Transportation Research Part D 47 (2016) 67–76

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny

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ARTICLE INFO

Article history:

Keywords:
Shipping and the environment
Greenhouse gases
Abatement cost and options
MARPOL
IMO

ABSTRACT

Emission regulations for Sulphur oxides (SOx) and nitrogen oxides (NOx) are motivated by health- and other environmental objectives in local and regional settings, while global warming concerns motivate policies for carbon dioxide (CO_2). We point out that the direction chosen by the International Maritime Organization (IMO) – to tighten SOx and NOx limits globally – carries important risks. First, extending to a global setting the present regulations in coastal emission control areas (ECAs, in North America and Northern Europe) gives negligible or negative environmental benefits, and raises global warming impacts. Second, 'end-of-pipe' solutions, such as scrubbing and tuning, become dominant responses, and they reduce energy efficiency. Third, the adoption of these end-of-pipe solutions carry risks of deflecting attention from development of cleaner fuels and improving energy efficiency. Distinguishing local environmental benefits from global ones is important in general, and our research concludes that in the case of shipping, this distinction better serves the needs of the local environment, the global climate, and conserves on abatement costs.

Introduction

Emissions from maritime transport account for 10–15% of global anthropogenic sulphur (SOx) and nitrogen oxide (NOx) emissions, and about 3% of global carbon dioxide (CO_2) emissions (Smith et al., 2014). Current maritime emission regulations set limits for SOx and NOx for health and environmental reasons, and for CO_2 in order to mitigate global warming (Eide et al., 2013). This study analyses risks following from the direction chosen by the International Maritime Organization (IMO) – to extend locally and regionally motivated emissions regulations, i.e. the emission control areas in North America and Northern Europe (ECAs), to a globalized scheme that applies even at high seas. From 2015, within these ECAs fuel combustion is restricted to a sulphur content of maximum of 0.1%. From 2016 onwards, new-built vessels that operate fully or parts of their time in North America must reduce their NOx emissions by 75% compared to the global threshold for vessels built after 2011. From 2020, the global limit for fuel sulphur content outside of ECAs will be reduced from the present maximum of 3.5–0.5%.

There are several reasons to question these environmental policies. First, the emissions of NOx and the SOx now to be reduced actually *mitigate* global warming (Lauer et al., 2007; Eyring et al., 2010), whereas emissions of black carbon (BC) and methane (CH_4) – remaining unrestricted – contribute to global warming (Jacobson, 2010; Bond et al., 2013; Myhre and Shindell, 2013; Fuglestvedt et al., 2014; Lindstad and Sandaas, 2016). Metrics that weight emitted gases according to

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http://dx.doi.org/10.1016/j.trd.2016.05.004
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their global warming potential (GWP), to report them in terms of "CO_2 *equivalents*", have become standard currency to benchmark and communicate the relative and absolute contributions to climate change (Shine, 2009). GWP gives negative weights for emitted exhaust gases and particles that have a cooling effect, and positive weights for those that have a warming effect.

Second, the present approach to NOx emissions through technical standards neglects that the reductions come at the cost of higher fuel consumption (Lindstad et al., 2015a) and, thus, CO_2 emissions. Third, stricter SOx rules also tend to raise fuel consumption on a well to propeller basis, i.e. either when refineries remove sulphur from heavy fuel oils (HFO), or when scrubbers clean the exhaust gas from combustion at sea (Lindstad et al., 2015b). Fourth, the current IMO legislation and testing standards (MARPOL Convention) assumes that the engines are operated at medium to high loads. In reality, vessels today commonly operate more at low to medium power, and at high power loads in rough seas or when it is required to arrive on time in the next port. Engines that for regulatory reasons are tuned to minimize emissions at high loads will under operations at lower loads render combustion less efficient, and thus yield higher emissions per kW h of all exhaust gases, including CO_2.

Previous studies of the of stricter fuel emission regulations have mainly focused on the ECAs and the technical options and costs of complying with the regulations from 2015 onwards (Brynjolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015b). Less attention have been on the climate impact of the 2020 global sulphur cap and the stricter NOx regulations. Lindstad et al., 2015a).

For these reasons, the present study focuses on how operators will comply with global policies from 2020. First, we establish the costs for the alternative abatement compliance options and thus responses from 2020 onwards. Second, the cost and climate impacts of the most cost efficient abatement options are compared with the present situation (2015). Third we quantify the benefits and costs of alternative policy approaches towards environmental management, concluding that the present approach is biased in direction of scrubbers, which is an end-of-pipe option we believe is largely misguided.

The employed model is described in Section "Model description"; its application and data are presented in Section "Application and data set"; the analysis and results in Section "Analysis" and the results obtained are discussed in the final section with respect to their implications for policy development.

Model description

We need assessment of costs, emissions and fuel consumption, see Lindstad et al. (2011, 2014, 2015b), and limit our attention to the vessels and their use, i.e. we do not include port side consequences.

The vessel's annual fuel consumption consists of the fuel consumption in the ECA and non-ECA sailing. Adding the port stays, we get

$$\begin{aligned} F^{O} &= \left(\sum_{\substack{i=1 \\ i \notin ECA}}^{n} \frac{D_i}{v_i} \cdot P_i \cdot K_{fp}^{O} \right), \\ F^{ECA} &= \left(\sum_{\substack{i=1 \\ i \in ECA}}^{n} \frac{D_i}{v_i} \cdot P_i \cdot K_{fp}^{ECA} + T_{lwd} \cdot P_{port} \cdot K_{fp}^{ECA} \right) \end{aligned} \tag{1}$$

where F^{O} denotes the fuel consumption outside an ECA, while F^{ECA} denotes the consumption for sailing inside ECA and for staying in port. These are the two terms for each voyage.

