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Regulating Air Emissions from Ships

The State of the Art on Methodologies, Technologies and Policy Options

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Regulating air emissions from ships: the state of the art on methodologies, technologies and policy options

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Executive summary

In recent years public concerns regarding the environmental impacts of maritime transport have increased. This is because maritime transport is the fifth largest contributor to air pollution and carbon emissions, and the growth rate of trade makes the problem even more pressing. However, considerable environmental improvements are obtainable by changing shipping practices. The international regulatory framework that governs the sector makes it complex to design policy strategy to abate air emissions, such as greenhouse gases (GHGs), from international maritime transport.

The current policy actions dealing with air emissions relate mainly to the quality of fuel used and to the technological options available. Market-based instruments such as emissions trading are being discussed at international level within the International Maritime Organization (IMO). Furthermore, the inclusion of the maritime transport sector within the EU Emission Trading Scheme is on the EU strategy to address GHGs. The complexity of air pollution and climate change policies for the international maritime transport sector calls for a wide range of considerations to be taken into account requiring policymakers: 1) to set binding long-term emission reduction goals, 2) to take action in a flexible manner, 3) to ensure knowledge and technology sharing of innovative practices, and 4) transparency, administrative feasibility.

The following Reference Report summarises the key findings of several years' research activity and provides a reference framework for analytical tools designed to support the regulation of air emissions from ships. It outlines the 'state of the art' with regard to the main methodological aspects of designing policy measures to regulate air emissions from maritime transport, namely identification of the impacts, estimation of emissions, and identification and selection of technological and policy options to abate air emissions from ships. The ultimate aim of this Report is to provide analytical tools to help define a policy strategy for regulating air emissions from ships, by providing various insights into how to best design and apply efficient and equitable policy instruments.

Reducing the impacts of maritime transport on the environment is a challenging task, since these impacts are not only due to navigation but also to the activities carried out in ports. **Chapter 1** analyses the main links between environmental impacts and activities/events of the maritime transport sector. The analysis suggests that air emissions from the maritime transport sector account for a significant portion of total emissions, affecting air quality and contributing to climate change and human health problems. In addition, the existing trend suggests that the situation will worsen in the future. CO_2 emissions from shipping activities are estimated to account for 3-5% of total CO_2. Moreover, it has been estimated that, without any countermeasures, sulphate emissions will increase by 10-20% over the main shipping routes in 2012, contributing up to 5.2% of the total tropospheric sulphate burden. These results include uncertainty but also highlight the urgent need to take action. **Chapter 2** provides a critical analysis of the main data and methodologies available to estimate air emissions from ships. This chapter highlights some of the limitations of the current methodologies as well as the scarcity and limited availability of data concerning maritime transport activities. The analysis takes particular account of the estimation and geographical characterisation of air emissions. The chapter classifies the different data sources which are available (or will be in the near future) to maritime transport researchers. A conclusion of this section is that there is at present no optimum source of information, in terms of accuracy, coverage and comprehensiveness. However, and this is key, different data sources may be used together in order to reduce their overall uncertainties. **Chapter 3** provides some insights into how to design a sector-based policy strategy to abate air emissions from maritime transport, taking into account the complexity of the current contribution of the sector to global and local air emissions. Criteria for selecting the most appropriate option are then discussed, focussing on the cost effectiveness of different options. Here the basic aim is to select the option which achieves specified objectives at least cost. The chapter identifies the main elements which characterise this approach. These will be taken into account in the analysis of the technological and policy options to abate air emissions from ships carried out into the subsequent chapters. With respect to the technological options, **Chapter 4** describes the technologies that might be used to reduce fuel consumption and pollutant emissions. The analysis provides an estimation of the costs of these technologies, which is key to assessing the feasibility of their application in the subsector.

Chapter 5 provides an overview of the complexity of the maritime regulatory system and how environmental issues are currently integrated into this framework, and defines the main elements of the regulation. This chapter summarises the current international debate on the regulation of GHGs arising from international maritime transport. It identifies the Kyoto Protocol's principle "*common but differentiated responsibilities and respective capabilities*" and the IMO's "*no more favorable treatment"* concept as the core elements of this debate. **Chapter 6** outlines the main elements of the European Union's position on regulating air emissions from international maritime transport, and discusses the inclusion of international shipping in the EU Emission Trading Scheme.

Our results show that, because of the high uncertainty in air emissions estimations, further research is required in this field. In fact, a scientific debate is now open on the most appropriate way to address the issue of how to estimate air emissions. The scarce or limited availability of data concerning maritime transport activities has resulted in the widespread use of different calculation methodologies. In addition, the application of new technologies which enable more detailed traffic data acquisition puts the usefulness of the methodologies proposed so far further into question. The increasing impact of maritime transport on the environment is also related to the growth rate of trade, which makes the problem even more pressing. This is related to the intensive nature of the production and consumption of goods and services, which have been stimulated by several factors such as the new global dimension of modern production and consumption which has re-shaped European and world trade, and the use of *just-in-time* techniques which allow manufacturers and wholesalers/retailers to dispense with warehouses. These issues call for environmental strategies to regulate air emissions from ships to be integrated into a broader framework which takes into account all the pillars relating to the sustainable development of transport.

In conclusion, this Report identifies the methodological aspects of designing an environmental strategy to regulate air emissions from ships and illustrates how the current policy actions are integrated into an international framework.

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List of Abbreviations

AIS	Automatic Identification System
AMVER	Automated Mutual-Assistance Vessel Rescue System
CLRTAP	Convention for Long-range Transboundary Air Pollution
Dwt	Deadweight tonnage
ECA	Emission Controlled Area
EDGAR	Emission Database for Global Atmospheric Research
EEDI	Energy Efficiency Design Index
EEZ	Exclusive Economic Zone
EGR	Exhaust Gas Recirculation
EIA	U.S. Energy Information Administration
EMSA	European Maritime Safety Agency
ETS	Emission Trading Scheme
FBC	Fluidized Bed Combustion
GHG	Greenhouse gas
GT	Gross Tonnage
HAM	Humid Air Motor
HAP	Hazardous Air Pollutants
HFO	High Fuel Oil
ICAO	International Civil Aviation Organization
ICOADS	International Comprehensive Ocean-Atmosphere data-set
IEA	International Energy Agency
IEM	Internal Engine Modification
IMO	International Maritime Organization
JRC	Joint Research Centre of the European Commission
LMIU	Lloyd's Maritime Intelligence Unit
LMIS	Lloyd's Maritime Information System
LRF	Lloyd's Register Fairplay
LRIT	Long Range Identification Tracking
MAC	Marginal Abatement Cost
MD	Marine Distillates
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
METS	Maritime Emission Trading Scheme
MGO	Marine Gas Oil
MoU	Memorandum of Understanding
MSCM	Maritime Sectoral Crediting Mechanism
MERS	Maritime Emission Reduction Scheme
NERI	National Environmental Research Institute of Denmark
OSV	Off-shore Support Vessel
PM	Particulate Matter
RINA	Registro Italiano Navale
SCR	Selective Catalytic Reduction
SECA	SOx Emission Control Area
SFOC	Specific Fuel Oil Consumption
SNCR	Selective Non-Catalytic Reduction
STEEM	Ship Traffic Energy Environmental Model
TEU	Twenty-Foot Equivalent Unit
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention of Climate Change
UNCLOS	1982 United Nations Convention of the Law of the Sea
UNECE	United Nations Economic Commission for Europe
USACE	U.S. Army Corps of Engineers
VOC	Volatile Organic Compounds
WiFE	Water in Fuel Emulsion

Introduction

In recent years, public concerns regarding the environmental impacts of maritime transport have increased. The analysis of the main impacts of maritime transport activities on air quality highlights the fact that the sector is responsible for a notable amount of total CO_2 emissions and air pollutants. In addition, the existing trends suggest that the situation will worsen in the future.

