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1 Introduction

The awareness raised in the late 1990's that environmental impact from shipping is significant at local, regional and global scale is today well established knowledge[1-8]. The initial research scope on contribution to global emissions sulphur oxides (SO_X) and nitrogen oxides (NO_X) emissions are now extended to include also carbon dioxide (CO_2). The leak to media[1] on the upcoming report on CO_2 emissions from shipping, commissioned by IMO, even suggests the situation to be far more severe than previously thought. Further, shipping emissions of particulate matter (PM) have been attributed adverse health effects at a global scale. Still, in inter modal comparison shipping has the potential of being an attractive choice of transportation for both long and short distances, especially for bulk commodities and raw materials[8, 9]. The adaptation of shipping toward environmental sustainability has begun and for instance the subject is pointed out as one out of five clean energy trends in 2008[10].

During 1995-2005, the freight transportation (tkm) within the EU-25 increased with 34.6% which corresponded to a 39.1% share of freight transportation within the EU-25 in 2005. The corresponding numbers for inland navigation show a 5% increase of freight transportation (tkm) to a 3.3% share of freight transportation in 2005. Passenger transport on inland waterways are negligible and the share of passenger transport at sea decreased with 11.1% during the period 1995-2004, resulting in a share of 0.8% of passenger transport in 2004[11]. Hence the total emissions from inland navigation are comparatively small compared to the emissions from total shipping.

The present focus on reducing emissions to the atmosphere is much due to the extensive debate on global warming. However, indirect effects of e.g. marine pollution from shipping could possibly also have larger scale impact, but that field of research is even less explored than the effects of shipping on the atmospheric environment. The old device "the solution to pollution is dilution" is obviously not valid to the atmospheric environment and even if the total volume of the oceans exceeds that of the atmosphere, it is also a matter of scales; both geographical (spatial), where the emission/discharge occur, and time scales involved, e.g. in the ocean circulation. Recent ecotoxicological studies on marine plankton communities revealed that a single exposure of pyrene[2], at concentrations below the corresponding maximum allowed concentration for discharge of bilge water altered both species composition and the number of individuals in the community[12]. There were significant synergistic effects with nutrient enrichments, which further enhanced the differences. Of course further research is needed to evaluate the generality of these results, but still it is an indication that the focus on environmental impact from shipping on the atmosphere might need to be extended to include effects on the aquatic environment as well.

The scope of this study was to describe environmental impact from shipping, with focus on emissions. The discussion includes both atmospheric and aquatic impacts of emissions, while other areas of environmental impact from shipping such as oil spills, antifouling paints, garbage and sewage discharge, and spreading of invasive species through ballast water will not be further discussed.

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[1] The Guardian, February 13 2008.

[2] Pyrene is a model substance for Poly Aromatic Hydrocarbons (PAHs) that are present in oil and also byproducts from combustion. PAHs are generally found to be toxic and some compounds also mutagenic and carcinogenic.

2 Environmental impact of shipping – present situation

Shipping exhausts contribute to both atmospheric and aquatic pollution of SO_X, NO_X and PM. The burning issue of climate change and global warming adds CO_2 to the list of gases that needs to be reduced from shipping. As a matter of fact, reduction of CO_2 emissions is probably the biggest challenge not only for shipping, but for the entire transport sector. The primary emissions of SO_X and NO_X can also act as precursors inducing secondary atmospheric impact such as formation of PM (of varying diameter), ozone and acid deposition. Lately, concerns about secondary effects of emissions on the marine environment have also received attention. For instance the discussion on ocean acidification as a secondary effect from increased CO_2 levels in the atmosphere is a relatively new research area for marine biologists[13], as a potential lowering of oceanic pH may affect biological calcium carbonate structures. Emissions from ships are regulated by IMO's Annex VI of MARPOL 73/78 on "Regulations for the Prevention of Air Pollution from Ships".

Despite a decade of modelling efforts, the heterogeneous nature of the world fleet and the many technical, operational and environmental parameters influencing the production, environmental fate and effect of emissions from shipping still present a challenge in terms of construction of realistic models to describe and predict the environmental impact from shipping[14-17]. Top-down approaches based on sale statistics of marine bunker fuel are generally coarse, and bottom-up approaches based on fleet activity data for navigation are generally limited due to incomplete data in-put. Global estimates of shipping in the scientific literature is still dominated by top-down approaches[3, 5, 18, 19] and the differences between the best estimates of annual global bunker consumption are large; in the range 200[18]-289[3]MT per year. The European share of global shipping has been estimated to approximately 1/3[20], implying that the discrepancies of different estimates of global bunker consumption could almost correspond to the entire European share. However, as more recent studies (including the upcoming UN-report) points at higher consumptions and the estimate used in this report will be 280 MT[5].

