

## **Environmental regulations in shipping:**

### **Policies leaning towards globalization of scrubbers deserve scrutiny**

Haakon Elizabeth Lindstad<sup>1\*</sup>, Gunnar S. Eskeland<sup>2</sup>

<sup>1</sup>*Norwegian Marine Technology Research Institute (MARINTEK), Trondheim, Norway*

<sup>2</sup>*Norwegian School of Economics (NHH) and SNF and CenSES, Bergen, Norway*

#### **ABSTRACT**

Emission regulations for Sulphur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>) are motivated by health- and other environmental objectives in local and regional settings, while global warming concerns motivate policies for carbon dioxide (CO<sub>2</sub>). We point out that the direction chosen by the International Maritime Organization (IMO) – to tighten SO<sub>x</sub> and NO<sub>x</sub> 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.

*Keywords: Shipping and the Environment; Greenhouse gases; Abatement cost and options; MARPOL; IMO.*

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\* Corresponding author: Lindstad@marintek.sintef.no

## 1. INTRODUCTION

Emissions from maritime transport account for 10 to 15 % of global anthropogenic sulphur (SO<sub>x</sub>) and nitrogen oxide (NO<sub>x</sub>) emissions, and about 3% of global carbon dioxide (CO<sub>2</sub>) emissions ([Smith et al., 2014](#)). Current maritime emission regulations set limits for SO<sub>x</sub> and NO<sub>x</sub> for health and environmental reasons, and for CO<sub>2</sub> 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 NO<sub>x</sub> 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% to 0.5 %.

There are several reasons to question these environmental policies. First, the emissions of NO<sub>x</sub> and the SO<sub>x</sub> 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<sub>4</sub>) – remaining unrestricted - contribute to global warming ([Jacobson, 2010](#); [Bond et al., 2013](#); [Myhre and Shindell, 2013](#); [Fuglestedt et al., 2014](#); [Lindstad and Sandaas, 2016](#)). Metrics that weight emitted gases according to their global warming potential (GWP), to report them in terms of "*CO<sub>2</sub> 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 NO<sub>x</sub> emissions through technical standards neglects that the reductions come at the cost of higher fuel consumption ([Lindstad et al., 2015a](#)) and, thus, CO<sub>2</sub> emissions. Third, stricter SO<sub>x</sub> 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 kWh of all exhaust gases, including CO<sub>2</sub>.

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 NO<sub>x</sub> 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 2; its application and data are presented in section 3; the analysis and results in section 4 and the results obtained are discussed in the final section with respect to their implications for policy development.

## 2. MODEL DESCRIPTION

We need assessment of costs, emissions and fuel consumption, see [Lindstad et al. \(2011; 2014; 2015b; 2016\)](#) 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

$$F^O = \left( \sum_{\substack{i=1 \\ i \notin ECA}}^n \frac{D_i}{v_i} \cdot P_i \cdot K_{fp}^O \right), \quad (1)$$

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

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  $P_i \cdot K_{fp}$  is the fuel required per produced kWh, as a function of engine load,  $T_{lwd}$  is time spent in port.

The annual emissions,  $\varepsilon$  per pollutant are calculated as expressed by equation 2:

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

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

GWP per kWh produced and per ton transported are calculated by equation 3.

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

Here,  $\varepsilon_e$  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 equation 4

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

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 equation 5

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

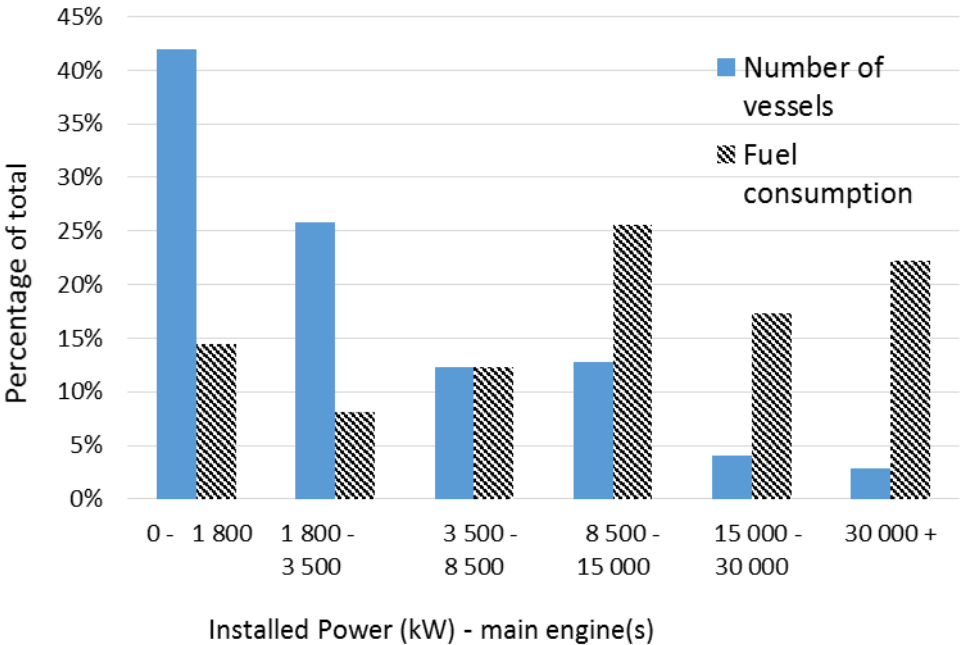
Here  $C_v^{capex}$  denotes the annual costs of the abatement technology used, comprising annualized capital costs and operating costs.

