refineries (Concawe, 2009, 2012; Shell, 2016; Silva, 2017) have published figures that conversion or desulphurisation consumes energy equivalent to 10–15% of the energy content in the residual fuel input. Both conversion and desulphurisation require substantial capital expenditures. Purvin and Gertz (2009) have estimated desulphurization cost to be 145 USD per ton of fuel to achieve a sulphur content of less than 0.5% and the conversion cost to distillate with less than 0.1% to be 305 USD per ton both in 2020 prices. In comparison, the MEPC submission (MEPC 59/6/5) estimates the cost of switching from residual to distillate to be 145 USD per ton. Plain et al.(2006) and Shell (2016, 2017) have taken a different approach and linked the conversion cost to the oil price. Shell's figures indicate that the total conversion cost, including energy, operational and financial cost, is in the magnitude of 15% of the crude oil price. In this study, we estimate desulphurisation costs as 12.5% of the crude oil cost plus 25 USD per ton, reflecting a somewhat long term perspective in which costs are passed on to users, and where costs are not coming much down with volume and experience (we will see that desulphurisation of HFO is not very competitive relative to scrubbers for vessels with large annual fuel consumption).

In Fig. 1, to emphasize the broader patterns relevant for equipment acquisition, we display the recent history of average annual fuel prices per ton of oil equivalent (TOE) for diesel for marine applications, crude oil (Brent blend), HFO, as well as the price differential between diesel and HFO for the period from 2006 to 2016. We also show the coal price, to show that residual fuel oil will find its way to marine applications if that is possible, rather than to power plants – since these pay considerably less per TOE when

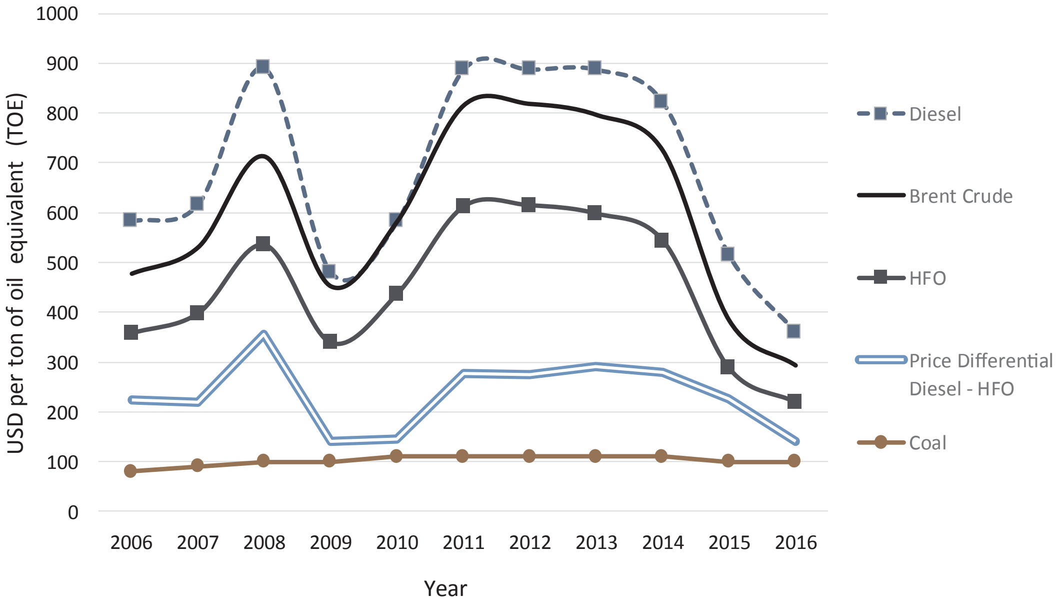


Fig. 1. Development of fuel prices per ton of oil equivalents (TOE) from 2006 to 2016. Data Source: Bunker World; EIA – US Energy Information Administration; BP Statistical Review of World Energy (2017); all figures are yearly averages.

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

Ship type and sizegroup - (dwt indicates average vessel size)	No. of vessels	Installed power (kW)	Design speed (knots)	Speed in % of design speed (%)	Days at sea 2012	Fuel per vessel	
						Low case estimate (ton)	High case estimate (ton)
General Cargo 7′ dwt	2900	3300	13.6	74	166	1800	2900
Tanker 9′ dwt	900	3200	12.8	69	148	2400	4600
LNG & LPG 7′ dwt	1100	3800	14.2	84	180	3200	4300
Chemical Tanker 15′ dwt	1050	5100	14.1	83	181	3700	4800
Container 9′ dwt	1100	6000	16.5	75	190	3700	5900
Dry Bulk 42′ dwt	5400	10 100	15.1	77	170	4000	6000
General Cargo 22′ dwt	2000	7400	15.8	76	174	4400	6900
Reefer 6′ dwt	1100	5000	16.8	80	173	5100	7200
Tanker 44′ dwt	650	8600	14.8	79	164	6100	8800
Dry Bulk 80′ dwt	2300	10 900	15.3	78	191	6200	9200
Ferry - RoPax > 2′ GT	1200	15 500	21.6	65	215	7000	15 000
Container 20′ dwt	1300	12 600	19.5	71	200	7500	13 300
Tanker 70′ dwt	400	12 100	15.1	81	183	7800	10 800
Chemical 43′ dwt	1200	9300	15.0	82	183	7900	10 600
Tanker 110′ dwt	900	13 800	15.3	76	186	9000	14 100
Ro-Ro & Vehicle 12′ dwt	1300	10 100	19.2	77	243	9200	14 200
Dry Bulk 180′ dwt	1200	17 300	15.3	76	202	9600	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	1700	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	43 000
Cruise > 10′ GT	250	42 600	21.3	73	261	42 000	71 600
Totals	31 000	12 950	16.5	74	190	7400	12 400