To improve reliability of trend analysis of shipping emissions it is necessary to have complete and accurate data sets. Therefore UNFCCC[3] and UNECE[4] recommend their respective conventions countries to use a bottom-up approach, but still top-down approaches are accepted if fleet activity data is missing[21-23]. This trade-off between methodological simplicity and data availability on one hand and accuracy and validity of the results on the other hand is also well described in an Entec report from 2005[24], commissioned by the European Commission, where different assignments of ship emissions investigated. Hopefully improved vessel movement identification technologies, such as AIS (Automated Identification System[25]), can open the door for improved data input quality, which most likely will significantly narrow the confidence intervals of the modelled emissions including their environmental impact[14]. Not only will it be possible to assess the real fuel consumption, but also it is possible to include the spatial significance of e.g. SO_X and NO_X pollution. However, to get a complete picture it is required that all ships are monitored and this might take a while since the initial regulation only applies to passenger ships and ships larger than 300GRT. The presently available estimates of global impact from shipping generally include vessels larger than 100GRT. However, the fuel consumption of vessels 100-500GRT is estimated to be less than 8 % of the total consumption[18].

[3] United Nations Framework Convention on Climate Change
[4] United Nations Economic Commission for Europe

Despite the challenges of making global estimates of the emissions from ships, it might be even more difficult to find relevant information at regional scales as the emissions may be subject to long range transport. On the other hand, when trying to estimate potential costs associated with the emissions, it is clear that emissions released near shore are likely to have a higher impact for e.g. inland acidification and human health effects than do emissions at Open Ocean. There is also a significant difference when discussing long lived climate gases as CO_2, which will stay in the atmosphere for centuries, compared to e.g. sulphur oxides which will have more regional effects. The report "Quantification of emissions from ships associated with ship movements between ports in the European Community" (2002)[16] commissioned by the European Commission is based on a bottom-up approach and the data from that inventory will serve as base for the European estimates in this study. Additionally, data on inland navigation will be used from Eurostat data[11, 26].

2.1 Atmospheric impact

2.1.1 Emissions with impact on climate change

2.1.1.1 Carbon dioxide

The debate on climate change, has completely altered the previously accepted view of CO_2 as a harmless rest product from combustion; "…during combustion [of polyethylene], nothing else is formed but CO_2 and water…". Today combustion of any product originating from fossil fuel is recognized to contribute to global warming. In 2007 the Intergovernmental Panel on Climate Change was honored with the Nobel Peace Prize and the discussion on how to reduce the CO_2 emissions is definitely of global concern. Different greenhouse gases have different global warming potential (GWP) depending on the absorption of infrared radiation by a given species, the spectral location of its absorbing wavelengths and the atmospheric lifetime of the species. The global warming potential of CO_2 is by definition set to 1. Other greenhouse gases can have GWP that in comparison are several thousand times than CO_2 GWP. Of the anthropogenic greenhouse gases in the atmosphere CO_2 is estimated to be responsible for the largest share of global warming and recent studies indicate that the global warming effect from present CO_2 will persist for thousands of years[6, 27]. To quantify the global warming effect from different sources Radiative Forcing (RF) is used. RF is expressed in W/m^2 and describes the change in the atmosphere energy balance due to addition of e.g. a greenhouse gas as CO_2, compared to preindustrial times. The enhanced warming of the atmosphere is the result of the re-establishment of a radiative equilibrium.

As stated by Kågeson in April 2008[9], the fuel consumption and sequential CO_2 production from shipping is not known. Depending on the approach used to assess the fuel consumption, either top-down or bottom-up, and the assumptions made in each respective model, calculations of global CO_2 emissions from international shipping reported in literature span over a wide range (Table1). In January 2008 the upcoming results from a study commissioned by IMO leaked to media and the annual CO_2 emissions was said to be 1120 Tg or nearly 4.5% of the global CO_2 emissions. This is close to 30% higher emissions than the previously highest estimates.