### 3. 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). Figure 1: shows number of vessels and bunker consumption as a function of installed engine power.

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



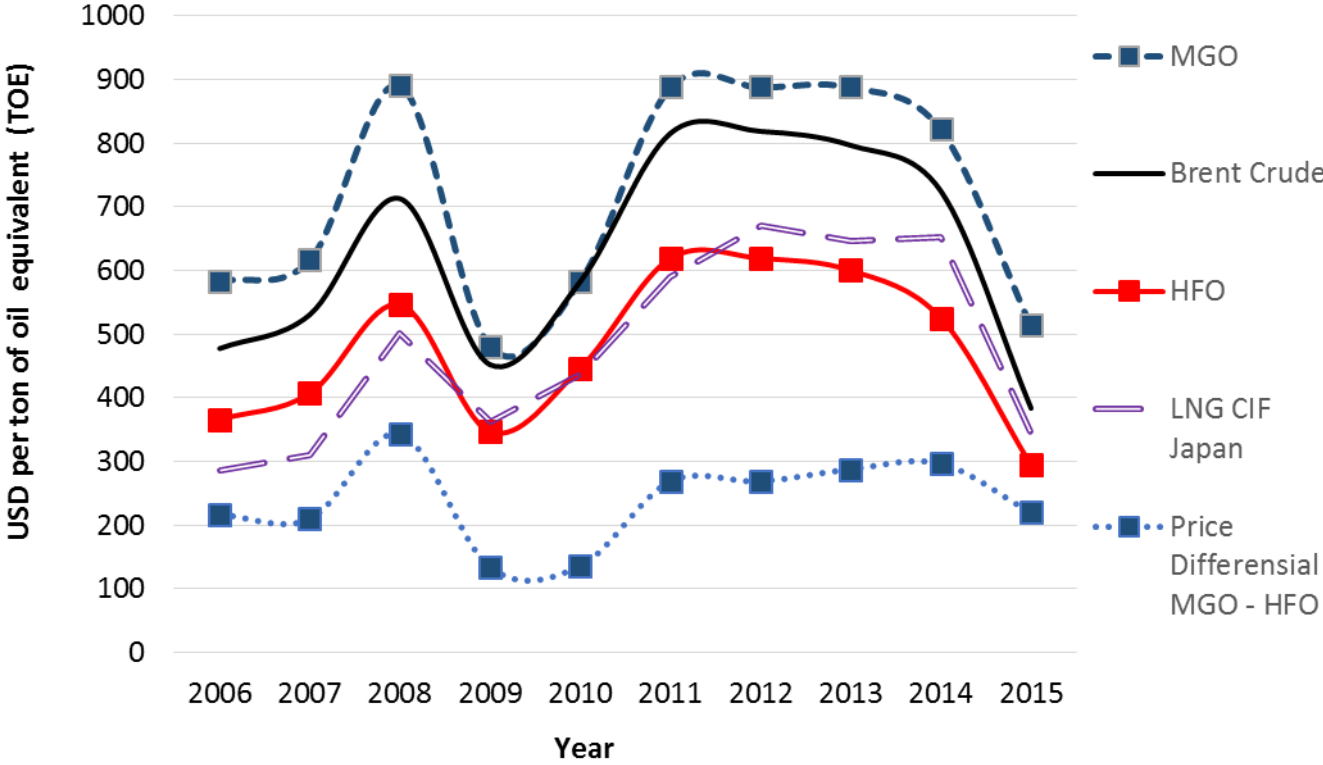
Main observations are that the vessels with engines sizes up to 1800 kW represents 41 % of the fleet in numbers of vessels and only 17 % of the annual fuel consumption, while vessels above 30 000 kW represents 3 – 4 % of the fleet and more than 20 % of the fuel consumption.