During a voyage, the sea conditions will vary, and this is handled by dividing each voyage into sailing sections (i, here), with a distance D_i for each sea condition influencing the vessels speed v_i and the required power P_i. K_{fp} is the fuel required per produced kW h, as a function of engine load, T_{lwd} is time spent in port.

The annual emissions, ε per pollutant are calculated as expressed by Eq. (2):

$$\varepsilon = \sum_{i=1}^{n} \frac{D_i \cdot P_i \cdot K_{ep}}{v_i} \tag{2}$$

Here, K_{ep} is the emission factor for the pollutant as a function of engine load. Emissions per kW h produced increases when engine load is reduced.

GWP per kW h produced and per ton transported are calculated by Eq. (3).

$$GWP_t = \sum_{i=1}^{n} \varepsilon_e \cdot GWP_{et} \tag{3}$$

Here, ε_e represents emissions of pollutant e and GWP_{et} is the GWP factor for each pollutant within the given time frame.

The annual fuel and abatement cost is given by Eq. (4)

$$C_a = C^{ECA} \cdot F^{ECA} + C^{O} \cdot F^{O} + C_v^{capex} \tag{4}$$

Here C^{ECA} and C^{O} represents the cost per ton of fuel.

Hence, the annual costs increase as a function of abatement technology and fuel is given by Eq. (5)

$$\Delta C_a = C^{ECA} \cdot F^{ECA} \cdot + C^{O} \cdot F^{O} + C_v^{capex} - C^{HFO} \cdot F^{HFO}. \qquad (5)$$

Here C_v^{capex} denotes the annual costs of the abatement technology used, comprising annualized capital costs and operating costs.

Application and data set

Since 1970, maritime transport expressed either in tons transported or in ton-miles freight work (miles in this text are nautical miles), has increased by 250%. This compares to a 170% increase in global energy consumption and a 90% increase in global population (Eskeland and Lindstad, 2015). During this period, global GDP (or output) has grown at the same pace as maritime transport. The environmental consequences of this increased sea trade have become important in the current climate debate (Lenton et al., 2008). The current world fleet (2012) consist of 106,000 vessels above 100 Gross tons (GT). In this study, the starting point for our analysis is data on the fleet and fuel and emissions as published by the Third IMO GHG study (Smith et al., 2014). Fig. 1 shows number of vessels and bunker consumption as a function of installed engine power.

Main observations are that the vessels with engines sizes up to 1800 kW represents 41% of the fleet in numbers of vessels and only 17% of the annual fuel consumption, while vessels above 30,000 kW represents 3–4% of the fleet and more than 20% of the fuel consumption.

Historically, large seagoing vessels have used heavy fuel oil (HFO) with a sulphur content of up to 3.5%, while smaller vessels have used distillates with sulphur content lower than 1.0%. Heavy fuel oil consists of low quality fractions of crude that remains in the refinery process after the extraction of lighter fractions such as naphtha, petrol, diesel, jet fuel, and light fuel oil. Increased environmental concern in recent years have challenged this practice. The International Maritime Organization (IMO) has approved regulations for Emission Control Areas (ECAs) such as North Sea and the Baltic that limit fuel sulphur content to maximum 0.1% starting in 2015. These rules globalize sulphur limits to 0.5%, starting in 2020. Such rules allow the continued use of higher sulphur fuels in combination with scrubbers that reduces the SOx in the exhaust-gas to specified limits.

In this study we compare: heavy fuel oil (HFO-2.7%) with maximum sulphur content up to 3.5%; distillates with sulphur content up to 0.5% (MDO-0.5%) in combination with use of marine gas oil (MGO) with sulphur content up to 0.1% in the ECA's; liquefied natural gas (LNG) and also liquefied pressurized Gas (LPG) in vessels carrying LPG as the cargo. HFO, MDO and MGO are used in traditional diesel engines, while LNG is used in diesel dual-fuel engines. Dual-fuel engines can operate on traditional fuels such as HFO, MDO, and MGO or on LNG, where the LNG is injected at either high or low pressure. In this study, we focus on high-pressure LNG injection systems, since these engines achieve nearly complete combustion of the methane (CH_4), contrasting low-pressure systems that emit considerable amounts of un-combusted methane. In Fig. 2, we show the average annual price per ton of oil equivalent (TOE) for each of these fuels for the period from 2006 to 2015. In addition, the figure includes a plot of the price difference between MGO and HFO.

Main observations are that MGO is consistently the most expensive of the fuels. The price for HFO is consistently lower than the crude price. LNG is cheaper than the crude oil and the price of LNG is closer to HFO than to the Crude price. This LNG price is considerably higher than the cost for pipeline delivered gas in US, i.e. Henry Hub. Producing LNG from gas requires huge capital investments and approximately 10% of the energy for conversion. The price differential between MGO and HFO is typically higher when crude prices are high.