Indeed, CO_2 emissions from shipping activities are estimated to account for 3-5% of total CO_2 emissions (see for example IMO, 2009). In addition, estimates show that in 2050 maritime transport will be responsible for 15% of total CO_2 emissions. For other air pollutants, in Lauer *et al.* (2009) it has been estimated that, in the event of no countermeasures being taken, sulphate emissions will increase by 10-20% over the main routes in 2012, contributing up to 5.2% to the total tropospheric sulphate burden.

Despite this scenario, considerable environmental improvements could be obtained by changing shipping practices (Krozer *et al.*, 2003). The current policy actions dealing with emissions relate mainly to the quality of fuel used and to the available technological options.

Market-based instruments such as emissions trading are being discussed at international level within the International Maritime Organization (IMO).

Furthermore, the inclusion of the maritime transport sector within the EU Emission Trading Scheme is on the EU strategy to address GHGs.

The complexity of air pollution and climate change policies for the international maritime transport sector calls for a wide range of considerations to be taken into account (Montgomery, 1972; Tietenberg, 2003) requiring policymakers: 1) to set binding long-term emission reduction goals, 2) to take action in a flexible manner, 3) to ensure knowledge and technology sharing of innovative practices, and 4) transparency, administrative feasibility.

The present Reference Report summarises the main findings of a several year's research activity[1] which was carried out to provide a reference framework of the analytical tools for regulating air emissions from ships. It outlines the state of the art concerning the main methodologies for designing policy measures to regulate air emissions from maritime transport, namely identification of the impacts, estimation of emissions caused by shipping activities, and identification and selection of technological and policy options to abate air emissions from ships. The ultimate aim is to give analytical tools to help define a policy strategy for regulating air emissions from ships, providing some insights into how to design and apply efficient and equitable policy instruments. The first step to take towards achieving this objective is to accurately assess the air emissions from the maritime transport sector in terms of quantification and location.

Chapter 1 of this Report identifies the main environmental impacts related to maritime transport activities, focusing on impacts on air quality, and gives a critical analysis of the main methodologies for estimating air emissions from ships.

Chapter 2 classifies these methodologies on the basis of the approach followed (bottom-up or top-down) with respect to the total emissions calculation and geographic characterisation. This chapter highlights some limitations of the current methodologies and the scarcity and limited availability of data concerning maritime transport activities.

The Report recommends using cost effectiveness analysis as the basic criterion for selecting and/or combining policy options to design a sectoral environmental strategy (**chapter 3**).

1 The results of this activity have been published in several EUR reports: Miola , A., Ciuffo, B., Marra, M., Giovine, E. (2010) "Analytical framework to regulate air emissions from maritime transport" (EUR24297 – ISBN 978-92-79-15308-2); Miola *et al.* (2009) "External costs of transport Case study: Maritime transport"(EUR23837 – ISBN 978-92-79 12534-8); Miola *et al.* (2008) "Review of the measurement of external costs of transport in theory and practice" (EUR23714 – ISBN 978-92-79-11279-9); Andreoni *et al.* (2008) Cost effectiveness analysis of the Emission Abatement in the Shipping Sector Emissions" (EUR23715 – ISBN 978-92-79-11280-5).

Chapter 4 describes the technologies that might be used to reduce fuel consumption and pollutant emissions. The different technologies are grouped into five categories depending on the specific sector in which they are implemented (Ship design, Propulsion, Machinery, Operation and Fuel - Wartsila, 2009). The analysis gives an estimation of the costs of such technologies, which is a key consideration in assessing the feasibility of their application in the sector.

Chapter 5 summarises the current international debate on the regulation of GHGs from international maritime transport. This chapter identifies the Kyoto Protocol's principle "*common but differentiated responsibilities and respective capabilities*" and the IMO's *"no more favorable treatment"* concept as the core elements of this debate.

Finally, **Chapter 6** outlines the main elements of the European Union's position on regulating air emissions from international maritime transport, and discusses the inclusion of international shipping in the EU Emission Trading Scheme.

Our results show that, given the high level of uncertainty in air emissions estimations, further research is needed in this field. In fact, a scientific debate is currently underway on the most proper way estimate air emissions. The scarce or limited availability of data concerning maritime transport activities has led to a plethora of different calculation methodologies to estimate air emissions from shipping over the past decades.

In addition, the application of new technologies for more detailed traffic data acquisition puts the usefulness of methodologies proposed so far further into question.

Moreover, as has been pointed out, the increasing relevance of the environmental impacts of maritime transport is also related to the growth rate of trade, which makes the problem even more pressing.

This aspect is related to the intensive nature of production and consumption of goods and services, which have been stimulated by several factors such as the new global dimension of modern production and consumption which has re-shaped European and world trade, and the use of *just-in-time* techniques which allow manufacturers and wholesalers/retailers to dispense with warehouses (OECD, 2002).

These issues call for the integration of environmental strategies for regulating air emissions from ships into a broader framework which incorporates all the pillars of sustainable transport.

In conclusion, this Report identifies the methodological aspects of designing an environmental strategy to regulate air emissions from ships and describes how to integrate this strategy in an international framework.

1. Maritime transport activity and the environment: the impacts on air

Reducing the impacts of maritime transport on the environment is a challenging task, since these impacts are not only due to navigation but also depend on a number of other activities, such as those carried out in ports for instance. The main maritime transport activities are summarised in the following categories (Bickel *et al.* (2006)):

- navigation, which involves the transport, storage and loading/unloading of goods and passengers (the activities that deserve the most attention are mooring, docking and leaving the port);
- construction, maintenance, cleaning and dismantling of ships and vessels, which can either be carried out at port or in nearby areas;
- construction and maintenance of the port terminal in terms of land consumption and waste generated.

Each maritime transport activity carried out in port, at sea or during ship construction/maintenance/dismantling, results in different environmental impacts on air, water, ecosystems and other services. These impacts, as well as those deriving from accidental events or/and illegal actions, have to be considered when evaluating the overall impact of the maritime transport sector on environmental quality.