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 SO<sub>x</sub> 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<sub>4</sub>), contrasting low-pressure systems that emit considerable amounts of un-combusted methane. In Figure 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.

Figure 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 June 2015; All figures are yearly averages

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

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.

Table 1: Fuel and Abatement Options

| Fuel and Abatement Option  | Fuel Price<br>January<br>2016 | Price Increase<br>compared to<br>HFO | Basic<br>Capex | Additional<br>Capex per<br>1000kW<br>installed<br>power | Other<br>additional<br>cost per ton<br>of fuel |
|----------------------------|-------------------------------|--------------------------------------|----------------|---|--|
|                            | USD/ton                       | USD/ton                              | USD            | USD   | 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

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.

## **4. ANALYSIS**

### **4.1 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 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 figure 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.

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 |                      |                       |                             | Abatement Cost per ton        |                                  |                    |                      |     |                           | Share of total fuel |     |
|---|----------------|--------------------|----------------------|-----------------------|-----------------------------|-------------------------------|----------------------------------|--------------------|----------------------|-----|---------------------------|---------------------|-----|
|   |                | DWT                | Installed Power (kW) | Fuel per vessel (ton) | Fuel cost per vessel if HFO | Additional Fuel cost with MGO | Lowest Abatement cost per vessel | Scrubber open loop | Scrubber closed loop | LNG | Total fuel in million ton |                     |     |
| MGO & MDO gives lowest cost                                       |                |                    |                      |                       |                             |                               |                                  |                    |                      |     |                           |                     |     |
| Service - Tug   | 14             | 600                | 120                  | 2 300                 | 500                         | 75 000                        | 75 000                           | 75 000             | 435                  | 815 | 701                       | 7.3                 |     |
| General Cargo   | 11             | 600                | 1 900                | 1 100                 | 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                  | 1 000                 | 700                         | 105 000                       | 105 000                          | 105 000            | 294                  | 571 | 411                       | 15.5                |     |
| Miscellaneous   | 3              | 000                | 60                   | 2 000                 | 800                         | 120 000                       | 120 000                          | 120 000            | 275                  | 520 | 420                       | 2.4                 |     |
| Service - Other   | 3              | 400                | 2 300                | 3 200                 | 1 100                       | 165 000                       | 165 000                          | 165 000            | 219                  | 402 | 358                       | 3.7                 |     |
| Offshore  | 6              | 500                | 1 700                | 4 700                 | 1 300                       | 195 000                       | 195 000                          | 195 000            | 202                  | 360 | 358                       | 8.5                 |     |
| Passenger Ferry   | 3              | 200                | 170                  | 2 000                 | 1 200                       | 180 000                       | 180 000                          | 180 000            | 190                  | 360 | 280                       | 3.8                 |     |
| Tankers   | 6              | 600                | 3 300                | 1 700                 | 1 500                       | 225 000                       | 225 000                          | 225 000            | 154                  | 294 | 214                       | 9.9                 |     |
| Dry Bulk  | 1              | 200                | 3 300                | 1 600                 | 1 500                       | 225 000                       | 225 000                          | 225 000            | 153                  | 293 | 211                       | 9.9                 |     |
| General Cargo   | 2              | 900                | 7 300                | 3 300                 | 1 800                       | 270 000                       | 270 000                          | 260 000            | 142                  | 262 | 221                       | 5.2                 |     |
| Cruise  | 270            | 410                | 1 900                | 2 000                 | 300 000                     | 300 000                       | 240 000                          | 121                | 231                  | 166 | 0.5                       |                     |     |
| Tankers   | 2              | 400                | 47 600               | 9 600                 | 3 000                       | 450 000                       | 450 000                          | 360 000            | 118                  | 198 | 234                       | 7.2                 |     |
| Ferry - Ro-Pax  | 1              | 700                | 400                  | 1 500                 | 2 200                       | 330 000                       | 330 000                          | 240 000            | 110                  | 212 | 142                       | 3.7                 | 24% |
| Open loop Scrubber gives lowest cost                              |                |                    |                      |                       |                             |                               |                                  |                    |                      |     |                           |                     |     |
| Dry Bulk  | 5              | 400                | 41 700               | 10 100                | 4 000                       | 600 000                       | 600 000                          | 380 000            | 95                   | 160 | 181                       | 21.6                |     |
| Container   | 1              | 100                | 8 600                | 6 000                 | 3 700                       | 555 000                       | 555 000                          | 330 000            | 88                   | 157 | 143                       | 4.1                 |     |
| Tankers   | 1              | 200                | 15 300               | 5 100                 | 3 800                       | 570 000                       | 570 000                          | 320 000            | 83                   | 151 | 128                       | 4.6                 |     |
| General Cargo   | 2              | 000                | 22 500               | 7 400                 | 4 400                       | 660 000                       | 660 000                          | 360 000            | 81                   | 142 | 135                       | 8.8                 |     |
| Ferry - Ro-Pax  | 1              | 200                | 3 200                | 15 500                | 7 000                       | 1 050 000                     | 1 050 000                        | 510 000            | 72                   | 118 | 141                       | 8.4                 |     |
| Ro-Ro&Vehicle   | 1              | 300                | 1 000                | 1 500                 | 3 900                       | 585 000                       | 585 000                          | 280 000            | 71                   | 137 | 80                        | 5.1                 |     |
| Dry Bulk  | 2              | 300                | 82 000               | 10 900                | 6 200                       | 930 000                       | 930 000                          | 430 000            | 70                   | 119 | 123                       | 14.3                |     |
| Reefer  | 1              | 100                | 5 700                | 5 000                 | 5 100                       | 765 000                       | 765 000                          | 340 000            | 67                   | 122 | 94                        | 5.6                 |     |
| Container   | 1              | 300                | 20 400               | 12 600                | 7 500                       | 1 125 000                     | 1 125 000                        | 480 000            | 64                   | 108 | 113                       | 9.8                 |     |
| Dry Bulk  | 1              | 200                | 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   | 1              | 700                | 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   | 1              | 300                | 11 800               | 10 100                | 9 200                       | 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            | 7 300              | 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   | 1              | 100                | 6 700                | 3 800                 | 3 200                       | 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%                  |     |
| Totals  | 106            | 000                |                      |                       |                             |                               |                                  |                    |                      |     |                           | 291.0               |     |