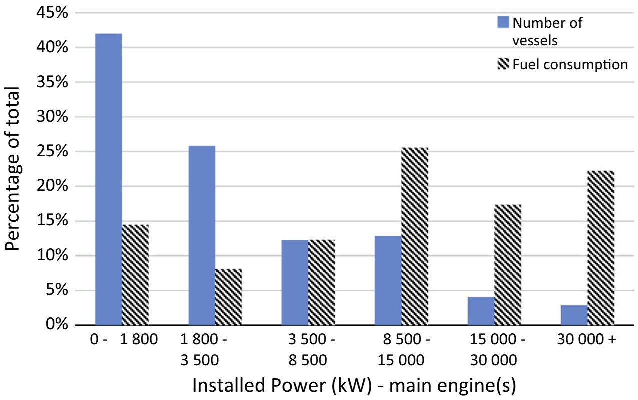

Fig. 1. Number of vessels and bunker consumption as a function on installed power.

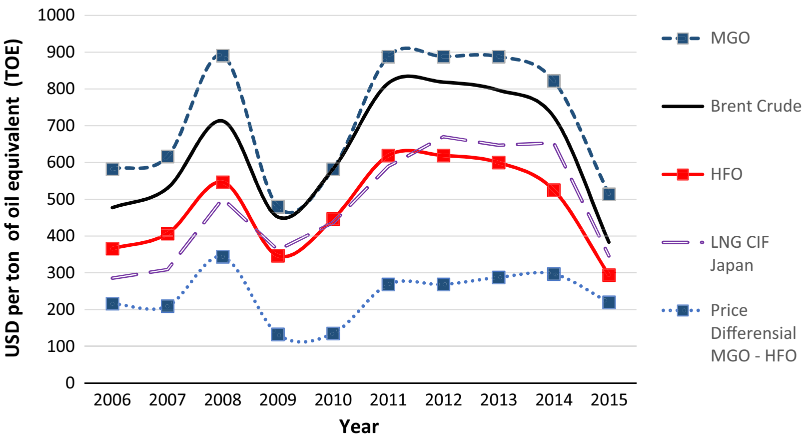

Fig. 2. Development of Fuel prices per ton of oil equivalents (TOE) from 2006 to 2015. Data Source: Bunker World; eia – US Energy Information Administration; BP Statistical Review of World Energy (2015); all figures are yearly averages.

The estimated cost of alternative abatement options and the respective fuels are as shown in Table 1. It should be noted that the cost of retrofitting an existing vessel will be higher than when the equipment is installed as part of a new built process, however if the installation is done when the ship is idled or docked for other reasons, the additional costs will be small. For vessels built after 2016, the stricter North American NOx rules will raise engine costs, but since this will be an additional cost of the same magnitude, i.e. 0.1–2.0 MUSD for all the assessed options (dependent on the applied technologies and the engine size), it does not influence the ranking of the assessed options. We assume that the price differential between HFO and MGO and MDO will be of the same magnitude as seen since 2006, i.e. between 100 and 300 USD per ton of fuel.

The capital expenditure for the abatement options will consist of two parts: a fixed amount, which is independent of engine size, and an additional amount, which increases linearly with the engine size. For both scrubber options, there will be an additional expense per ton of fuel to cover for the energy (fuel) required running the scrubber, for chemicals and for the deposit of waste. This cost element is highest for the closed loop scrubber, due to the extensive chemical treatment of the water circulating in the closed loop cycle. Combining these costs with the operational vessel characteristics enables us to calculate abatement cost per ton of fuel, as a function of vessel type and size.

Analysis

Cost as a function of abatement option

We first investigate abatement cost per ton of fuel for the abatement options as a function of vessel type (150 USD per ton HFO and 300 per ton MGO are used as input prices). Results are shown in Table 2. All assessments are based on comparing fuel prices per energy content, i.e. tons of oil equivalents (TOE). Annual fixed and operational cost – excluding fuel and the specific additional cost per ton of fuel – are calculated to be 12% of the capex for the abatement option.

An open loop scrubber is an important option for almost all vessels, and its costs are reported in dollars per ton of annual fuel in the fourth column from the right. Thus, with vessel groups ranked from top in terms of declining abatement costs, this column shows at which price differential per ton of fuel the vessel group finds an open loop scrubber to be less costly than

Table 1
Fuel and abatement options.

Fuel and abatement option	Fuel price January 2016 USD/ton	Price increase compared to HFO USD/ton	Basic Capex USD	Additional Capex per 1000 kW installed power USD	Other additional cost per ton of fuel USD/ton
HFO – AS IS	150	–	–	–	–
MGO	300	100–300			
MDO	300	100–300	–	–	–
HFO – open loop scrubber	150	–	1,500,000	100,000	20
HFO – closed loop scrubber	150	–	3,000,000	100,000	40
Gas on LNG/LPG vessels	150	–	2,000,000	100,000	
LNG	150	–	2,000,000	400,000	

Cost figures based on; MAN DIESEL 2013; Norwegian NOx Fond 2014; Lindstad et al. (2015b); Dialogue with industry and ongoing projects.

Table 2
Sulphur abatement cost per ton of fuel as a function of vessel type and size.