burning coal.

In terms of broad patterns, we may observe that the price differential between diesel and HFO has varied between 100 and 350 USD per ton, while HFO has been about 75% of the crude oil price. The price differential between diesel and crude oil has been around 100 USD per ton, and this refinery margin is varying fairly independently of the crude oil price. The assumptions employed in the following are that the diesel price is 100 USD per ton higher than the crude oil price, and the HFO price is 75% of the crude oil price.

4. Fuel consumption

Annual fuel consumption for a seagoing vessel is a function of operational pattern, sea conditions and parameters characterizing the vessel (Eqs. (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 (Smith et al. (2014), 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. The high case estimate corresponds to 95% of the design speed with the same days at sea as in the low case estimate, which gives consumption per vessel type more in line with the situation in 2007 (Buhaug et al. 2009; Lindstad et al. 2012). Table 1 shows annual fuel consumption per vessel type. The first column shows vessel type and size, i.e. average dwt for the group. Followed by: 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.

The main observations are that low case speeds as percent of design speeds vary from 59% for the large container vessels up to 88% for the large LNG carriers. Average annual fuel consumption per vessel for the fleet as a whole is 7400 tons in low case conditions and 12 400 tons based on the high-case assumptions.

5. Analysis

We now examine abatement options in terms of costs per ton of fuel as a function of crude oil price and annual fuel consumption. Tankers of three different sizes are used to illustrate the basic relationships. First, the smallest a 15 000 dwt chemical tanker with a design speed of 14 knots and annual fuel consumption in the range of 3700–4800 tons. Second, the 110 000 dwt tanker which is an Aframax crude oil carrier with a design speed of 15 knots and 9000–14 000 tons in annual fuel consumption. Third, the largest a very

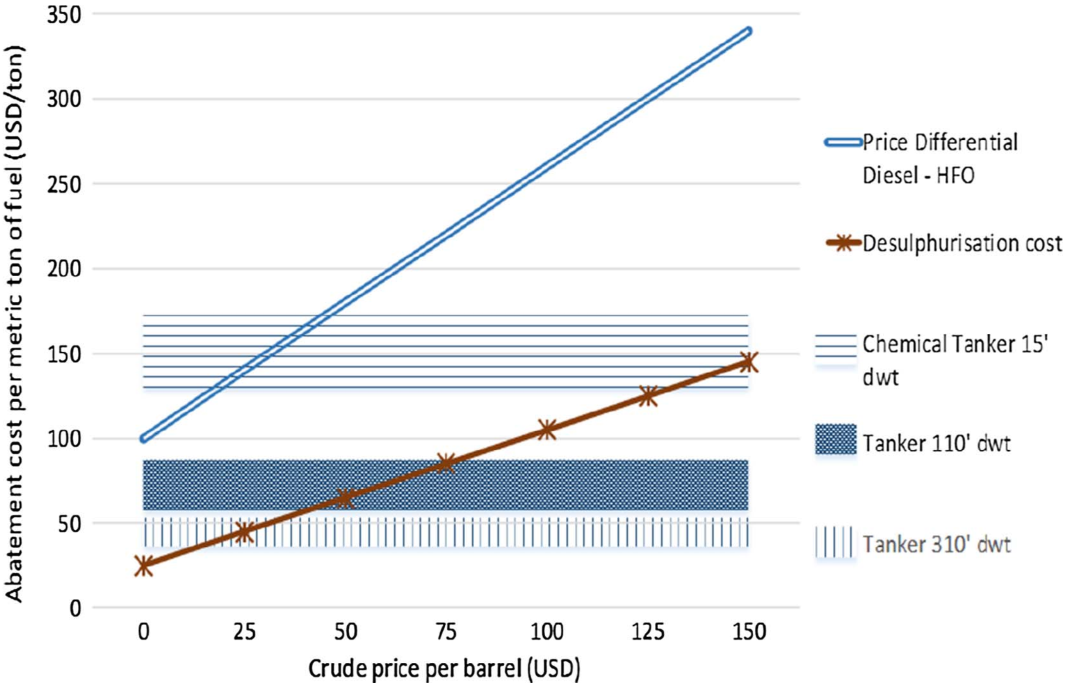


Fig. 2. Abatement costs for retrofitted scrubbers per ton of fuel, compared to costs of compliant fuels, for tankers of 15 000 dwt, 110 000 dwt and 310 000 dwt tankers.