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.

#### **4.2 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:** Emissions factors in gram per kWh and the applied GWP factors

|                     | Power                            | CO <sub>2</sub> | BC    | CH <sub>4</sub> | CO   | N <sub>2</sub> O | NO <sub>x</sub> | SO <sub>2</sub> | OC   | NET<br>GWP <sub>20</sub> | NET<br>GWP <sub>100</sub> |     |
|---------------------|----------------------------------|-----------------|-------|-----------------|------|------------------|-----------------|-----------------|------|--------------------------|---------------------------|-----|
| Previous<br>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<br>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<br>- 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<br>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 <sub>20</sub> factors        |                 | 1     | 1200            | 85   | 5.4              | 264             | -15.9           | -141 | -240                     |                           |     |
|                     | GWP <sub>100</sub> factors       |                 | 1     | 345             | 30   | 1.8              | 265             | -11.6           | -38  | -69                      |                           |     |

GWP factors based on World average excluding Arctic: , BC - Collins et al. 2013; CH<sub>4</sub> - IPCC 2013; CO - Fry et al 2012; N<sub>2</sub>O - IPCC 2011; Nox - Fry et al 2012; SO<sub>2</sub> - IPCC 2013; OC - IPCC 2013

Table 3 shows, that CO<sub>2</sub> and SO<sub>x</sub> emissions per kWh at low power are approximately 10 % higher than at high loads. Furthermore, CH<sub>4</sub> emissions doubles at low power. NO<sub>x</sub> 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<sub>20</sub> and GWP<sub>100</sub> from the lower panel are applied, showing that the ‘dirtiest’ fuel is ‘cooling’ when using the twenty year scale (GWP<sub>20</sub>) and ‘carbon neutral’ (about as much cooling as warming) when using the more frequently applied hundred year scale (GWP<sub>100</sub>). In sum, at low loads, both the higher CO<sub>2</sub> emissions due to lower fuel efficiency and the higher emissions of other species result harmful in terms of warming.

In figure 3, we first investigate the climate impact expressed in CO<sub>2</sub>- equivalents, as a function of power load, evaluated at a 20-year time horizon (GWP<sub>20</sub>). 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<sub>2</sub> equivalent) denote net warming or cooling, as shown in the right hand column of figure 3. Fig. 4 shows comparable results for a 100-year time horizon (GWP<sub>100</sub>).