Ship type	No. of vessels	Average per Vessel			Fuel cost per vessel if HFO	Additional fuel cost with MGO	Lowest abatement cost per vessel	Abatement Cost per ton				Share of total fuel
		DWT	Installed power (kW)	Fuel per vessel (ton)				Scrubber open loop	Scrubber closed loop	LNG	Total fuel in million ton	
MGO & MDO gives lowest cost												
Service – Tug	14,600	120	2300	500	75,000	75,000	75,000	435	815	701	7.3	
General Cargo	11,600	1900	1100	600	90,000	90,000	90,000	342	662	488	7.0	5%
Lowest cost given by price differential between HFO and MGO & MDO												
Fishing	22,100	180	1000	700	105,000	105,000	105,000	294	571	411	15.5	
Miscellaneous	3000	60	2000	800	120,000	120,000	120,000	275	520	420	2.4	
Service – Other	3400	2300	3200	1100	165,000	165,000	165,000	219	402	358	3.7	
Offshore	6500	1700	4700	1300	195,000	195,000	195,000	202	360	358	8.5	
Passenger Ferry	3200	170	2000	1200	180,000	180,000	180,000	190	360	280	3.8	
Tankers	6600	3300	1700	1500	225,000	225,000	225,000	154	294	214	9.9	
Dry Bulk	1200	3300	1600	1500	225,000	225,000	225,000	153	293	211	9.9	
General Cargo	2900	7300	3300	1800	270,000	270,000	260,000	142	262	221	5.2	
Cruise	270	410	1900	2000	300,000	300,000	240,000	121	231	166	0.5	
Tankers	2400	47,600	9600	3000	450,000	450,000	360,000	118	198	234	7.2	
Ferry – Ro-Pax	1700	400	1500	2200	330,000	330,000	240,000	110	212	142	3.7	24%
Open loop Scrubber gives lowest cost												
Dry Bulk	5400	41,700	10,100	4000	600,000	600,000	380,000	95	160	181	21.6	
Container	1100	8600	6000	3700	555,000	555,000	330,000	88	157	143	4.1	
Tankers	1200	15,300	5100	3800	570,000	570,000	320,000	83	151	128	4.6	
General Cargo	2000	22,500	7400	4400	660,000	660,000	360,000	81	142	135	8.8	
Ferry – Ro-Pax	1200	3200	15,500	7000	1,050,000	1,050,000	510,000	72	118	141	8.4	
Ro-Ro&Vehicle	1300	1000	1500	3900	585,000	585,000	280,000	71	137	80	5.1	
Dry Bulk	2300	82,000	10,900	6200	930,000	930,000	430,000	70	119	123	14.3	
Reefer	1100	5700	5000	5100	765,000	765,000	340,000	67	122	94	5.6	
Container	1300	20,400	12,600	7500	1,125,000	1,125,000	480,000	64	108	113	9.8	
Dry Bulk	1200	177,000	17,300	9 600	1,440,000	1,440,000	580,000	60	99	112	11.5	
Dry Bulk	300	271,400	22,200	11,400	1,710,000	1,710,000	670,000	59	95	115	3.4	
Container	110	177,000	83,000	30,200	4,530,000	4,530,000	1,780,000	59	85	140	3.3	
Tankers	900	109,300	13,800	9 000	1,350,000	1,350,000	530,000	58	98	100	8.1	
Container	1700	46,800	30,500	14,600	2,190,000	2,190,000	840,000	57	90	117	24.8	
Tankers	500	162,300	18,800	10,900	1,635,000	1,635,000	620,000	57	94	105	5.5	
Container	900	87,300	59,500	25,600	3,840,000	3,840,000	1,410,000	55	82	121	23.0	
Ro-Ro&Vehicle	1300	11,800	10,100	9200	1,380,000	1,380,000	490,000	53	92	79	12.0	
Tankers	600	313,400	27,700	19,100	2,865,000	2,865,000	890,000	47	76	82	11.5	
Cruise	250	7300	42,600	42,000	6,300,000	6,300,000	1,530,000	36	61	54	10.5	67%
LNG or LPG gives lowest cost												
LNG & LPG	1100	6700	3800	3200	480,000	480,000	290,000	91	167	89	0.0	
LNG & LPG	500	68,500	22,600	18,500	2,775,000	2,775,000	510,000	44	81	28	9.3	
LNG & LPG	50	121,300	37,400	34,100	5,115,000	5,115,000	690,000	38	67	20	1.7	4%
Total	106,000										291.0	

using the cleaner fuels (MGO and MDO). Two arbitrary lines are drawn, at abatement costs of 300 dollars and 100 dollars per ton of fuel, respectively. As shown in Fig. 2, this range of fuel price differential is seen historically, so vessels with abatement costs in this range will choose between an open loop scrubber and reliance on cleaner fuels depending on price expectations and other assumptions in the year that they are built/serviced. It is a fixed cost element in the scrubber option which makes it relatively less expensive for vessels with a high share of fuel costs in their cost structure, so a tendency is seen downwards in the table that vessels are larger, less advanced (i.e. cheaper), move faster, or a combination of these.

Main observations from Table 2 are; first at the top of table two vessel types, service – tug as well as small general cargo vessels would not choose scrubbers unless in a scenario with expectations of a high (unrealistic) fuel price differential exceeding 300 dollars per ton. Second follows vessels, which with an open loop scrubber get an abatement costs between 100 and 300 USD per ton of fuel. This implies that if the price difference between HFO and MGO is in the high end of this interval, open loop scrubbers will give the lowest cost for all these vessels. Vice versa, if it is in the low end, MGO will give the lowest abatement cost for all these vessels. In total these vessels represents 50% of the fleet and 24% of the total fuel consumption. Third for all other vessels except gas carriers, annual fuel costs are high, and open loop scrubbers give the lowest cost, with abatement cost from 30 to 100 USD per ton of fuel. These vessels add up to 23% of vessels and 67% of the fuel consumption. For gas carriers, using gas gives the lowest abatement cost if the gas price equals the price of the HFO, but even here, open loop scrubbers will be quite competitive.