Table 1. Variation of estimates of the global CO_2 emissions from different studies

	CO_2 Tg/year
Endresen 2003[18]	557
Corbett and Köhler 2003[3]	912
Eyring 2005[5]	812
Unpublished IMO study	1120

Based on data from ENTEC (2002)[16], CE Delft (2006)[28] has further developed the CO_2 emissions from shipping in the EU in relation to global emissions compiled in Table 2. The statistics in Table 2 includes inland waterways. However, its share is not resolved in the data above. From the EU publication Panorama of Transport 2007[11], the energy consumption from inland navigation (as opposed from inland waterways) does not include international marine bunker fuels, but diesel oils. For year 2004, the annual consumption was 5047 ktoe (kilo tonnes of oil equivalents) for inland navigation within the EU-25. Using an average emission factor for inland navigation from Georgakaki (2004)[29], gives a CO_2 emission from inland navigation of 15.9Tg/year or 2.1% of the CO_2 emissions from global shipping and approximately 10% of the shipping within the EU, which is well in line with the share of freight transport by inland navigation in the EU.

Table 2**.** CO_2 emissions estimates year 2000 from EU15 + Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia. Source: CE Delft (2006)[28].

	CO_2 emissions from shipping in the EU			CO_2 emissions from shipping, global estimate		
	Tg/year	Share of global shipping (%)	Share of tot EU emissions (%)	Tg/year	Share of global shipping (%)	share of total global emissions
Operators						
All operators	153.3	20.3	3.7	756.7	100	2.7[a]-4.5[b]
EU-flagged ships	71.4	8.85	1.7	196.6	25.1	0.70-1.2
Operations						
All operations	153.3	20.3	3.7	756.7	100	2.7[a]-4.5[b]
All operations to and from EU ports	152.4	20.1	3.70			
In ports	10.2	1.35	0.25	30.2	3.99	0.11-0.18
In territorial waters	38.3	5.06	0.93			
Exclusive economic zone	120.6	15.9	2.9			

[a] Eyring 2005[5].
[b] Unpublished study 2008.

2.1.1.2 Ozone precursors

Emissions of NO_X, carbon monoxide (CO) and volatile organic carbons (VOC) can lead to formation of ozone (O_3) which in spite of being short lived has potential of higher specific contribution to global warming than does CO_2[30]. NO_X exhibits dual properties as it also contributes to break down of methane (CH_4) with GWP 25 over 100 years, which according to Lauer et al (2007)[7] cause a negative radiative forcing of the same magnitude as the positive from O_3 formation.

Table 3 VOC emissions year 2000

VOC emissions within the EU			VOC from global shipping	
Emissions from ships within EU (Tg/yr)	Tot EU emissions (Tg/yr)	EU Shipping share of tot EU emissions (%)	Tg/yr	EU Shipping share (%)
0.099[24]	11[26]	0.87	27.5	0.36[18]

2.1.1.3 Particulate matter impacting the earth's radiative forcing

Particulate matter can either be formed as primary particles during the combustion process, or formed from other combustion by-products; mainly SO_X, but also NO_X. The major concern about PM is probably the adverse impact on human health, which is further discussed below under paragraph 2.1.2. However, PM also has intrinsic impact on climate change. At regional level PM acts as condensation nuclei inducing cloud formation, which contributes to a cooling effect. However as this process is taking place at regional scale its significance at global scale is unclear. In the Polar Regions, and other glacier areas, PM can accelerate the effects from global warming as it contributes to enhanced melting when the precipitation of PM forms a dark layer, decreasing the albedo of the ice or snow[31]. The reflective properties of the former white surface start to absorb solar energy as it turns darker, thus warm the ice and increase the melting rate. The share of PM from shipping in this respect is not known.

2.1.2 Pollution and health aspects

A generalized effect pattern, trying to illustrate direct and indirect effects of emissions from shipping is shown in Fig1.

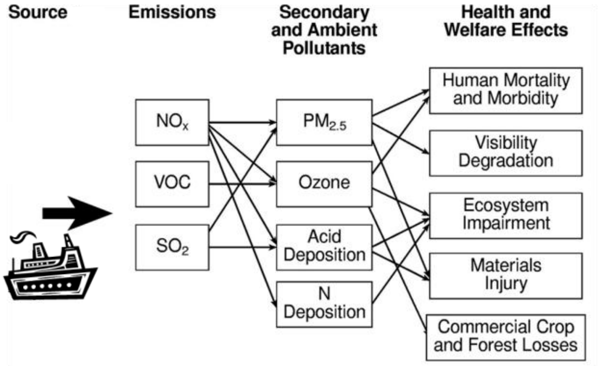

Fig 1. Linkages from emissions to effects. Modified from Chestnut et al 2006[32].