The links between environmental impacts and activities/events of the maritime transport sector are shown in Table 1.

	Activities-events/Impacts	AIR					WATER		SOIL/SEDIMENT				ECOSYSTEM		OTHER	
		Local Air Pollution (NOx, SO2, CO2, CO, VOC, PM)	Noise	Vibration	Odour	Global Air pollution impact	Water pollution	Water turbidity	Soil/sediment pollution	Acidification	Erosion	Land consumption	Biodiv. loss	Habitat Loss/Degradation	Congestion	Waste generation
In ports	Manoeuvring	X	X	X		X		X		X	X					
In ports	Loading & Unloading/ Operations on terminals	X	X	X	X	X	X		X	X						X
In ports	Hotelling (lighting, heating, refrigeration, ventilation, etc.)	X	X	X		X				X						X
In ports	Dredging	X	X			X	X	X		X			X	X		X
In ports	Land traffic (heavy vehicle, railway)	X	X	X		X	X		X	X			X	X	X	
In ports	Waste disposal/illegal dumping	X	X		X	X	X	X	X	X		X	X	X		X
In ports	Port expansion/ Infrastructures construction and maintenance	X	X	X		X	X	X	X	X	X	X	X	X		X
In ports	Fuel deposits				X		X		X			X	X	X		X
In ports	Discharge of ballast water						X	X	X				X	X		X
In ports	Dumping of black (sewage) and gray (shower, sink, and galley) water				X		X	X	X				X	X		X
In ports	Bulk handling and Goods movement	X	X	X	X	X	X		X	X					X	X
In ports	Industrial activities	X	X	X	X	X	X		X	X		X	X	X	X	X
In ports	Spills				X		X	X	X				X	X		X
At sea	Cruise	X	X			X				X			X	X		
At sea	llegal dumping						X	X	X				X	X		X
At sea	Dumping of black (sewage) and gray (shower, sink, and galley) water				X		X	X	X				X	X		X
At sea	Spills				X		X	X	X				X	X		X
Ships building, maintenance, dismantling	Hull paintings	X			X		X		X	X			X	X		X
Ships building, maintenance, dismantling	Metal degreasing	X			X		X		X	X			X	X		X
Ships building, maintenance, dismantling	Demolition	X	X		X	X	X		X	X			X	X		X

Table 1. Impacts due to maritime transport activities, including illegal activities and accidental events.

Source: A. Miola et al. (2009: 23).

Most maritime transport activities have an impact on water, as can be expected due to their proximity to the sea. In particular, several chemical products used for transport activities as well as substances transported by ships can end up being discharged into the sea, causing water pollution. These discharges can derive from authorised activities, accidents and illegal actions.

Soil pollution arising from the maritime transport sector is mainly the result of the terrestrial activities in port areas which can lead to soil and sediment contamination, acidification, the degradation of natural habitats and the consequent loss of biodiversity. In addition, port activities and their related infrastructures in these areas occupy and consume land.

In terms of air pollution impacts, ship emissions to the atmosphere comprise ozone and aerosol precursors (NO_x, CO, VOCs, SO_2, *etc.*) and the emissions of greenhouse gases (GHG). The effects of these pollutants are well documented. SO_2 and NO_x can become converted into sulphate and nitrate particles. Exposure to fine particles is associated with increased mortality and morbidity. Shipping emissions contribute notably to the formation of ground-level ozone, especially in closed regions (e.g. the Mediterranean region, *etc.*).

The deposition of sulphur and nitrogen contributes to excess critical loads of acidity. Nitrogen oxides lead to eutrophication, which affects biodiversity both on land and in coastal waters. An additional contribution of shipping to climate change is brought by the darker fraction of the particulate matter emitted, known as black carbon. This contribution is due to GHG emissions and to the aliquot of particulate matter defined as black carbon. Black carbon can absorb energy from incoming sunlight. This phenomenon is particularly relevant in the Arctic area, where black carbon is responsible for accelerating the melting process of snow and ice. Warming in the Arctic area has an impact on the Arctic climate and thus on the global climate system.

For the scope of this Report, the next paragraph provides a detailed analysis of the impacts of maritime transport on air quality and GHGs emissions. This analysis will help identify the main fields of policy intervention for abating air emissions from ships.

1.1. Impacts on Air

Emissions from the maritime transport sector represent a significant and increasing source of air pollution.

The health and environmental impacts of air pollutants are highly dependent on the proximity of the emission sources to sensitive receptor sites. This means that, compared to land-based sources, at least some maritime emissions have less obvious health and environmental impacts since they can be released far from populated areas or sensitive ecosystems. However, in harbour cities ship emissions are often a dominant source of urban pollution and need to be addressed, in particular when considering fine particulate matter.

Furthermore, emissions from ships are transported in the atmosphere over several hundreds of kilometres, and thus can contribute to air quality problems on land even if they are emitted at sea. This pathway is especially relevant for the deposition of sulphur and nitrogen compounds (Cofala *et al.*, 2007).

In general, all ship activities lead to air pollutant emissions (Trozzi, 2003). Concerning ship building/maintenance/dismantling activities, the principal emissions are dust, particles, gases (e.g. from welding), odours and aerosols. Considering specific activities, the emission of volatile organic compounds (VOCs) from metal degreasing and painting activities represents a major problem (European Environment Agency, 2002). As regards hull surface cleaning, paint removal, changes of zinc anodes, and paint application, the main elements that have an impact on the environment are dust emissions (from sandblasting, grinding, *etc.*) and emissions of solvents, where solvents contain VOCs and hazardous air pollutants (HAPs) (Hayman *et al.*, 2000). The demolition or major modification of ships can produce asbestos, heavy metals, hydrocarbons, ozone depleting substances and other pollutants. As already mentioned, all these ship building/maintenance/dismantling activities can either be carried out in the port or in other areas. It should also be taken into account that, for economic reasons, many shipping vessels use heavy fuel oil with high sulphur content (just to give an idea, the sulphur content of standard marine fuel is 2,700 times higher than that of conventional diesel for cars). The main air emissions resulting from burning this type of fuel include:

- Sulphur Dioxide (SO_2);
- Nitrogen Oxides (NO_x);
- Volatile Organic Compounds (VOCs);
- Particulate Matter (PM);
- Carbon Dioxide (CO_2) and other GHGs.

The amount of gases emitted from marine engines into the atmosphere is directly related to total fuel oil consumption, which depends on different factors such as the hull shape, the loading conditions, the roughness of the hull, the condition of the engine, *etc.* Auxiliary engines also contribute to the total exhaust gas emissions. This contribution to air emissions is particularly significant for cruise ships, which have a constant need for ancillary power to meet lighting and ventilation demands both at sea and in port. In general, ship emissions in port depend on manoeuvring time and cargo operations (vessel-type dependent) (Endresen *et al.*, 2003).

Emissions can also result from onboard incineration of waste, which can lead to dioxins and other heavy metals being released into the atmosphere.