Emissions to air and climate impact and as a function of abatement option

To assess the climate impact of the assessed abatement options, we use the emission factors and global warming potential (GWP) as specified in Table 3.

Table 3 shows, that CO_2 and SOx emissions per kW h at low power are approximately 10% higher than at high loads. Furthermore, CH_4 emissions doubles at low power. NOx emissions increase by 50% at low power and the ratio of BC emissions at low power to BC emissions at high power increases more drastically than for any other emissions species. In the two columns to the right in Table 3, the weights GWP_{20} and GWP_{100} from the lower panel are applied, showing that the 'dirtiest' fuel is 'cooling' when using the twenty year scale (GWP_{20}) and 'carbon neutral' (about as much cooling as warming) when using the more frequently applied hundred year scale (GWP_{100}). In sum, at low loads, both the higher CO_2 emissions due to lower fuel efficiency and the higher emissions of other species result harmful in terms of warming.

In Fig. 3, we first investigate the climate impact expressed in CO_2-equivalents, as a function of power load, evaluated at a 20-year time horizon (GWP_{20}). Emissions contributing to global warming are positive values in the figure, while those contributing to global cooling are negative values; the red and white marker (CO_2 equivalent) denote net warming or cooling, as shown in the right hand column of Fig. 3. Fig. 4 shows comparable results for a 100-year time horizon (GWP_{100}).

Fig. 3 shows that the warming impact expressed in CO_2 equivalents (GWP_{20}) is lowest at high power for all the assessed fuels and abatement options. Beyond this, the main observations are that continued use of Heavy Fuel Oil (HFO 2.7%) gives a large net cooling effect; while all the fuel and abatement options which satisfies the IMO 2020 regulations gives a large warming effect. We also observe that in areas where local air pollutions is a key priority, LNG gives the lowest pollution in terms of NOx and SOx.

Fig. 4 demonstrates that the differences between the assessed options are smaller for a 100-year time horizon. Over this longer time horizon, the impact of CO_2 emissions becomes more important relative to the shorter-lived species such as methane, and the overall effect is that maritime shipping is closer to climate neutral than actually cooling. Another observation is that while in a 100-year horizon the effect of continued use HFO 2.7% is about climate neutral, the warming effects

Table 3
Emissions factors in gram per kW h and the applied GWP factors.

		Power	CO_2	BC	CH_4	CO	N_2O	NOx	SO_2	OC	NET GWP_{20}	NET GWP_{100}
Previous studies	Buhaug et al., 2009		595	0.067	0.06	1.4	0.02	14.8	10.3	0.2		
	Peters et al., 2011		595	0.067	0.06	1.4	0.02	14.8	10.3	0.2		
This study	HFO – 2.7% S	High	570	0.05	0.05	1	0.02	12.0	10.0	0.2	−1004	63
		Low	630	0.20	0.10	2	0.02	18.0	11.0	0.2	−991	70
	HFO & Scrubber – 0.5% S	High	590	0.025	0.05	1	0.02	12.0	2.0	0.2	114	378
		Low	650	0.075	0.10	2	0.02	18.0	2.2	0.2	120	382
	MDO – 0.5% S	High	570	0.025	0.05	1	0.02	12.0	2.0	0.2	94	358
		Low	630	0.15	0.1	2	0.02	18.0	2.2	0.2	190	387
	MGO – 0.1% S	High	570	0.025	0.05	1	0.02	12.0	0.4	0.2	320	419
		Low	630	0.15	0.10	2	0.02	18.0	0.4	0.2	438	454
	LNG – dual fuel high pressure	High	450	0.005	0.5	1	0.02	9.0	0.1	0.2	304	352
		Low	490	0.050	1.0	2	0.02	12.0	0.1	0.2	398	389
	GWP_{20} factors		1	1200	85	5.4	264	−15.9	−141	−240		
	GWP_{100} factors		1	345	30	1.8	265	−11.6	−38	−69		

GWP factors based on World average excluding Artic: BC – Collins et al. (2013); CH_4 – IPCC (2013).
CO – Fry et al. (2012); N_2O – IPCC (2011); NOx – Fry et al. (2012); SO_2 – IPCC (2013); OC – IPCC (2013).