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 scale economy of scrubbers with respect to vessel size. For newbuildings, the required annual time charter cost to operate the vessel and earn back the scrubber investment over 15–20 years is typically about 12–15% (8–11% for the capital and 4–5% for the operational cost (Lindstad et al., 2011, 2015a, 2015b)). 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 Fig. 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 instead using compliant fuels. The upper part of the shaded areas corresponds to the low case fuel estimate, and the lower part to the high fuel case estimate. The explanation is that when fuel consumption increases the financial and operational cost of the scrubber will be divided on more tons and the cost per ton of fuel will be reduced. Moreover, the upper curve shows the cost increase per ton of fuel compared to today if the diesel option is selected (Price differential Diesel minus HFO).The lower curve shows the cost increase if the desulphurised fuel (LSHFO $<$ 0.5%S) is selected, i.e. desulphurization cost.

We may first observe that the scrubber options – horizontal fields - 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. The fixed cost element in the scrubber installation process is high for small vessels with low annual consumption. As a result, for this tanker, the cost curve indicates that diesel is a competitive option 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 (LSHFO $<$ 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 high ooil prices lends scrubbing on board an advantage. Thus, the fuel options benefit from low crude prices, but are punished at high oil prices due to their energy requirements.

Fig. 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. The figure has annual fuel consumption on the x-axis and installed power on the y-axis. The three dotted lines in the figure leaning upwards to the right represent level-curves for the abatement costs, i.e. cost increase of 200, 100 and 50 USD per ton of fuel. The grey bars (areas) represent the typical ranges for annual fuel consumption by vessel type. For example an average LNG 70 000 dwt vessel typically consumes between 18 000 and 27 000 ton of fuel, and has an abatement cost with a scrubber of approximately 50 USD per ton. While the LNG 120 000 vessel which consumes more, i.e. between 34 000 and 43 000 ton of fuel gets an abatement cost with a scrubber of less than 50 USD per ton.

Main observations from Fig. 3 are that when installed power increases, a higher annual fuel consumption is required to keep abatement cost per ton constant. As an example, with an installed power of 10 000 kW, an annual fuel consumption of 8000 tons or more is needed to achieve an abatement cost of less than 100 USD per ton. Doubling engine size to 20 000 kW, the required fuel