Focusing on all port operations and air pollution, the main factor to take into consideration is that each category – ocean/sea-going vessels, harbour craft, cargo handling equipment, trucks and locomotives – is mainly powered by diesel engines, which are significant contributors to air pollution.

The most relevant shipping activities that contribute to air pollution are (Trozzi, 2003):

- loading and unloading of petroleum products (VOCs);
- dry docks (evaporative VOCs);
- passenger car traffic (combustion and evaporative VOCs);
- heavy vehicle and railway traffic (combustion compounds).

As a result, especially in port areas, ships contribute to harmful levels of pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and lead (Pb). Nitrogen oxide (NO_x) and PM can contribute to many serious health problems including premature mortality and asthma attacks (IAPH, 2007).

The presence of these pollutants has local and global impacts. Impacts on local (or regional) air quality are mainly linked to pollutants such as PM, NO_x and sulphur, while the GHGs (*e.g.* CO_2) have a global impact on climate.

As far as local air pollution is concerned, port areas have historically developed in very close proximity to urban areas, and port operations can affect the people living and working in these areas. The negative effects on local air quality and human health are largely dominated by the presence of NO_x, PM (2.5 or 10), acid deposition and nitrogen deposition.

NO_x emissions also can cause nutrient overload in water bodies, which can result in eutrophication. The excess of nutrient nitrogen can be detrimental to the fragile balance of ecosystems, including marine ecosystems. In addition, particles and NO_2 linked to air emissions from maritime transport activities can have impacts on visibility by reducing the visual range, as highlighted by Holland *et al.* (2005).

SO_2 emissions also negatively impact public health; in particular, sulphate particles can induce asthma, bronchitis and heart failure.

Sulphur and nitrogen compounds emitted from ships can also produce impacts not directly linked to human health. They can, indeed, cause acid depositions that can be detrimental to the natural environment (lakes, rivers, soils, fauna and flora). Emissions of these compounds at sea can exert an influence on vegetation and land-based objects many thousands of kilometres away.

Health effects can result in the reduction of oxygen delivery to the body's tissues and organs (such as the heart and the brain). CO can have significant cardiovascular effects on those who suffer from heart disease. The central nervous system can also be affected. Breathing high levels of CO can result in blurred vision, reduced ability to work or learn, and reduced manual dexterity. CO also contributes to the formation of smog (IAPH, 2007).

At the global level, carbon dioxide is the most significant trace constituent that has an effect on global climate change. Shipping is one of the contributors to the world's total CO_2 emissions: 870 million tonnes in 2007, increasing by a factor of between 2.2 and 3.3 in 2050 according to IMO (2009).

The study by the IMO (2000) highlights that, due to the highly nonlinear response in ozone formation from emissions of precursors such as CO and NO_x, ship emissions over oceans far removed from industrial regions such as the Atlantic and Pacific Oceans generate higher levels of ozone formation than emissions over polluted coastal regions (*e.g.* the North Sea).

Moreover, the study by Schreier *et al.* (2006) underlines that particle emissions from ships change the physical properties of low clouds, due to the so-called indirect aerosol effect. Particles and their precursors from ship emissions can act as cloud condensation nuclei (CCN) in the water-vapour saturated environment of the maritime cloud. Aerosols can re-radiate the sun's energy, causing temporary cooling effects that mask the long-term warming effect of GHGs. In addition, ship emissions modify existing clouds by decreasing the effective radius, while they increase droplet concentration and optical thickness. These effects seem to be particularly prevalent in areas where the background pollutant concentrations are low, as at open sea.

An additional contribution of shipping to climate change is brought about by the darker fraction of the PM emitted, known as black carbon. Black carbon accounts for around 10% of the total PM emitted (Lack *et al.*, 2009). Its capability to absorb the energy derived from incoming sunlight makes it particularly dangerous in the Arctic and Antarctic areas where it plays an important role in the acceleration of the snow and ice melting process. This phenomenon, which is particularly relevant in the northern hemisphere where most ship activities are carried out, may significantly contribute to modification of the climate system of the Arctic region and thus that of the entire planet. At the moment, the shipping sector is estimated to be responsible for around 2% of total black carbon emissions (Lauer *et al.*, 2007). This percentage reaches the interval from 10 to 50% near the major shipping routes (Marmer *et al.*, 2009) and, furthermore, it is constantly increasing.

1.2. Conclusion

The analysis of the main impacts of maritime transport activities on air highlights the responsibility of the sector for a notable amount of total CO_2 emissions and air pollutants. For example, in Lauer *et al.* (2009) it has been estimated that, without any countermeasures, in 2012 sulphate emissions will increase by 10-20% over the main routes, contributing up to 5.2% to the total tropospheric sulphate burden. These results show the complexity of the situation and the urgent need for action to be taken. The increasing pressure of the maritime sector on the environment could be halved by adopting local and global emission restriction policies. The first step to take towards achieving this objective is to quantify the air emissions from the maritime transport sector. The next chapter gives an overview of the main methods for estimating the air emissions deriving from shipping activities and compares their results in order to define a reference framework.

2. Evaluating emissions from the maritime transport sector: state of the art

As highlighted in the previous chapter, emissions from the maritime transport sector account for a significant portion of total emissions, affecting air quality and contributing to climate change and human health problems. The estimation and geographical characterisation of maritime transport emissions are therefore important to the work of, for instance, atmospheric scientists or policy makers who try to analyse and address the problems associated with them.

In general, the level of detail achieved and achievable within a certain study depends on the approach followed (bottom-up or top down) and the specific purpose of the analysis itself.

For example, emissions of CO_2 may be analysed at a global scale, whereas NO_x and SO_x emissions should be analysed at a more local scale since their greatest effects are produced on the environment in which they are released.

In a bottom-up approach, each single element involved in a certain phenomenon is modelled and then the global impact is evaluated by aggregating the impacts of the different elements.

For the evaluation of emissions arising from maritime transport, two dimensions have to be considered: the quantity of emissions produced and where they are emitted. For both dimensions we can use a bottom-up or a top-down approach, or a mixture of the two:

- *Full bottom-up approach*: the pollution that a single ship emits in a specific location is evaluated. By integrating the evaluation over time and over the fleet it is possible to evaluate total emissions and their geographic distribution;
- *Bottom-up approach in the evaluation of total emissions, but top-down in the geographical characterisation*: a single vessel is considered in the analysis, but nothing is known about its position. By making assumptions, it is possible to provide an estimate of the total emissions which are later geographically characterised using different criteria;
- *Top-down approach in the evaluation of total emissions, but bottom-up in the geographical characterisation*: this analysis starts by considering a single maritime route or a particular geographic cell and evaluating the global activity which is carried out on it, no matter which vessel carries out the activity. Emissions from the individual cells are then aggregated to calculate total emissions and assumptions are made in order to assign total emissions to the different ships (or at least to the different categories);
- *Full top-down approach*: total emissions are calculated without considering the characteristics of the individual vessels, and are later spatially assigned.