2.1.2.1 Sulphur oxides

The emissions of SO_X originate from the sulphur content of the fuel. The dominant constituent, making up approximately 95% of the SO_X emissions from combustion of fossil fuel, is sulphur dioxide, SO_2. Sulphur dioxide is a toxic gas, directly harmful for both human health and plants. A secondary effect of SO_X emission to the atmosphere is formation of sulfate aerosols, very fine airborne particles, which according to WHO[33, 34] and Corbett[35] can be held responsible for significantly increased annual mortality e.g. in Europe. This is further discussed under section 2.1.2.3. A third, well recognised, result of SO_X emissions is the formation of acid rain, when the sulphur oxides together with water and oxygen form sulphuric acid in clouds[36].

The global rolling three-years average sulphur content in marine bunker is 2.7% and less than a few percent of the world marine bunker contains more than 4.5% sulphur, which was the global cap set by IMO in 2005. This rather toothless global sulphur content cap was proposed to be revised during the IMO Marine Environment Protection Committee (MEPC) 57th session in April 2008 and the new cap, effective from 1 January 2012, would be max 3.5% sulphur content. Likely the formal decision will be taken in October 2008[37].

Since May 2005 a regulatory approach of reducing sulphur emissions in particularly sensitive sea areas was implemented as the Baltic Sea, followed by the North Sea in 2006, was adopted as Sulphur Emission Controlled Areas (SECA). In SECA areas the emissions of sulphur is required to be less than corresponding to burning of fuel of 1.5% sulphur content. During the recent MEPC meeting, new regulations regarding SO_X emissions in SECAs were also suggested and the proposed schedule involves a stepwise lowering of the allowed sulphur emission in SECAs, corresponding to max 1% sulphur from 1 March 2010 and then 0.1% from 1 January 2015. Hopefully the new suggested stepwise reduction of sulphur content in fuel marks the beginning of a new era towards a more positive attitude in the development towards sustainable shipping. If the proposed regulations are adopted another consequence will be that it eliminates any further discussions on a trading scheme regarding SO_X emissions, as there will not be sufficient emissions to trade.

Table 4. SO_X emissions from shipping year 2000

SOx emissions within the EU			SO_X from global shipping	
Emissions from ships within EU (Tg/yr)	Tot EU emissions (Tg/yr)	EU Shipping share of tot EU emissions (%)	Tg/yr	EU Shipping share (%)
2.58[16]	10[26]	25	12[5]	22

While the international shipping is primarily regulated by the IMO, the inland waterway regulations falls within the EU (Directive 93/12/EEC COM (2007)18), which aims at a stepwise reduction of fuel sulphur content down to 10ppm in mid 2011. However, when this directive was adopted it was criticized for not fully taking advantage of the capacity of the present inland waterway fleet and e.g. the organization Inland Navigation Europe asked for an immediate cut to 10ppm, implemented from 2008[38]. Their main arguments were that the vast majority (98%) of the fleet operating on inland waterways are already fitted with engines that can handle fuel down to 10ppm of sulphur. Further the incitement of installation of new engines that cannot operate on fuel of a sulphur content exceeding 50ppm is removed by an intermediate level of 300ppm until mid 2011.

2.1.2.2 Nitrogen oxides

Nitrogen makes up about 79% of our atmosphere in the form of dinitrogen gas (N_2). During combustion of fossil fuel, N_2 from the atmosphere reacts with atmospheric oxygen O_2 and form nitrogen oxides, NO_X. NO_X is a generic name for nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NO_X increases with increased time and temperature of the combustion process. Thus, the trend of development towards more efficient engines, which accelerated after the oil crisis in 1973 also brings increased formation of NO_X. Since the first IMO regulations on NO_X (Annex VI,[39]) entered into force in 2000 the specific fuel consumption of marine engines has remained constant. The estimated NO_X emissions from shipping in EU are listed in Table 5. In case of BAU the NO_X emissions from shipping are forecasted to exceed land-based emissions within the EU in 2015-2020[36]. The modelled decreasing trend from land-based NO_X emissions have recently been verified from long term satellite observations[40].

Table 5. NO_X emissions from shipping year 2000.

NO_X within the EU			NO_X from global shipping	
Emissions from ships within EU (Tg/y)r	Tot EU emissions (Tg/yr)	EU Shipping share of tot EU emissions (%)	Tg/yr	EU Shipping share (%)
3.62[16]	12[26]	29	21.4[5]	17

The environmental impacts from NO_X depend on the actual form of NO_X. Similar to SO_X, NO_X can react with water in the atmosphere forming (nitric) acid which has a potential acidifying effect to soils and lakes. More significant is the eutrophying effect, through increased nitrogen load to lakes, soils and coastal estuaries. Further, ground-level ozone is formed when sunlight catalyses the reaction between NO_X and VOC. Hence indirect effects of damaged vegetation and reduced crop yield are partly due to NO_X emissions. Ozone has also negative impact on human health through damages of lung tissue and reduction in lung function. Other threats to human health originating from NO_X are a wide range of toxic compounds such as nitrate radicals, nitroarenes and nitrosamines, which even may cause biological mutations. Particle formation due to NO_X reacting with ammonia, water vapour and other compounds are also known to have adverse effects on human health (see further on particulate matter). Finally, nitrous oxide (N_2O) is a greenhouse gas, but the share N_2O from combustion is rather low[41].