**Fig 3:** Gram CO<sub>2</sub> eq. impact per kWh with a 20 year time horizon (GWP 20) as a function of fuel and abatement option – Atlantic (Northern hemisphere)

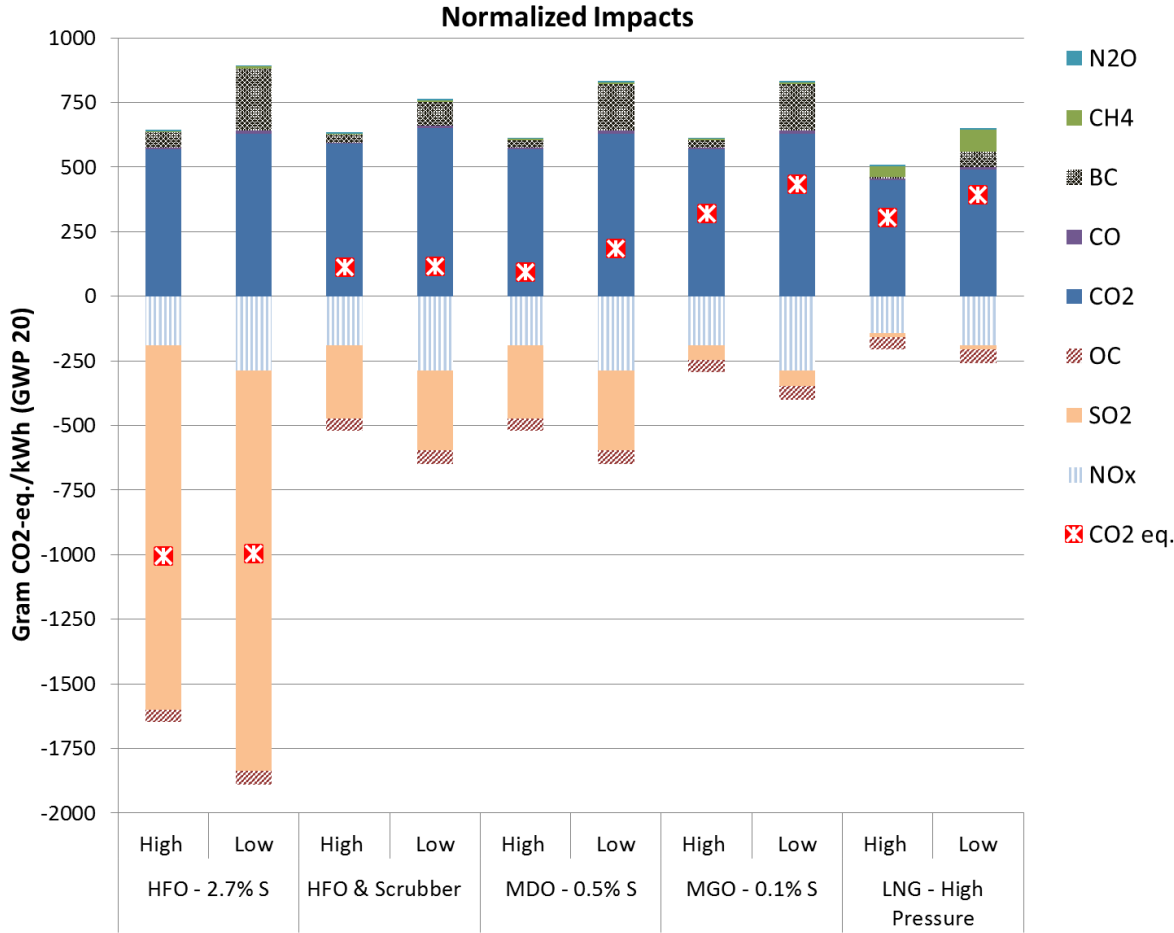


Fig. 3 shows that the warming impact expressed in CO<sub>2</sub> equivalents (GWP<sub>20</sub>) is lowest at high power for all the assessed fuels and abatement options. Beyond this, the main observations are that continued use of Heavy Fuel Oil (HFO 2.7%) gives a large net cooling effect; while all 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:** Gram CO<sub>2</sub> eq. impact per kWh with a 100 year time horizon (GWP<sub>100</sub>) as a function of fuel and abatement option – Atlantic (Northern hemisphere)