In Table 2 the key works found in the literature review are subdivided according to the above-mentioned classification. Due to data availability, nearly all the studies evaluate emissions attributable to vessels whose gross tonnage (referred to as GT in the remainder of this Report) is greater than 100.

Several inventories have been established over the past two decades.

The works are grouped on the basis of the classification provided in the preceding paragraph and ordered more or less chronologically. The debate on the evaluation of maritime emissions is still open and has resulted in several different estimations being made over the past decade. These are not all that easy to compare, since different contexts are analysed and different assumptions are made.

Table 2. Classification of the main studies concerning the evaluation of emissions from maritime transport

		Dimension 2: ***Emissions geographical characterisation***	
	Approaches	*Bottom-up*	*Top-down*
Dimension 1: Emissions evaluation	*Bottom-up*	Entec (2005) Wang *et al*. (2007a, 2007b) Corbett *et al*. (2009) Jalkanen *et al*. (2009) Olesen *et al*. (2009) Schrooten *et al*. (2009) Miola *et al*. (2009) Wang *et al*. (2010) Paxian *et al*. (2010) Tzannatos (2010)	Endresen al. (2003,2004*,2007) Corbett and Koehler (2003*,2004*) Eyring *et al*. (2005) Winther (2008)* Dalsoren *et al*. (2008) IMO (2009)
	Top-down	Georgakaki *et al*. (2005) Wang and Corbett (2005, 2007) Wang *et al*. (2008) Winebrake *et al*. (2009)	Corbett and Fischbeck (1997) Corbett *et al*. (1999) Skjolsvik *et al*. (2000) Endresen *et al*. (2007)

** Paper does not include the geographical characterisation of emissions*

In IMO (2009) an attempt is made to homogenise the results of different studies. Figure 1 shows the estimates of the IMO expert group which confirm the results from Corbett and Koelher (2003) rather than those from Endresen *et al.* (2003) (the works opening the debate). In addition, the graph clearly highlights the high level of uncertainty introduced by the different methodologies used to estimate emissions.

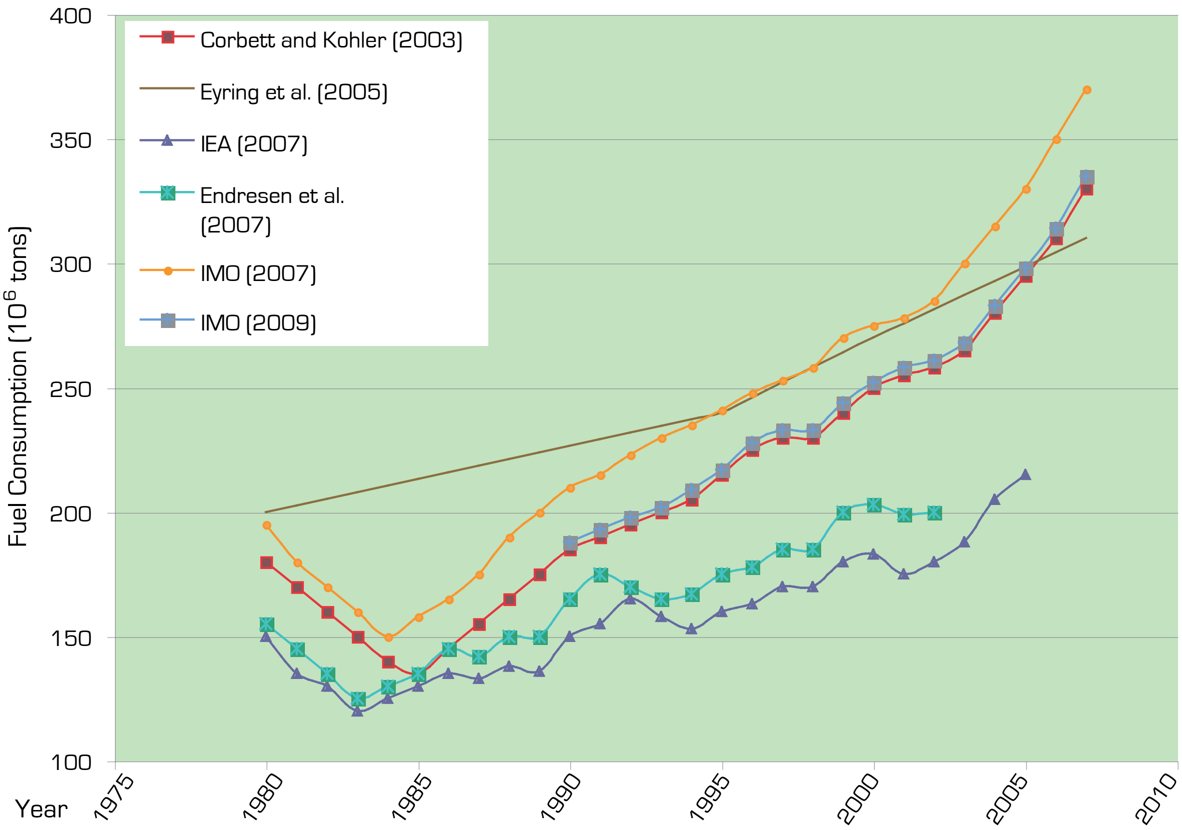

Figure 1. Fuel consumption estimation and evolution from different sources. Our elaborations on IMO data (IMO, 2009).

This uncertainty is numerically quantified in Table 3, which considers the estimated CO_2 emissions for different base years. The year of reference varies and, in order to avoid the introduction of further distortions, no attempt is made here to homogenise the results; however, most of the studies consider the year 2001.

Table 3. CO_2 emissions from international shipping: different results from different sources

	Study	Base Year	Global CO_2 Emissions from Maritime Transport (Mt)
International Shipping*	Corbett *et al.* (1999)	1993	453
	Skjolsvik *et al.* (2000)	1996	430
	Endresen *et al.* (2003)	2001	557
	Corbett and Koelher (2003)	2001	805
	Eyring *et al.* (2005)	2001	812
	Endresent *et al.* (2007)	2000	625
	Wang *et al.* (2008)	2001	650
	Edgar (2009)	2001	440
	IEA	2001	550
	EIA	2001	610
	IMO consensus (2009)	2001	652
	Eyring *et al.* (2009)	2000	780
	Edgar (2009)	2004	520
	Dalsoren *et al.* (2008)	2004	654
	IMO consensus (2009)	2004	755
	Eyring *et al.* (2009)	2005	960
Total Shipping	Corbett and Koelher (2003)	2001	912
	Eyring *et al.* (2005)	2001	887
	IMO consensus (2009)	2001	784
	Paxian *et al.* (2010)	2006	695
	IMO consensus (2009)	2006	1008
EU** 200 M	Wang *et al.* (2008)	2001	90
	Edgar (2009)	2001	62
	Entec (2005)	2000	121
EU Tot	Paxian *et al.* (2010)	2006	112
	Schrooten *et al.* (2009)	2005	77

** International Shipping is defined as the shipping activities carried out between the ports of different countries. Total Shipping is made up of International Shipping, Domestic Shipping and Fishing.*

*** EU is defined as the union of the following countries: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom of Great Britain and Northern Ireland. 200 M refers to emissions which are estimated to be emitted within 200 nautical miles from the coast, whereas the total estimate (EU Tot) refers to all traffic to and from EU countries.*

Regarding global CO_2 emissions, Table 3 shows a slight convergence of the different studies, which leads to an estimate with a higher degree of consensus (more similar results are obtained now that more reliable information on vessels' activities are available). The table also includes the estimate provided by the International Energy Agency (IEA) and by the U.S. Energy Information Administration (EIA) as reported by IMO (2009) (tonnes of fuel sales have been converted into tonnes of CO_2 according to Corbett *et al.*, 2009).