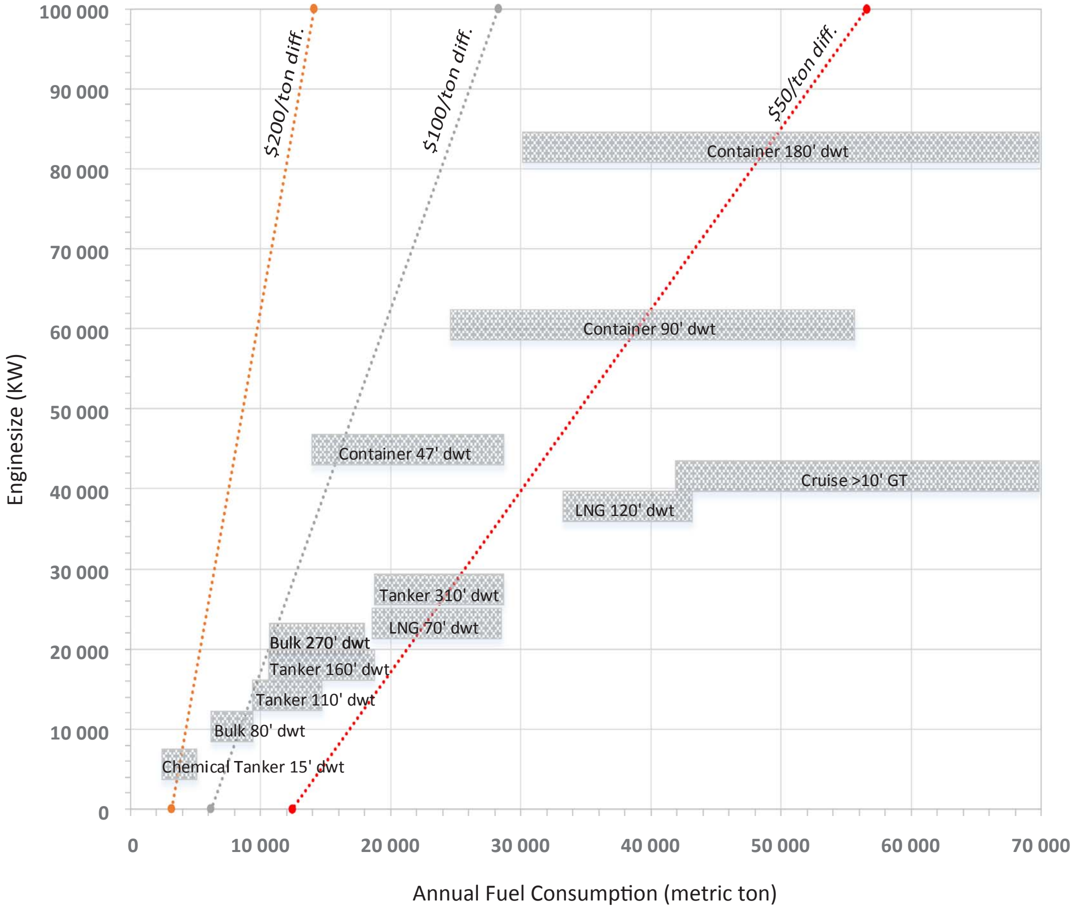


Fig. 3. Scrubber abatement costs in USD per ton of fuel as a function of engine size and annual fuel consumption for a selection of vessels types currently using HFO.

consumption is 11 000 tons or more.

To discuss implications, let us use the comparison between market conditions in 2007–2012. In 2012, speeds at sea were lower and vessels on average had more idle days due to greater capacity relative to transport demand, and higher fuel prices. In 2007 fuel consumption per vessel was consequently higher. 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; Sea 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 alternative abatement options can influence the speeds of the vessels.

We use an 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 for all the 27 vessels. Assumed newbuilding price is 50 million USD. Our calculations are based on a transportation leg of 2500 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.

Fig. 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 on the left-hand side. We can thus read reduction or increase of CO_2 emissions as a function of speed change. In the right-hand panel, we can identify the speed which minimises ship owner's cost, both for ballast and for laden voyage legs. For diesel as an abatement option, the letter A is used to mark the cost-minimising speed (right) and corresponding emission levels (left), B is used for HFO & Scrubber, and C is used and for HFO without scrubber (i.e. today's conditions). The assumed prices for HFO and diesel are 300 and 500 USD per ton of oil equivalents, respectively, which is approximately 2017 cost levels with a crude oil price level of 50 USD per barrel.

From Fig. 4 we can see that present practices, using HFO alone, the lowest cost for the ballast leg is found at 12 knots, and on the loaded leg it is 11 knots, which is not far from the average of 12–13 knots corresponding to current speeds for Aframax tankers.