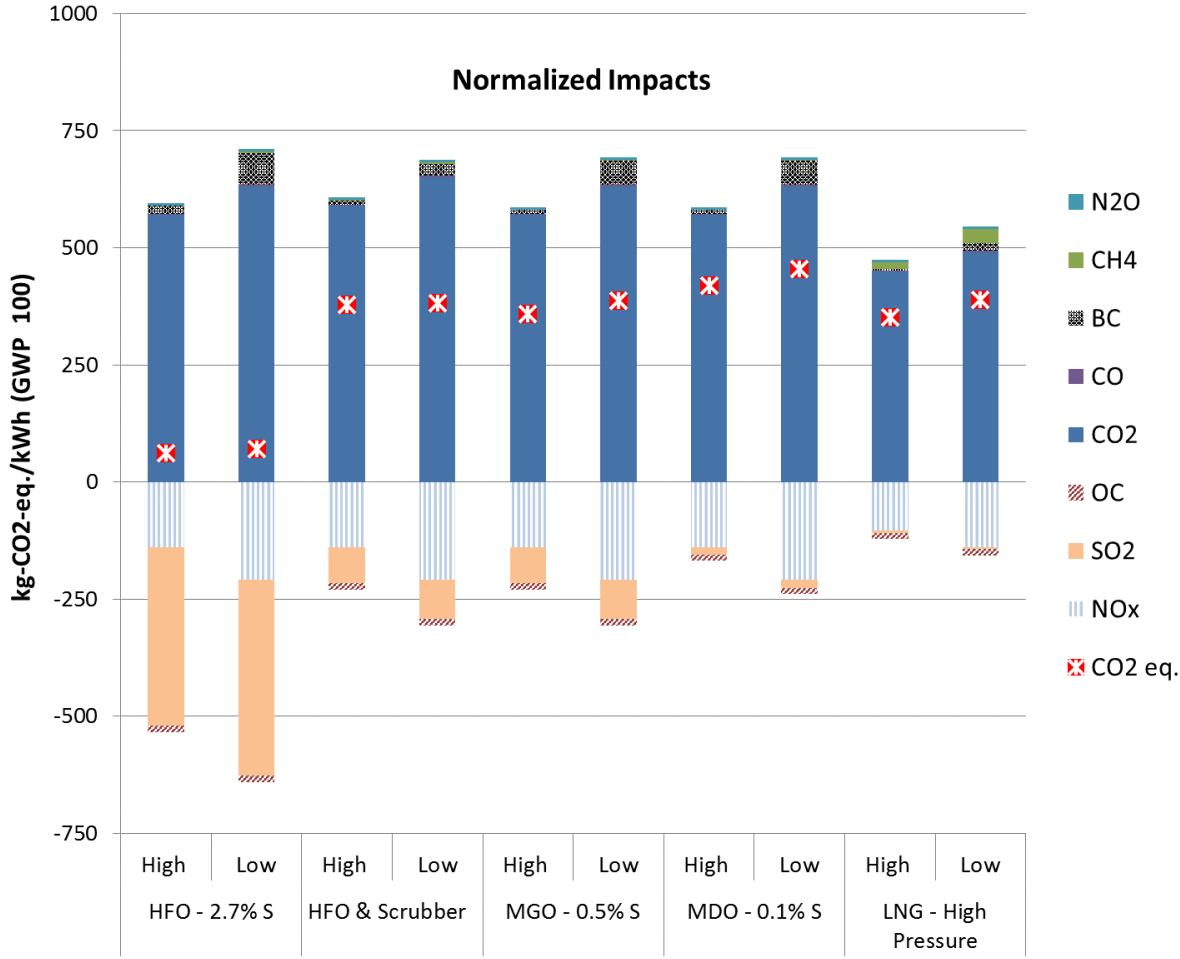
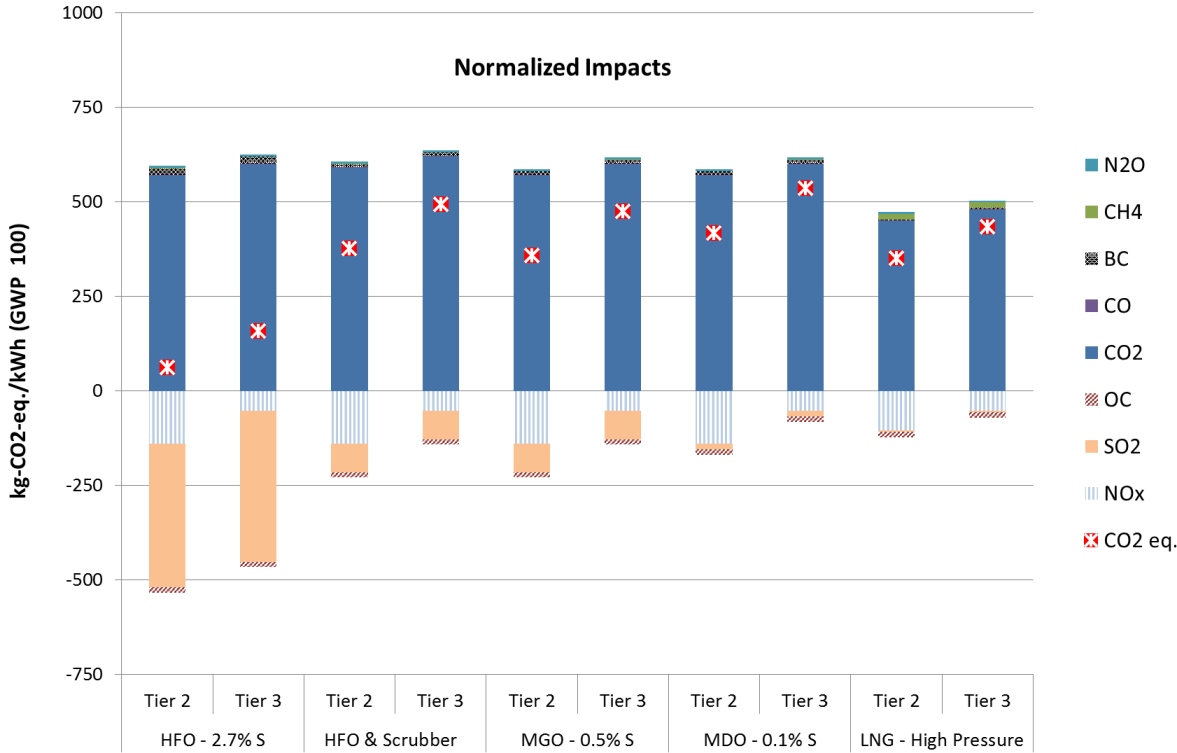