Table 3 also reports the average CO_2 emissions estimated by Eyring *et al.* (2009). Moreover, in their work, Eyring *et al.* (2009) report the upper and lower limits of global CO_2 emissions as retrieved from the same studies reported in this report. In particular, for the year 2000, the lower limit is found to be 560 Tg(CO_2), while the upper limit is 1,360 Tg(CO_2).

For the year 2005, the lower limit is 450 Tg(CO_2), while the upper limit is 1,660 Tg(CO_2). This means that from 2000 to 2005 overall uncertainty has increased from 50% to 100% of the total estimates.

This further confirms the need for different approaches to the problem (improvements are expected in the coming years as a result of the application of more sophisticated full bottom-up approaches).

Such uncertainties are also reflected in the studies that consider the European context. Results are reported in Table 3 (EU Tot). Different approaches yield a 70% uncertainty level for the estimation of emissions due to the maritime traffic in European ports for approximately the same year. In particular, in Schrooten *et al.* (2009) no hypothesis on the vessels' activities is made, but a proxy of the European Origin/Destination Demand matrix for goods (Eurostat, 2000) is used.

This transportation demand is then assigned to the European waterway network (in which maritime routes are explicitly taken into account) in order to derive the traffic figures on the different routes. The Lloyd's Register of Shipping is then used to estimate the other information required for the emissions calculation (such as the engine load factor, *etc.*). Results of the study are available upon request through the EX-TREMIS project website (http://www.ex-tremis.eu).

Paxian *et al.* (2010) and Faber *et al.* (2009) take a different approach. Here a full bottom-up approach is adopted. However, in order to overcome the uncertainties connected to the lack of information on shipping activities, the authors use vessel movement data from the Lloyd's Marine Intelligence Unit (LMIU) ship statistics. Such movements are identified for each vessel by its calls at successive ports. The shortest path is assumed to have been followed by the ship between each pair of ports (origin and destination).

In this way, a single source of information (LMIU statistics) is used both for technological and activity related information about a ship.

Unfortunately, only a portion (approximately 50%) of the movements of a vessel's fleet is monitored.

In order to overcome this problem, Faber *et al.* (2009) evaluates the total fuel consumption and emissions from the maritime sector and compares these with the so-called "consensus" estimates of IMO (2009). They then apply the ratio between consensus estimates and their estimates to correct results for a more limited context (*i.e.* fuel consumption and emissions from European maritime trade activities).

The next section classifies the different data sources which are available (or will be in the near future) for researchers of maritime traffic.

2.1. An inventory of possible maritime data sources

A key factor in defining the best approach to use for the evaluation of emissions is the availability of information concerning maritime traffic and vessels. The initial approaches adopted in the research to date (bottom-up for emissions evaluations, top-down for geographical characterisations) relied exclusively upon information about vessels, and made different assumptions on their activities. This approach is probably plausible (at least to a certain extent, see for example IMO, 2009), but it has certainly led to the current high level of uncertainties.

In the following sub-sections we will describe the main sources of information. The following information is usually necessary for the evaluation of ship emissions:

Ship type/category/length/GT (for possible aggregation into groups)

1. Ship type/category/length/GT (for possible aggregation into groups)
2. Power (kW) of the ship's main and auxiliary engines
3. Age of the main engines
4. Ship's service speed
5. Engine consumption (g/kWh)
6. Engine running hours
7. Engine load
8. Fuel type
9. Emission factors ($g_{pollutant}$/ g_{fuel}) or ($g_{pollutant}$/ kWh)
10. Routes covered by maritime traffic

Points 1, 2, 3, 4 and 8 relate to technical information on vessels. Some of these can be found in publicly accessible data sources, while others (in particular the power, fuel used, engine number and type) are only available in a few commercial databases. Points 4, 6 and 7 relate to information on the typical activity of a vessel which must be collected separately or by using some other available data source. Emission factors and other information that can be useful for refining the estimation have to be found in the scientific literature. Maritime traffic routes are important for the spatial characterisation of activities. Below we outline with vessels' technical specifications, then we present possible data sources of information on vessel activities and we finish with emission factors.

2.1.1. Technical information on International vessels

Only two sources of information on vessels have been used in the studies. These are analysed here:

- the World Merchant Fleet Database provided by the *Lloyd's Register Fairplay* (LRF[2]), (http://www.lrfairplay.com/)

- the *Lloyd's Marine Intelligence Unit* (LMIU) [3] database (http://www.lloydsmiu.com/lmiu/index.htm)

Other, less complete information on ships can be found in some dedicated search engines (such as Equasis http://www.equasis.org/EquasisWeb/public/HomePage?fs=HomePage, or Digital Seas, http://www.digital-seas.com/start.html) and in a number of ship registers from around the world (*e.g.* the Registro Italiano Navale, RINA, Germanischer Lloyd, GL). However, these are not mentioned in the scientific literature that we have reviewed.

2.1.2. Ship activities and geographic distribution of maritime traffic

An important parameter for the calculation of emissions is the definition of the number of hours each ship spends at sea. Until a few years ago, this information was retrieved from specific studies which provided average information (in Endresen *et al.*, 2003, it is suggested that data be taken from CONCAWE, 1994, or http://www.ssb.no/english/subjects/10/12/40/ which provides statistics from Norway for the year 2000).

Such references can be useful for rough estimations of emissions, but they cannot be considered satisfactory if compared with another source of this kind of information, the *Automatic Identification System (AIS)*. The AIS was introduced by the International Maritime Organization's (IMO) International Convention for the Safety of Life at Sea (SOLAS, 1974). As of December 2004, all international voyaging ships of 300 GT or more and all passenger ships regardless of size are required to have this system aboard (for further details see http://www.imo.org/Safety/mainframe.asp?topic_id=754). The main motivation for the adoption of this system was that it can provide precise information about the ships' position that can be used for collision avoidance (Ou and Zhu, 2008).

It is estimated that about 40,000 ships carried AIS equipment in 2008 (Ou and Zhu, 2008).

Information exchanged by each ship are (Ou and Zhu, 2008):

- *STATIC*: IMO number, length and beam, call sign and name, vessel type;

- *DYNAMIC*: position, time, course and speed over ground, heading, rate of turn;

- *VOYAGE RELATED*: draft, possible hazardous cargo, destination.