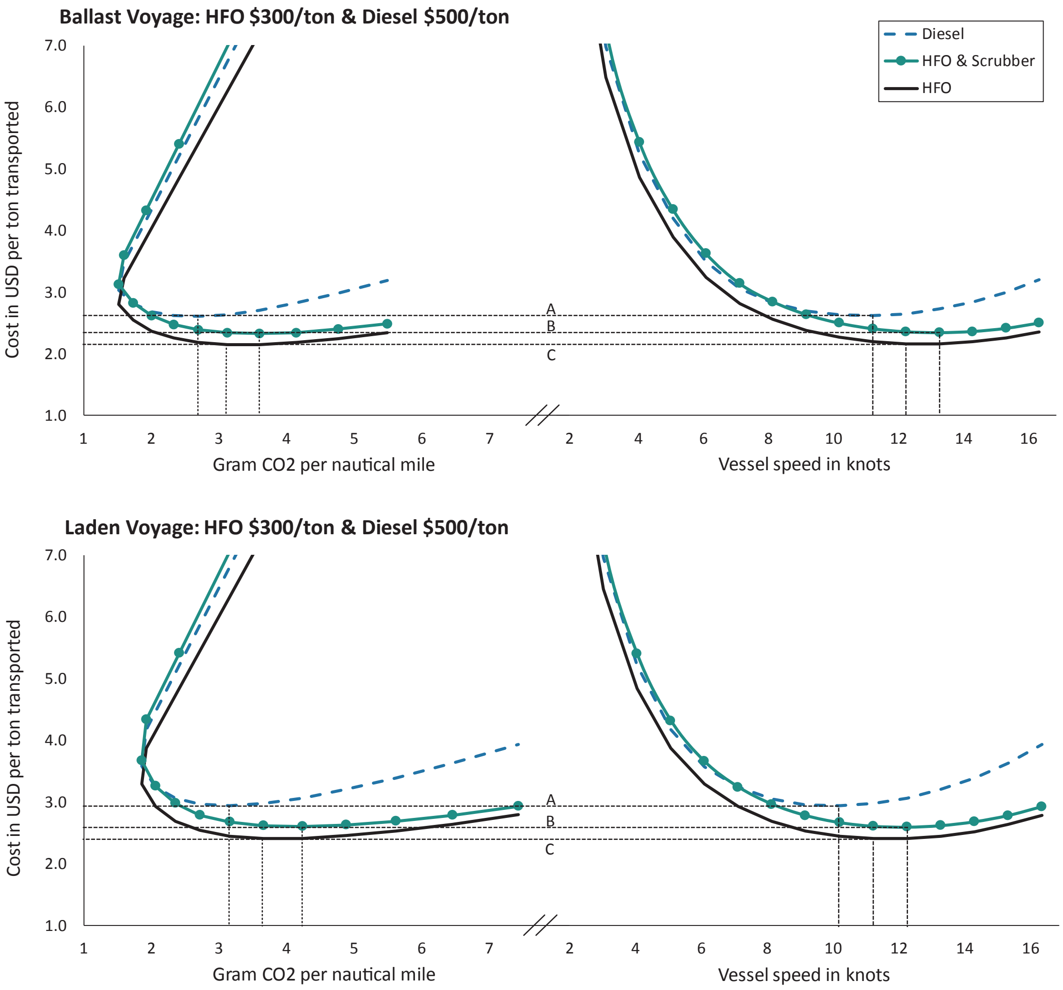


Fig. 4. Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 50 USD per ton.

Switching from HFO to the costlier diesel option reduces the cost minimising speeds by 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 by 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. The explanation is that installing a scrubber is a capital expenditure that increases the financial and operational cost of the vessel and hence gives larger weight to these cost elements versus the fuel cost. And contrary, with the diesel option it encourage speed reductions since it gives larger weight to fuel cost versus the financial and operational cost of the vessel. This reduces the speeds by one knot compared to HFO and CO_2 and emissions by 10–15%. 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 by 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 Figs. 5and 6, with 50% higher and lower fuel prices, corresponding to crude oil prices around 75 USD per barrel in Fig. 5 and 25 USD per barrel in Fig. 6.

From Fig. 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. Fig. 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 (LSHFO < 0.5% S) had been included in Figs. 4, 5 and 6 they would show cost-minimising speeds and CO_2 emissions per ton mile in between those for diesel and HFO, as is intuitive.

To generalize the sensitivity analysis for cost-minimising speeds, we also change the new-building price of the ship, and report combined results in Fig. 7. Here we can more clearly see the interplay between the initial investments costs ("capex" in Fig. 7) and the operating costs (affected by the fuel price), with higher speeds resulting in a triangle in the lower-right of Fig. 7 (in grey) where energy operating costs are not too high compared to vessel fixed costs. When fuel costs play a smaller role in the overall economics, pressures for higher outputs raise vessel speeds, allowing energy (and emissions) to substitute for capital. Thus, for all initial measures