2.1.2.3 Particulate matter

During combustion of fossil fuel particulate matter (PM) is formed through several different pathways. Primary particles are formed in the engine, while the secondary particles are formed in the atmosphere as a result of emitted precursors. Studies have shown a strong dependence between high sulphur content of the fuel and high amounts of emitted particles[7, 38, 42]. Lauer et al (2007)[7] concluded that 75% of the primary and secondary particles are related to the sulphur content.

The emitted PM affect cloud formation, which actually causes negative radiative forcing that theoretically could mask the total contribution to climate change from shipping. From this follows the paradox that implementation of fuel of lower sulphur content could be claimed to increase the net effect on climate change from shipping. However, this is not a valid argument for at least two reasons; firstly this effect of PM climate forcing acts on a regional scale and secondly continuous use of fuels of high sulphur content brings several other environmental and health aspects to consider from SO_X emissions (See section 2.1.2.1 above).

Current IMO regulations do not limit PM emissions. To enable quicker progress in reduction of PM, the EU may have to extend their inland waterway regulations of fuel sulphur content to all marine engines. In most of the studies concerning the PM emissions of medium-speed engines, only the smoke number is measured, although the efforts that are being made to reduce visible smoke is only part of the PM problem. The reason for this focus can largely be attributed to the overall bad image that a visible plume brings to the entire shipping business[43].

Table 6. PM emissions year 2000

PM			Global shipping PM Tg/yr	
Emissions from ships within EU Tg/yr	Tot EU emissions Tg/yr	EU Shipping share of tot EU emissions (%)	Tg/yr	EU Shipping share (%)
3.62[16]	No data	No data	21.4[5]	17

2.2 Aquatic impact

2.2.1 Indirect effects from emissions to the atmosphere

2.2.1.1 Acidification

The problems of acidification was for long intimately related to inland and freshwater ecosystems, especially in areas of granitic bedrock, implying a low natural buffering capacity to withstand acidic deposition. This acidification is due to formation of sulphuric and or nitrous acid from SO_X and NO_X emitted to the air. The acidic precipitation will lower pH, which led to damage on forest and lake ecosystems e.g. through increased release of heavy metals. Due to stricter regulations the emissions of SO_X and NO_X from land based sources of emissions, e.g. power plants. Therefore, the emissions from shipping will account for an increasing share of these effects through mid or long-range transport.

Another type of acidification that lately has received much attention is the phenomenon occurring as a result from increased CO_2 levels in the atmosphere; ocean acidification[13, 44, 45]. The concern among marine biologists is that it may be more difficult for marine organisms to form biogenic calcium carbonate ($CaCO_3$), but recently it has been concluded that the response to a high-CO_2 world is highly species specific[46]. Some species are negatively impacted whereas others are actually stimulated, while a third type might not be sensitive at all. Other studies also indicate that it is not the decrease in pH that affect marine organisms, but the increased CO_2 in the water[47, 48].

2.2.1.2 *Eutrophication*

The significance of atmospheric deposition as source of inorganic nitrogen to the ocean has previously been verified[49-52], but not until 2007, the impact of NO_X from shipping on eutrophication in the Baltic Sea was assessed by Stipa et al[53]. Emission data combined with AIS data revealed that a month's worth of ship emissions could increase the available inorganic nitrogen by 5-20% within 10 km of the shipping lane. The largest contribution (32% of total ship emissions) was from ships built after the year 2000 followed by 28% share from ships built between 1990 and 2000. In some areas and seasons shipping contributed up to 50% of the total atmospheric input to the Baltic Sea or 12.5-15% of the total nitrogen input. Further research efforts is needed to verify the shipping share of eutrophication in other areas, but without a doubt the results of Stipa et al[53] stresses the need for stricter regulations as proposed by the IMO.