2 In June 2009, Lloyd's Register-Fairplay was taken over by the American IHS. The new name for the company is now IHS Fairplay. In this report the old name was kept so as not to confuse the readers who may not be aware of the change.

3 The name of the Lloyd's Maritime Intelligence Unit has changed in Lloyd's List Intelligence. As above, in this report the old name was kept so as not to confuse the readers

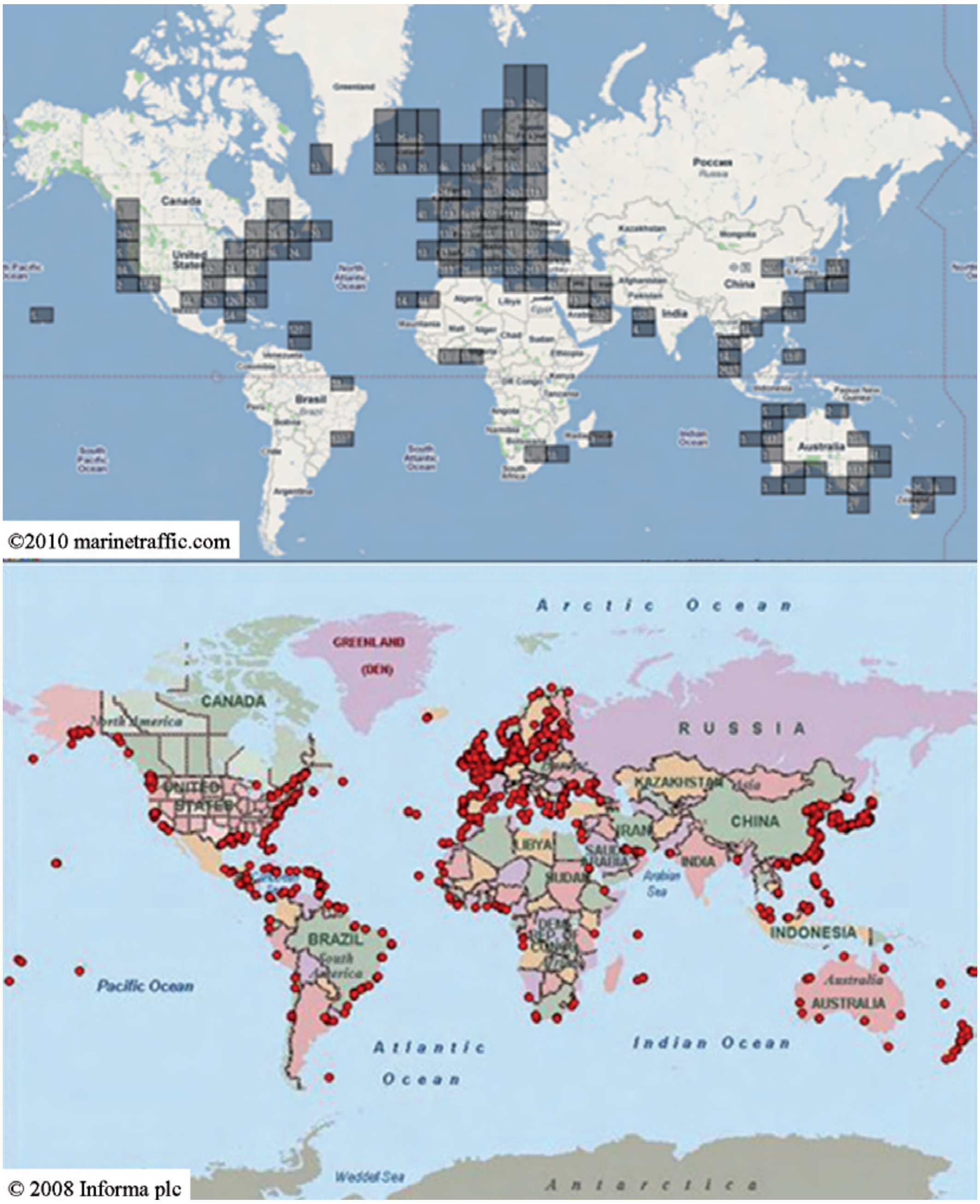

Figure 2. **AIS coverage areas. Image on top by courtesy of Marinetraffic.com, ©2010, Marinetraffic.com -University of the Aegean; imagine down the LMIU network by courtesy of Lloyd's List Group, © 2008 Informa plc, All rights reserved.**

The signal sent by each ship is not encrypted and thus can be read by any AIS receiver in a range of about 10 nautical miles. This allowed groups of volunteers and private companies to collect such data and make them available (either free of charge or against payment). To the authors' knowledge, the main providers of AIS data are *Marinetraffic.com* (www.marinetraffic.com), *Lloyd's MIU AIS* (www.lloydsmiu.com/lmiu/ais/index.htm) and *AIS Live* (http://www.aislive.com/).