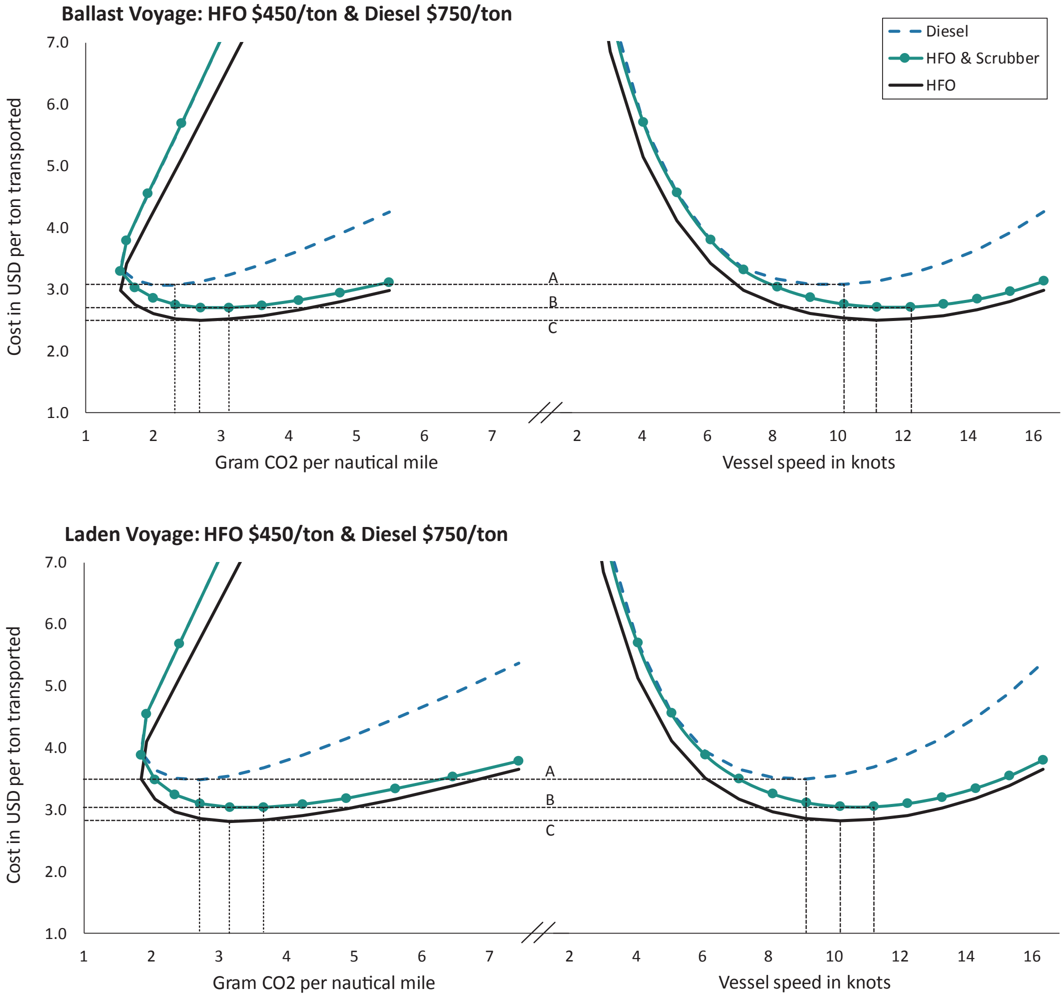


Fig. 5. Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 75 USD per ton.

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.

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. The scrubber options, in contrast, raise CO_2 emissions per ton mile output performed relative to HFO, not so much because scrubbing uses energy – though it does – but because fuel costs are lower and fixed costs are higher.

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, raise freight rates, prolong the lifetime and intensity of use for younger existing vessels, while shortening that of some older ones. This type of effect, called *new source bias* in the literature (or grandfathering, see, for instance, Nelson et al. (1993), is neither unusual in other industries nor in itself detrimental, but is worth noticing also for maritime shipping: as environmental policies are changing cost structures and often biased in favour of existing assets, keeping an eye on how operations are affected for existing assets may influence the overall policies. In the present case, we may expect over time that other policy instruments are found either to influence speeds or to address the sailings of vessels that are more polluting or less fuel efficient in other ways.

6. Conclusions

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

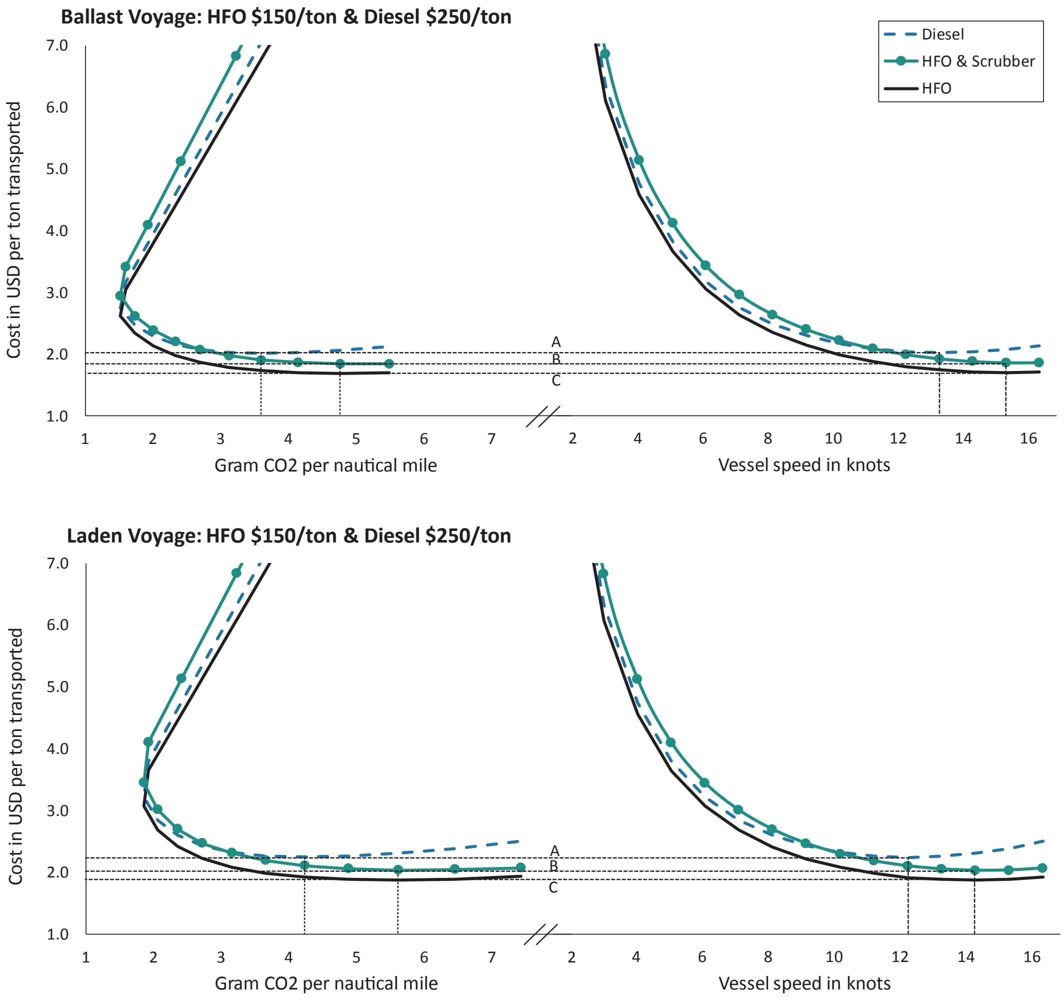
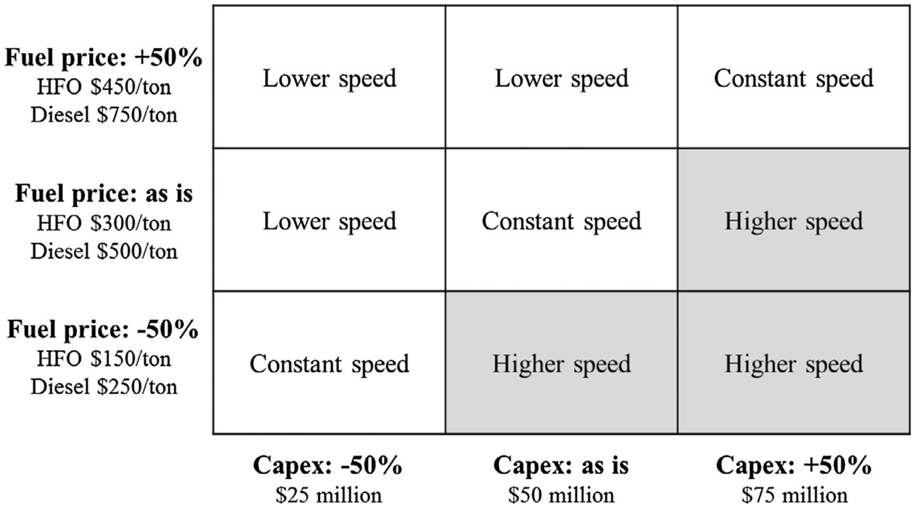