3 Outlook

As previously mentioned, forecasts of the extent of environmental impact from shipping are rough, mainly due to limited data availability, but also to the complex nature of the shipping industry (e.g. fuels bought in one port cause emissions elsewhere) and the world wide steadily increasing shipping activity. There are possible environmental measures that can reduce the future impact from shipping. Skjølsvik[8] et al made a comparison of the possible reduction potential of different measures, both technical and policy measures which are described in Table7. However, as concluded by Skjølsvik et al[8], in absolute numbers, the total global impact from shipping is probable going to increase despite any measures taken due to the annual expansion of the total global shipping activity. The same conclusion was drawn from the modelled data of Cofala et al 2007[54].

3.1 CO_2

Reduced energy (or fuel) consumption of fossil origin is today the only way to reduce CO_2 emissions, but naturally emissions of other gases and PM will also decrease correspondingly. Likely the future solution will not be a single energy source for ship propulsion, but a mixture of different concepts. Wallenius-Wilhelmsen's concept vessel design, E/S Orcelle, exhibits a range of different approaches from solar and wind energy to wave energy that produces hydrogen for the fuel cells onboard. Utilisation of hydrogen fuel has been discussed and might be an option for high speed trans-oceanic shipping[55], but there is substantial development required and any potential implementation will not likely be realised within the nearest 15 years[56].
The use of wind energy is today commercially available (www.skysails.com) and is claimed to reduce the annual fuel consumption (and thereby emissions) with 10-35% for cargo vessels with typical engine power of 5MW.

Kågeson[9] concludes that the easiest way of reducing the CO_2 emissions from shipping and finally manage to target the 20% reduction in 2020, step-wise lower the ceiling in the EU ETS. Parallel a harmonised CO_2-taxation would be introduced to targeting emissions from the non-trading sector. However, such an approach require that the member states are so concerned about climate change that they allow for a central (not on national basis) decision on the taxation. Another possible way to reach the targets in 2020 is inclusion of all CO_2 producing sectors and apply auctioning of Emission reduction units for the new sectors. There are ongoing discussions in the IMO about this subject. The European Community Shipowner's Association (ECSA) are positive to CO_2 emission trading and even though it would be preferable to have a global emission trading system, e.g. the system proposed by Kågeson includes measures to make it useless to bunker in an adjacent area to the EU ETS area and then release CO_2 inside the EU. This problem is resolved by proposed requirements to account for emission credits covering the past six months of fuel consumption (if not settled in a previous port within the EU ETS). The system is proposed to be handled similarly to that of bunker notes and is not in conflict with UNCLOS[5].

Table 7 CO_2 reduction potential by technical measures. Modified from Skjølsvik 2000[8].

Measures new ships	**Fuel/CO2 saving potential**		**Combined [1)]**		**Total[1)]**	
Optimised hull shape	5-20%	7.9-32Tg	5-30/%	7.9-48Tg	5-30%	7.9-48Tg
Choice of propeller	5-10%	7.9-16Tg				
Efficiency optimised	10-12% [2)] 2-5% [3)]	16-19Tg [2)] 3.2-7.9Tg [3)]	14-17% [2)] 6-10% [3)]	22-27Tg [2)] 9.5-16Tg [3)]		
Fuel (HFO MCO)	4-5%	6.3-7.9Tg				
Plant concepts	4-6%	6.3-9.5Tg	8-11%	13-17Tg		
Fuel (HFO to MDO)	4-5%	6.3-7.9Tg				
Machinery monitoring	0.5-1%	0.79-1.6Tg				
Measures, existing ships	**Fuel/CO2 saving potential**		**Combined [1)]**		**Total[1)]**	
Optimised hull maintenance	3-5%	4.7-7.9Tg	4-8%	6.3-13Tg	4-20%	6.3-32Tg
Propeller maintenance	1-3%	1.6-4.7Tg				
Fuel injection	1-2%	1.6-3.2Tg	5-7%	7.9-11Tg		
Fuel (HFO MCO)	4-5%	6.3-7.9Tg				
Efficiency rating	3-5%	4.7-7.9Tg	7-10%	11-16Tg		
Fuel (HFO to MDO)	4-5%	6.3-7.9Tg				
Eff. rating + TC upgrade	5-7%	7.9-11Tg	9-12%	14-19Tg		
Fuel (HFO to MDO)	4-5%	6.3-7.9Tg				

[1)] Where potential for reduction from individual measures are well documented by different sources, potential for combination of measures is based on estimates only
[2)] State of the art technique in new medium speed engines running on HFO
[3)] Slow speed engines when trade-off with NO_X is accepted

In addition to technical measures to cut CO_2 emissions, there are also operational measures. Of these, speed reduction is the most significantly effective measure, just like in road traffic. The reduction potentials from operational measures are compiled in Table 8.