Figure 4 demonstrates that the differences between the assessed options are smaller for a 100-year time horizon. Over this longer time horizon, the impact of CO<sub>2</sub> emissions becomes more important relative to the shorter-lived species such as methane, and the overall effect is that maritime 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 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 while to consider allowing continued use of heavy fuel oil at the high seas globally.

While we in table 3 and figures 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.

**Fig 5:** Gram CO<sub>2</sub> eq. impact per kWh with a 100 year time horizon (GWP<sub>100</sub>) as a function of fuel and NOx regulation – Atlantic (Northern hemisphere)



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 NO<sub>x</sub> emissions to the required levels in the low-NO<sub>x</sub> zones (Tier 3) and let it run in a more energy efficient mode (i.e. Tier 2) outside the low-NO<sub>x</sub> zones. If low NO<sub>x</sub>-zones are implemented in coastal zones globally, vessels built from 2016 onwards could be allowed to operate their engines in a pure CO<sub>2</sub> emission-minimizing mode in high seas, i.e. not satisfy even the first NO<sub>x</sub> regulations from 2001, in order to fully utilize the climate mitigation effect of high NO<sub>x</sub> and low CO<sub>2</sub> emissions.

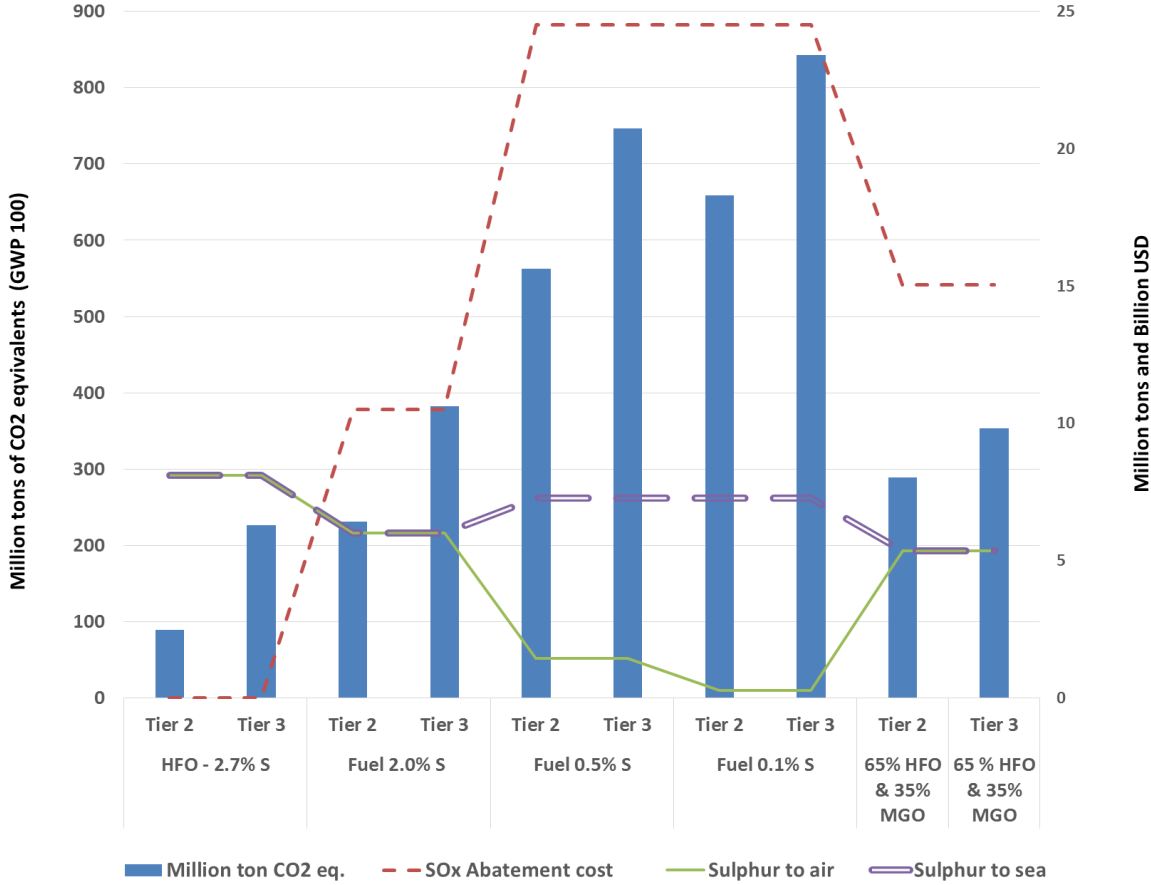
### **4.3 The larger Picture**

In 2012, global maritime fuel consumption was around 300 million tons, emitting 900 to 950 million tons of CO<sub>2</sub>, 19 to 23 million tons of NO<sub>x</sub>, and 11 to 13 million tons of SO<sub>x</sub>. 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 NO<sub>x</sub> per kWh produced (around 7 million tons of Nitrogen). With the stricter SO<sub>x</sub> and NO<sub>x</sub> 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 (CO<sub>2</sub> equivalent tons – GWP<sub>100</sub>), but high SO<sub>x</sub> and NO<sub>x</sub> emissions including in coastal areas. The subsequent three pairs of columns show lower SO<sub>x</sub> and NO<sub>x</sub> 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 SO<sub>x</sub> emissions to air (but not much for the total of SO<sub>x</sub> 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 SO<sub>x</sub> and NO<sub>x</sub> emissions in zones near coasts and in ports.