Fig. 6. Cost and emissions per ton transported for a 110 000 dwt oil tanker with a crude oil price level of 25 USD per ton.



	Capex: -50% $25 million	**Capex: as is** $50 million	**Capex: +50%** $75 million
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

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

Our findings are: First, for the vessels with highest fuel consumption, on-board exhaust gas scrubbing and continued use of HFO gives the lowest cost, consistent with Lindstad and Eskeland (2016) and Lindstad et al. (2015b). Second, in a case with crude oil prices lower than 50 USD per barrel, diesel is an interesting abatement option for the smaller vessels that currently use HFO. Third, desulphurised HFO (LSHFO $< 0.5\%$ S) comes at a production cost which makes it a competitive abatement option for all vessels apart from the largest fuel consumers. The indicated role of LSHFO – for vessels in between large consumers that install scrubbers and smaller vessels that rely on diesel – is sensitive to our assumptions: we have not assumed great cost reductions through scale and time, but applied judgment to the few estimates found in the literature. Greatly reduced costs of Desulphurising HFO will reduce the role of scrubbers in the large vessel categories, much in the same way as lower diesel costs will reduce the role of LSHFO in the middle range of fuel consumers.

An effect we explore in some detail is that when scrubbers are employed, it encourages to operate vessels at higher speeds. Then, fuel consumption and CO_2 emissions per ton-mile rises, since higher speed requires power input more than proportionally to transportation work performed. For the owner, the additional fuel consumption is less important than the reward for better utilization of the scrubber and the vessel. With diesel as an abatement option, the higher fuel cost reduces speeds, in our example the estimates are speed reductions in the range of 1–2 knots. For CO_2 emissions, 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 manmade 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 from our analysis may thus be that environmental policy analysis integrating across both local and global problems will be rewarding. Another lesson may be that implications of environmental policies shall also be analysed according to what they do with the operation of the assets (vessels) regulated, and with the replacement of these assets. Often – and in this case – environmental policies come in a shape which result in a 'new source bias': they slow down the entry of new assets, and prolong the lives and intensify the use of (some, not the oldest) existing assets. In maritime shipping, intensified use means higher speeds and greater GHG emissions per ton-mile transportation work performed, and we may have good reasons to pay attention.

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References

Acciaro, M., 2014. Real option analysis for environmental compliance: LNG and emission control areas. Transp. Res. Part D 28, 41–50.

BP, 2017. Statistical Review of World Energy June 2017.

Brynolf, S., Magnusson, M., Fridell, E., Andersson, K., 2014. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transp. Res. Part D 28, 6–12.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W.-Q., Yoshida, K., 2009. Second IMO GHG study 2009. International Maritime Organization, London, UK.

Bunkerworld, 2016. Marine Bunker fuel Spot prices 2006–2015. Exported 6/11-2015, and updated 18/12-2016. < www.bunkerworld.com > .

Campling, P., Janssen, L., Vanherle, K., Cofala, J., Heyes, C., Sander, R., 2013. Specific evaluation of emissions from shipping including assessment for the establishment of possible new emission control areas in European Seas.