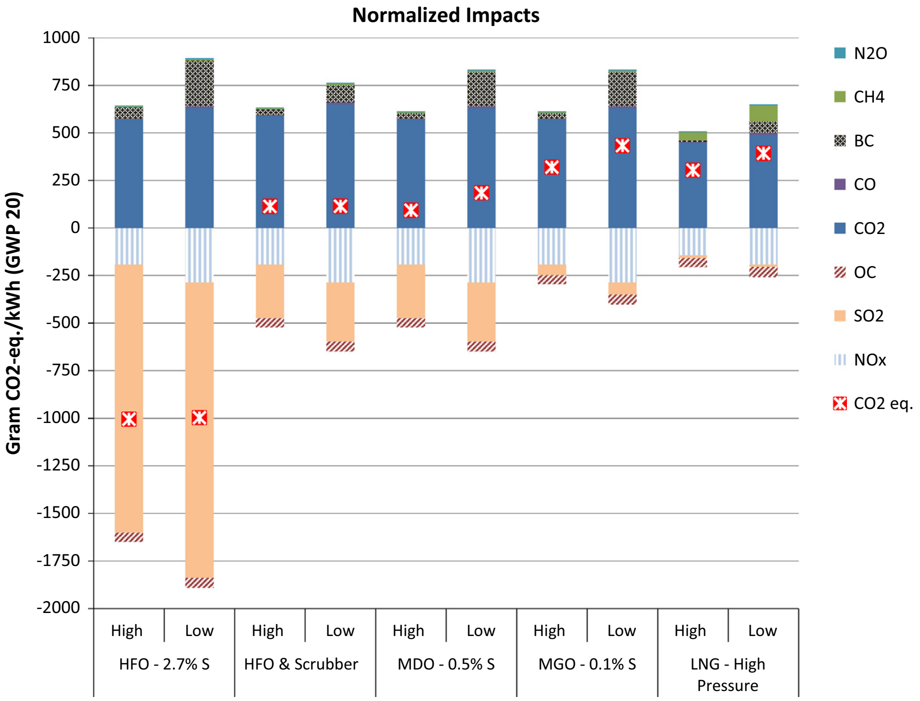

Fig. 3. Gram CO_2 eq. impact per kW h with a 20 year time horizon (GWP 20) as a function of fuel and abatement option – Atlantic (Northern hemisphere).

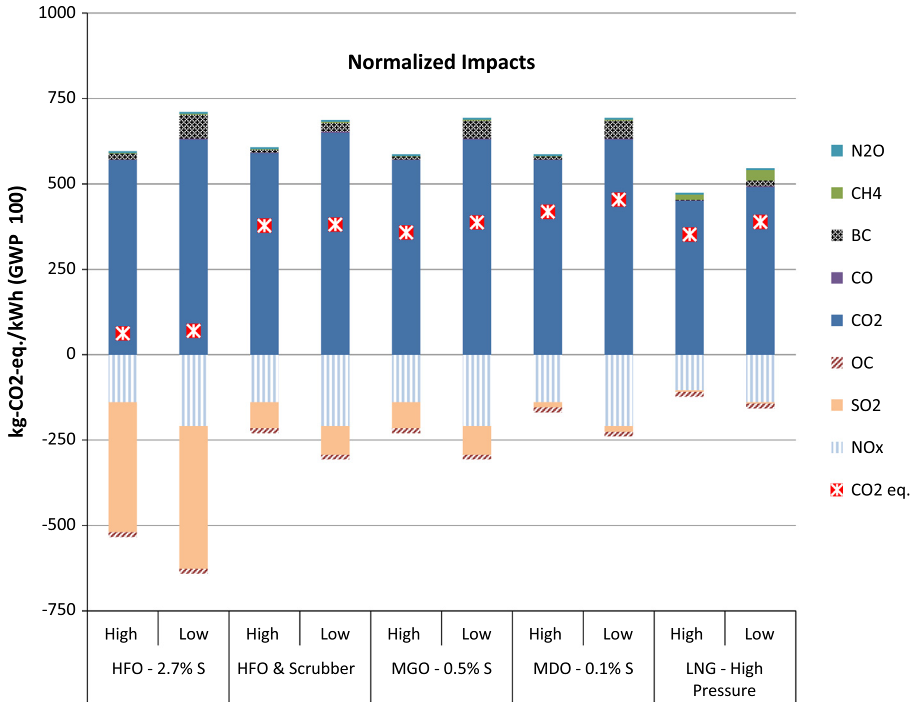

Fig. 4. Gram CO_2 eq. impact per kW h with a 100 year time horizon (GWP_{100}) as a function of fuel and abatement option – Atlantic (Northern hemisphere).

of all other options increase further, and the favourable impacts of dirty fuels are retained. In a climate change perspective, this highlights the value of limiting the extension of stricter SOx rules only to areas where local air pollution is a problem, i.e. close to coasts and populated areas. Hence, it may be worth wile to consider allowing continued use of heavy fuel oil at the high seas globally.

While we in Table 3 and Figs. 3 and 4 focused on the climate impact of globalizing the SOx regulations, Fig. 5 shows the impact of globalizing stricter NOx regulations. Here tier 2 represents the current worldwide NOx scheme for all vessels built from 2011 onwards. Tier 3 represents the NOx scheme currently applicable for vessels built from 2016 onwards in US and Canadian waters, and which might become a requirement in the North Sea and the Baltic ECA and in new ECA's globally.

The main observation is that the stricter NOx regulation increases the warming effect of shipping for all the assessed options. In a climate change perspective, this highlights the need to extend stricter NOx rules only in areas where local air pollution is a problem, i.e. close to coasts, populated areas and perhaps other identified characteristics of vulnerable ecosystems. On a new vessel, one can use engine technologies to reduce NOx emissions to the required levels in the low-NOx zones (Tier 3) and let it run in a more energy efficient mode (i.e. Tier 2) outside the low-NOx zones. If low NOx-zones are implemented in coastal zones globally, vessels built from 2016 onwards could be allowed to operate their engines in a pure CO_2 emission-minimizing mode in high seas, i.e. not satisfy even the first NOx regulations from 2001, in order to fully utilize the climate mitigation effect of high NOx and low CO_2 emissions.