[5] United Nations Convention on the Law of the Sea

Table 8 CO_2 reduction potential by operational measures. Modified from Skjølsvik 2000[8].

Option	Fuel/CO_2 saving potential		Combined [1)]		Total[1)]	
Operational planning/Speed selection			1-40%	1.6-63Tg	1-40%	1.6-63Tg
Fleet planning	5-40%	7.9-63Tg				
“Just in time” routing	1-5%	1.6-7.9Tg				
Weather routing	2-4%	3.2-6.3Tg				
Miscellaneous measures			0-5%	13-17Tg		
Constant RPM	0-2%	0-3.2Tg				
Optimal trim	0-1%	0-1.6Tg				
Minimum ballast	0-1%	0-1.6Tg				
Optimal propeller pitch	0-2%	0-3.2Tg				
Optimal rudder	0-0.3%	0-0.47Tg				
Reduced time in port			1-7%	1.6-11Tg		
Optimal cargo handling	1-5%	1.6-7.9Tg				
Optimal berthing mooring and anchoring	1-2%	1.6-3.2Tg				

[1)] Where potential for reduction from individual measures are documented by different sources, potential for combination of measures is based on estimates only

3.2 SO_X

Since the SO_X emissions originates from the sulphur content of the fuel, burning of fuel of lower sulphur content will decrease the emissions to the corresponding extent. Regarding fuel used for inland waterway shipping and for ships at berth the limit of 0.1% sulphur content is proposed from 1 January 2010 in the 2005/33/EC directive. Based on present annual fuel consumption of 5MT[57, 58] of marine diesel oil assumed on average to be of 0.2% sulphur content implies an annual reduction of 5 kT sulphur compared to BAU. Previous cost estimates related to adverse effects on human health due to shipping emissions in the EU harbours are € 8 200 per 1000 tonnes of SO_2 emitted and € 30 500 per 1000 tonnes of particles[59]. As shipping emissions along inland waterways cannot be assumed to solely affect as dense human populations as in harbours and therefore the application of the above estimated cost might overestimate the actual annual saving. However, the complexity of detailed such calculations is beyond the scope of this study and a rough estimate is in the vicinity of 41 k€ yr^{-1}.

Concerns about increased CO_2 emissions related to the refinery process of low-sulphur fuel oil were recently questioned[60] as their calculations showed that the overall CO_2 emission from combustion of the refined low-sulphur fuel increased with less than 1%. This may reduce the environmental incitement of alternate sulphur abatements such as seawater scrubbing (SWS). SWS is shown to be efficient in reducing the atmospheric sulphur emissions 70-95%, depending on the fuel used and conditions in the scrubber[61]. However, there is an ongoing discussion whether or not the method is suitable in enclosed or semi-enclosed areas such as harbours. As the discharge from SWS is acidified seawater, it depends on the chemical properties of the seawater, primarily the alkalinity, how efficient the buffering capacity of the ambient seawater is. Beyond sulphur reduction, SWS also gives opportunity to remove particulate matter from the exhausts and some studies also show a slight (a few percent) reduction of NO_X. From a regulating perspective however, it might be easier with a uniform (preferentially worldwide) switch to low sulphur fuel; ensuring availability of compatible fuels in all ports and not allowing for individual solutions on all ships. Finally, as the formation of PM to large extent is related to fuel sulphur content, PM emissions will likely be reduced if low-sulphur oils were used instead of high-sulphur fuels.

Table 9. Sulphur dioxide emission reduction efficiencies[59]

	Reduction Efficiency			
	SO_2	NO_X	PM	VOC
Sea water scrubbing	75%	0%	25%	0%
Fuel switch 2.7 →1.5% S	44%	0%	18%	0%
Fuel switch 2.7 →0.5% S	81%	0%	20%	0%
Fuel switch 0.5 →0.1% S	80%[a]	No data	No data	No data

[a]Cofala et al 2007[54]

3.3 NO_X

Regarding NO_X there are three different goals to be targeted to achieve significant reduction; optimised combustion, improved air charge characteristics or altered fuel injection system[59]. The involved techniques are different kinds of internal engine modifications (IEM), where the more basic IEM (mainly installation of slide valves) typically reduce NO_X with 20-30%, while more advanced IEM options such as retard injection, higher compression ratio or increased turbo efficiency, have potentials for approximately 30% NO_X reduction. The reduction efficiencies of the different methods are compiled in Table 10.

Table 10. Effectiveness of NO_X emission reduction. Modified from Skjølsvik 2000[8].