**Fig 6:** Global shipping emissions measured in CO<sub>2</sub> eq. as a function of SO<sub>x</sub> and NO<sub>x</sub> regulations (GWP<sub>100</sub>) and Abatement cost for SO<sub>x</sub>



Main observations are; first, that the stricter NO<sub>x</sub> 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, NO<sub>x</sub> 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<sub>2</sub> equivalent emissions are only 25 % of CO<sub>2</sub> emissions. Fourth, a globalized cap on Sulphur from 2020 triples the CO<sub>2</sub> equivalent emissions from shipping under Tier 2 NO<sub>x</sub> regulations. Fifth, if the whole fleet had to operate according to North American ECA regulation, i.e. 0.1 % Sulphur and Tier 3, the CO<sub>2</sub>

equivalent emissions would be at the same level as its total CO<sub>2</sub> emissions (850 – 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. NO<sub>x</sub> 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<sub>2</sub>), 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-NO<sub>x</sub> zones are implemented in coastal areas globally, the NO<sub>x</sub> regulation should require new vessels to operate in the strictest NO<sub>x</sub> mode (Tier 3) only in the low-NO<sub>x</sub> zones, while they run in a more energy efficient mode (i.e. Tier 2) outside low-NO<sub>x</sub>

zones. Alternatively, they can run the engine in a pure CO<sub>2</sub> emission-minimizing mode at the high seas, i.e. not satisfying even the first NO<sub>x</sub> regulations (2001), to fully utilize the climate mitigation effects of higher NO<sub>x</sub> emissions and lower CO<sub>2</sub> 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<sub>2</sub> equivalent emissions at only 35 to 40 % of CO<sub>2</sub> 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.

## 5. 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 SO<sub>x</sub> and NO<sub>x</sub> 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<sub>2</sub> 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.

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