The larger picture

In 2012, global maritime fuel consumption was around 300 million tons, emitting 900–950 million tons of CO_2, 19–23 million tons of NOx, and 11–13 million tons of SOx. With the 2012 fuel mix consisting of fuels with Sulphur content ranging from less than 0.1% in MGO, less than 1% in the ECA's (2012) and up to 3.5% in the heaviest fuel oils (HFO), the average Sulphur content in the fuel consumed globally was around 2% (6 million tons of Sulphur). For Nitrogen, the average emissions are 13–15 gram of NOx per kW h produced (around 7 million tons of Nitrogen). With the stricter SOx and NOx regulations from 2015 and 2016 in ECAs, and a global cap on Sulphur from 2020, the emitted amounts of Nitrogen and Sulphur to air from shipping will decline. This will reduce pollution locally, which makes sense in vulnerable areas with high pollution, but comes at a climate penalty and an abatement cost. It is therefore worth considering policies that are more careful about the role of local environmental benefits, since these can deliver greater greenhouse gas mitigation and come at a lower cost.

The investigated options are shown in Fig. 6. The first two columns show the whole fleet using HFO only, which gives the lowest abatement costs and only a small warming contribution (CO2 equivalent tons – GWP_{100}), but high SOx and NOx emissions including in coastal areas. The subsequent three pairs of columns show lower SOx and NOx emissions, at a cost of higher abatement costs *and* higher global warming contributions. Finally, an alternative scheme in the two columns to the right allows that 0.1% Sulphur Fuels are used close to coasts and in ports globally, and in sensitive areas such as the Arctic, while 2.7% HFO is used in all other areas. Without going into details, our estimate is that this implies a fuel mix of 35% with 0.1% Sulphur and 65% with 2.7% S (with a maximum of 3.5% S). As we can see, this alternative implies somewhat higher SOx emissions to air (but not much for the total of SOx emissions to air *and* sea, which is ecologically more relevant), but has much lower abatement costs, contributes less to global warming, and retains the importance of lower SOx and NOx emissions in zones near coasts and in ports.

Main observations are; first, that the stricter NOx regulations come at a high climate penalty if all engines are to operate in tier 3 mode globally (when engines are tuned for tier 3, NOx is reduced, but fuel efficiency drops); Second, the lowest climate impact of shipping is achieved if all vessels use HFO only. Third, with the 2012 fuel mix, maritime transport is still nearly climate neutral even in a 100 year' perspective, since CO_2 equivalent emissions are only 25% of CO_2 emissions. Fourth,

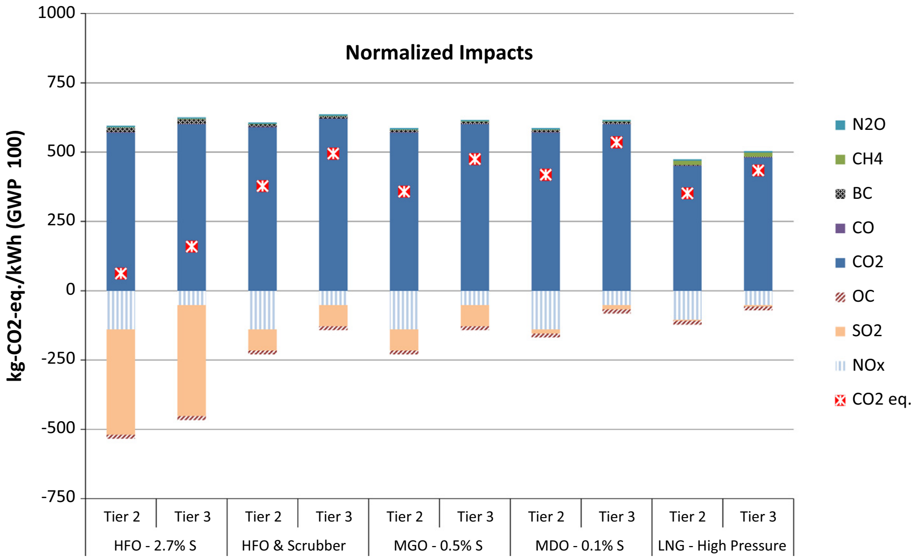

Fig. 5. Gram CO_2 eq. impact per kW h with a 100 year time horizon (GWP_{100}) as a function of fuel and NOx regulation – Atlantic (Northern hemisphere).