	Reduction Efficiency			
	NO_X	PM	VOC	CO
Basic Internal Engine Modifications – slide valves[a]	20%	Assumed ±0, Unconfirmed up to 50% reduction	Assumed ±0, Unconfirmed up to 50% reduction	Assumed ±0, Some increase is possible
Direct water injection	50%	±0	±0	±0
Humid Air Motors (HAM) and similar methods	70-85%	±0	±0	±0
Selective Catalytic Reduction (SCR)[b,c]	90%	±0	±0 75-90% if used in comb. with an oxidation catalyst	±0 50-90% if used in comb. with an oxidation catalyst

[a]Basic internal engine modifications may impact positively with reductions also of PM and VOC emissions dependent of fuel.
[b]SCR may reduce noise produced by the engine by 20-35dB(A). Noise it not known to be affected by any other of the techniques.
[c]NH_3 emissions from SCR low around 0.1g/kWh

to the ECSA[62]. The life time of a ship is estimated to be in the range of 20-30 The newly proposed reduction scheme (IMO April 2008)[37], which implies a stepwise reduction of NO_X (Table 11) would tighten the current standard of 17g/kWh.

However, due to the relatively slow renewal of the fleet, there will be several years that a large part of the world fleet will remain unaffected by the new limits. 2007, the average age of the European fleet was 11.13 years according years.

Table 11. The proposed Tiers I-III for NO_X.

	Ships constructed on or after[a]	NOX g/kWh
Tier I	1 Jan 2000	17
Tier II	1 Jan 2011	14.4
Tier III	1 Jan 2016	3.4

[a] For ships constructed between 1990 and 2000 with a diesel engine power output of >5MW and displacement per cylinder >90L, the limit is 17g/kWh.

3.4 PM

The reduction of PM is difficult to reduce from present available technologies as there are no available filters that can be used on exhausts from combustion of HFO. There are some techniques to minimize large soot particles, but their environmental impact and/or contribution to adverse health effects are probably small. The possibilities of using filters to reduce PM increase with lower sulphur content of fuel[43], which as seen in Table 9 also decreases the formation of PM which in turn leads to less clogging of filters. However, yet there are no available filters for the size of engines used in large ships, even if they would use low-sulphur oil.

Another measure that has been discussed to reduce PM is the installation of shore side electricity[63]. According to Jivén 2004[63], Shore side electricity or Cold Ironing, could be a cost-effective way of reducing not only PM, but also other emissions in port. The net CO_2 emission may also be reduced if the electricity produced for shore side power comes from renewable energy sources. However, the main positive effect is the reduction of regional effects of PM and acidifying deposition of SO_X and NO_X.

Cofala et al[54] made scenario calculations for different policy measures based on available technical measures, and found that the most cost-effective level of reduction included:

- Slide valve retro-fitting for all existing slow-speed engines
- Humid air motors for all newly built vessels
- 0.5% Sulphur content of fuel used in the present SECAs, the Baltic Sea and the North Sea
- (Optional additional control of sulphur content 1.5% for HFO of cargo ships within the 12-mile zone from the coast)

The foreseen effects from these measures in 2020, compared to a baseline scenario, are reduction of NO_X emissions by 28% and SO_2 reduction by 14% (16.3%). The cost of implementation would be 770 (830) million €/yr in addition to baseline costs. However, when taking into account the reduced land-based measures that otherwise would be necessary to achieve the thematic targets within the National Emissions Ceilings Directive, the net costs will be reduced by nearly 1.5 billion €/yr.

4 Conclusive Remarks

Emissions from ships were for long neglected while emissions of green house gases, acidifying and eutrophying substances from land based sources were subject to regulations in order to reduce anthropogenic climate forcing and pollution. After a decade of reports concluding that the environmental impact from ship emissions is significant at global, regional and local levels, policy measures are finally proposed to include shipping. With respect to CO_2, shipping will most likely be subject to an emission trading scheme, possibly through inclusion in the EU ETS. If the newly proposed IMO SO_X regulations are realised, there will be no room for emission trading with respect to sulphur. The proposed NO_X regulations tackles the emissions from new built ships, but there is a risk that a large number of vessels built before year 2000, and which do not fulfil the definitions for the new regulations, will maintain high contribution from shipping to global NO_X emissions. It is of great importance to continue the work towards standardised emission data from national inventories. Hence increased accuracy and more complete enable reliable analysis of emission trends, both from shipping and from other sources. Finally, the importance of not creating figurative watertight bulkheads between the approaches to regulate different gases needs to be stressed[64]. As reduction of one pollutant or greenhouse gas may imply increased emissions of something else, an overall holistic approach is necessary when discussing different measures.

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