Concawe, 2009. Impact of marine fuels quality legislation on EU refineries at the 2020 horizon < https://www.concawe.eu/wp-content/uploads/2017/01/rpt_09-3-2009-01906-01-e-2.pdf > .

Concawe, 2012. EU refinery energy systems and efficiency. < https://www.concawe.eu/wp-content/uploads/2017/01/rpt_12-03-2012-01520-01-e.pdf > .

Concawe, 2016. MARINE FUEL FACTS. < https://www.concawe.eu/wp-content/uploads/2017/01/marine_factsheet_web.pdf > .

Corbett, J., Wang, H., Winebrake, J., 2009. The effectiveness and cost of speed reductions on emissions from international shipping. Transp. Res. Part D 14, 593–598.

EnSys Energy and Navigistics Consulting, 2016. Supplemental marine fuel availability study. < https://www.ensysenergy.com/downloads/supplemental-marine-fuels-availability-study-2/ > .

Faber, J. et al., 2016. Assessment of fuel oil availability – final report July 2016 for the International Maritime Organization. < www.cedelft.eu > .

Jiang, L., Kronbak, J., Christensen, L.P., 2014. The costs and benefits of sulphur reduction measures: sulphur scrubbers versus marine gas oil. Transp. Res. Part D 28, 19–27.

Johansson, L., Jalkanen, J.P., Kalli, J., Kukkonen, J., 2013. The evolution of shipping emissions and the costs of regulation changes in the northern EU area. Atmos. Chem. Phys. 13 (22), 11375–11389.

Jonkeren, Olaf, van Ommeren, Jos, Rietveld, Piet, 2012. Freight prices, fuel prices, and speed. J. Transp. Econ. Policy 46(Part 2), 175–188.

Lindstad, H., Asbjørnslett, B.E., Strømman, A.H., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speed. Energy Policy 39, 3456–3464.

Lindstad, H., Asbjørnslett, B.E., Strømman, A.H., 2012. The importance of economies of scale for reductions in greenhouse gas emissions from shipping. Energy Policy 46, 386–398.

Lindstad, H., Eskeland, G., Psaraftis, H., Sandaas, I., Strømman, A.H., 2015a. Maritime shipping and emissions: a three-layered, damage based approach. Ocean Eng. 110 (2015), 94–101.

Lindstad, H., Sandaas, I., Strømman, A.H., 2015b. Assessment of cost as a function of abatement options in maritime emission control areas. Transp. Res. Part D 38, 41–48.

Lindstad, H., Eskeland, G.S., 2015. Low carbon maritime transport: how speed, size and slenderness amounts to substantial capital energy substitution. Transp. Res. Part D 41, 244–256.

Lindstad, H.E., Eskeland, G.S., 2016. Policies leaning towards globalization of scrubbers deserve scrutiny. Transp. Res. Part D 47, 67–76.

Lloyd's Register, 2012. Understanding exhaust gas treatment systems - guidance for ship owners and operators.

Nelson, R.A., Tietenberg, T., Donihue, M.R., 1993. Differential environmental regulation: effects on electric utility capital turnover and emissions. Rev. Econ. Stat. 75 (2), 368–373.

Plain, C. Benazzi, E., Guillaume, D., 2006. Residue desulphurisation and conversion. Digitalrefining.com/article/1000275.

Purvin, Gertz, 2009. Impacts on the EU Refining Industry & markets of IMO specification changes & other measures to reduce the sulfur content of certain fuels. Study carried out for DG Environment.

Psaraftis, H.N., Kontovas, C.A., 2010. Balancing the economic and environmental performance of maritime transport. Transp. Res. Part D 15, 458–462.

Sea at Risk and CE Delft, 2010. Going Slow to Reduce Emissions. < www.seas-at-risk.org > .

Shell, 2016. The bunker fuels challenge: how should you respond? Technology trends to watch. < http://www.shell.com/business-customers/global-solutions/industry-focus/the-bunker-fuels-challenge.html > .

Shell, 2017. Technology trends to watch – an introduction. Emerging sector paradigms and their potential impacts on refining margins, strategy and technology. Shell Global Solutions. < http://www.shell.com/business-customers/global-solutions/industry-focus/technology-trends-to-watch.html > .

Silva, M., 2017. Life cycle assessment of marine fuel production. Master thesis, NTNU.

Smith et al., 2014. The Third IMO GHG Study. < Imo.org > .

US Energy Information Administration. Historical Fuel and Crude oil prices. < http://www.eia.gov/petroleum/ > .

Wärtsilä, 2017. Personal communication with Stian Aakre at Wärtsilä Exhaust Gas Cleaning Systems, which provided us with acquisition cost and operational cost and performance for scrubbers.

Zis et al., 2015. Environmental balance of shipping emissions reduction strategies. Transp. Res. Rec. J. Transp. Res. Board 2479, 25–33 (July 2015).