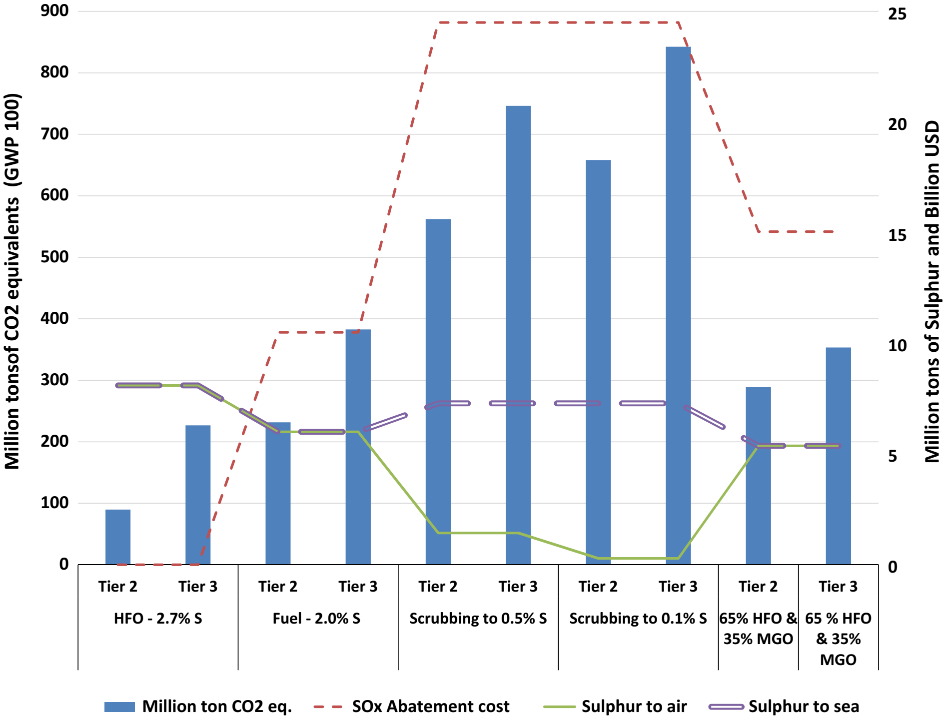

Fig. 6. Global shipping emissions measured in CO_2 eq. and abatement cost as a function of SOx and NOx regulations (GWP_{100}).

a globalized cap on Sulphur from 2020 triples the CO_2 equivalent emissions from shipping under Tier 2 NOx regulations. Fifth, if the whole fleet had to operate according to North American ECA regulation, i.e. 0.1% Sulphur and Tier 3, the CO2 equivalent emissions would be at the same level as its total CO_2 emissions (900–950 million tons). Sixth, for Sulphur, the figures show that the 2020 legislation gives the designated reductions when the focus is on emissions to air, but the emissions to sea rise, even compared to 2012 levels, due to the high adoption of open loop scrubbers.

At high seas, emissions to air of Sulphur and Nitrogen will mostly deposit in oceans, while in coastal areas much will deposit on land. On land, Sulphur in too high quantities has acidifying and damaging effects in ecosystems, human health and infrastructure. NOx exhaust gas emissions are undesirable too, at too high levels (health damages and over-fertilization). While the acidifying changes in the sea due to nitrogen and sulphur compounds are only a fraction of the effects from carbon dioxide (CO_2), the effects compounded in coastal areas are likely more damaging and undesirable in general. Research by Doney et al. (2011) has shown that acidification from shipping in coastal areas during the summer months can be as great as that from carbon dioxide. With scrubbers, this acidification effect in coastal areas will increase since the sulphur will be washed out directly in the sea, rather than spread out through winds and precipitation in a larger region.

The alternative scheme; i.e. 0.1% Sulphur Fuels close to coast and in ports globally, and continued use of 2.7% HFO in all other sea areas, gives the following benefits relative to the current direction of IMO rules. Reduction of the sulphur emitted to sea, with the largest reductions in the sensitive coastal areas, due to the 0.1% limit, and the fact that scrubbers will then be the cost effective option only for vessels that trade mainly in the ECAs (Lindstad et al., 2015b). This implies that ocean-going vessels will use of 0.1% fuels in coastal areas and ports, rather than scrubbers. If low-NOx zones are implemented in coastal areas globally, the NOx regulation should require new vessels to operate in the strictest NOx mode (Tier 3) only in the low-NOx zones, while they run in a more energy efficient mode (i.e. Tier 2) outside low-NOx zones. Alternatively, they can run the engine in a pure CO_2 emission-minimizing mode at the high seas, i.e. not satisfying even the first NOx regulations (2001), to fully utilize the climate mitigation effects of higher NOx emissions and lower CO_2 emissions. Finally, continued use of HFO at high seas will maintain the cooling effect of global shipping in the 20 years' perspective and keep the 100 year, CO_2 equivalent emissions at only 35–40% of CO_2 emissions. This comes at cost of 4–5 billion USD annually compared to the present level, and saves about 10 billion USD compared to current 2020 rules.

Conclusions

This study challenges the traditional environmental regulations approach for shipping activities and especially the globalization direction chosen by the International Maritime Organization (IMO). To tighten SOx and NOx limits globally carries important risks. Our first point is that to extend to a global setting the present regulations, and consequently to globalize costly responses to coastal emission control areas (ECAs, in North America and Northern Europe) gives environmental benefits that are negligible or actually negative. The second is that scrubbing and tuning becomes a dominant response. This is costly, including in terms of fuel efficiency and rising CO_2 equivalent emissions. When abatement becomes the dominant operating modus, rather than applied in certain areas only, it is, however, the lowest cost option to the ship-owner and the maritime shipping sector. Third, the adoption of these end-of-pipe solutions carries the risk of deflecting important development of clean fuels and other promising options. Distinguishing local environmental benefits from global ones is important in general, and our research concludes that in the case of shipping, this distinction better serves the needs of the local environment, the global climate, and conserves on abatement costs.

Acknowledgements

This study has been financed by the Norwegian Research Council through; the SFI Smart Maritime – Norwegian Centre for improved energy-efficiency and reduced emissions from the maritime sector, as well as the CenSES project.

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