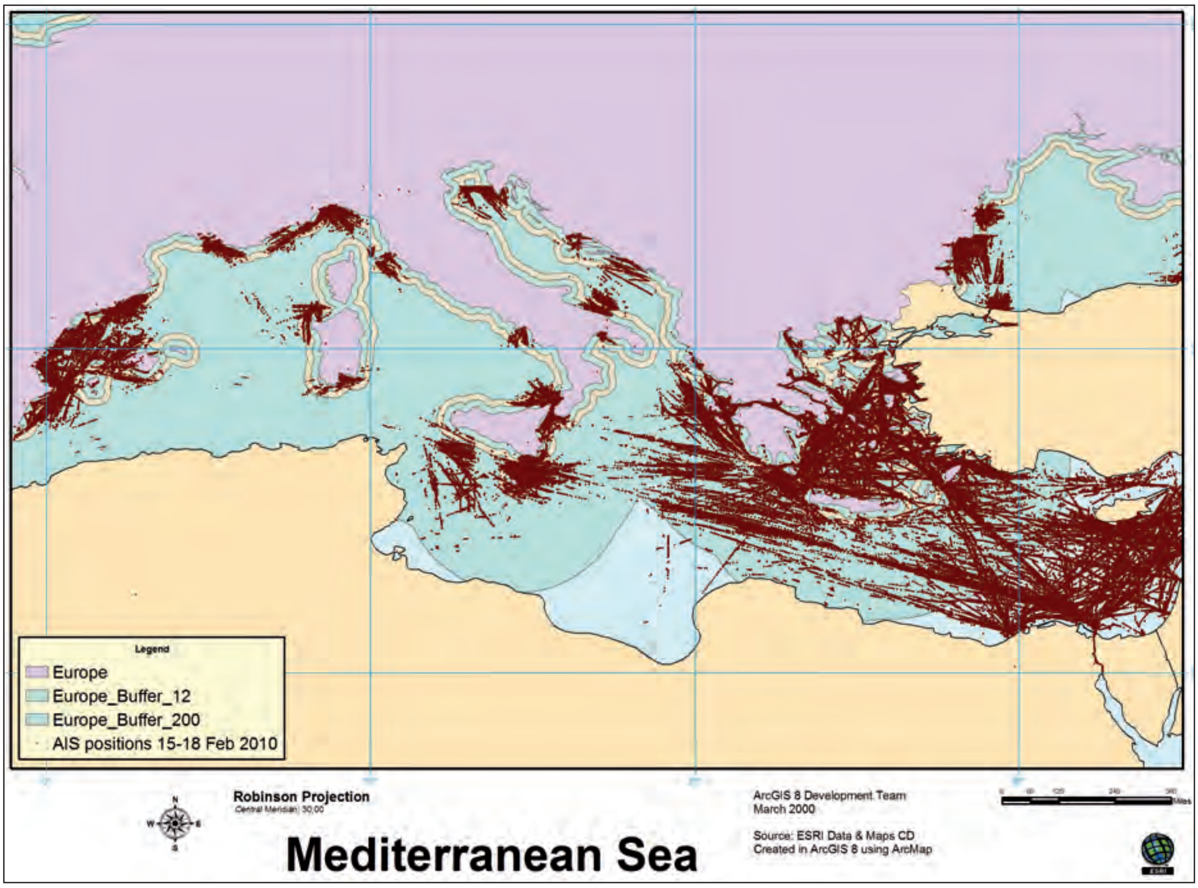

Figure 3. Ships' positions in the Mediterranean Sea in the period 15-18 February 2010 retrieved by the marinetraffic.com AIS network. Our elaborations.

Further to the definition of the ships' activities, AIS data may be usefully applied for the evaluation of the vessels' speed. The service speed provided by the ships' databases is an average value declared by the ships' operators. In order to calculate ships' fuel consumption and emissions, the operational speed of a ship would be required in addition to its service speed (as detailed in Corbett *et al.*, 2009). In particular, the relationship between fuel consumption and the ratio between operating speed and service speed is a cubic function (Corbett *et al.*, 2009), meaning that an estimation of the operating speed can be used to calculate an estimate of the fuel consumption and emissions. AIS data could therefore substantially improve the global estimation of emissions from maritime traffic.

However, some risks exist with AIS data. These are mainly connected to:

- Incomplete spatial coverage of maritime traffic. In Figure 2 this is pointed out. In addition, exceptions to the use of AIS data are given in the clause established in the IMO 22nd meeting of the General Assembly, resolution A.917(22);
- Penetration of the AIS technology in the fleet working in the area which is being considered. At the global level, approximately 50% of ships have this system on board (Ou and Zhu, 2008), but at the local scale the picture may be very different (for instance, according to a recent study, MARIN, 2008, the coverage rises to 90% in the Baltic Sea, meaning that in other areas the percentage of coverage will be much lower).
- Incomplete coverage for the entire route. For instance, the data available for the entire route may potentially only be connected with the departure and the arrival of the vessel. It is possible to have an estimate of the average cruise speed, but this is of course only an approximation. This problem can be overcome by using another data source, the *Long Range*

Identification and Tracking (LRIT) of ships. Although the LRIT contains less frequent information (collected only four times per day) it is available everywhere. It was established as an international system in 2006 by the IMO and applies to ships engaged on international voyages (in particular to all passenger ships, cargo ships of 300 GT and above, and mobile offshore drilling units).

All these problems could be reduced if a single entity were to take responsibility for accurate data collection and distribution. In Europe this role will be filled by the European Maritime Safety Agency (EMSA), which will take care of both AIS and LRIT data. This would lead to a considerable improvement in the data accuracy for European researchers in the maritime transport field.

A satellite system which can collect AIS information sent by ships is currently being developed. This would facilitate the procurement of AIS data no matter the distance of the vessel from the shore. This would of course considerably improve the usefulness of the AIS system. In any case, both LRF and LMIU claim that they can provide such data.

Further sources of data on vessel activities which can be used for the spatial characterisation of emissions are the *ICOADS* and *AMVER* datasets. ICOADS (International Comprehensive Ocean-Atmosphere Data Set) contains ship positions voluntarily recorded by ships. In 2003 about 4,000 ships reported their data to ICOADS (around 5% of the world's fleet). Historical information goes back to 1662 and therefore can be used to analyse the evolution of routes and navigation. Data are available through subscription to the ICOADS website.

AMVER (Automated Mutual-Assistance Vessel Rescue System) is used worldwide by search and rescue authorities to provide assistance to ships and persons in distress at sea. In 2004 about 9,000 ships reported to AMVER. Data, however, are not as easily accessible as they are from ICOADS.

To improve the geographical characterisation of emissions, Wang *et al.* (2008) used both AMVER and ICOADS datasets to create spatial proxies of traffic activities. AMVER, ICOADS and a combination of the two are available at http://coast.cms.udel.edu/GlobalShipEmissions/ as are the estimates of world's emissions from maritime transport provided by the authors.

AMVER and ICOADS data may be also used for the definition of an international waterway network, as in Wang *et al.* (2008).

An alternative way of drawing inferences about maritime traffic activities and their spatial distribution is to use the information on the origin/destination of freight and people carried by ships. Information of this type is available from different sources. In the U.S. such information is collected and published by the U.S. Army Corps of Engineers, which creates the Import Waterborne Data Bank on an annual basis (Wang *et al.*, 2010).

In Europe, traffic data are collected by the European Commission's EUROSTAT (http://epp.eurostat.ec.europa.eu), which asks each Member State to provide a summary of its annual transport activities. Data for each transport sector are freely available from http://epp.eurostat.ec.europa.eu/portal/page/portal/transport/data/database.

Additionally, information on traffic and emissions can be found as an output of funded research projects. As an example, the EX-TREMIS project (http://www.ex-tremis.eu) allows free access to the methodology adopted for the evaluation of emissions at a European level as well as to the outputs obtained.

A potential source of information for detailed ship activities in restricted areas may be the use of geostationary satellite observations. Geostationary satellites offer the possibility of continuously monitoring a certain area on Earth. They would therefore be very useful for the evaluation of ship activities around main ports. Schreier *et al.* (2010) used data from Meteosat-8 to analyse shipping routes around the west coast of Southern Africa. This represents a new and more sophisticated application, but at the moment seems less suitable for an extensive application.

2.1.3. Further information: emission factors

Emission factors are another important type of information for the estimation of emissions from ships.

Indeed, usually, the first step in the evaluation of emissions is the estimation of the fuel consumed by each ship (or fleet) on the basis of its activities. Specific fuel oil consumption (*SFOC*, measured in g/kWh) is therefore an important input to the appraisal. In IMO (2009) a possible estimation of SFOC is provided together with a discussion of the sources (Appendix 1, page 185). For auxiliary engines, a possible source of SFOC can be found in Oonk *et al.* (2003).

Once the fuel consumed has been calculated, it is possible to use emission factors to estimate the emission of different pollutants. In IMO (2009) emission factors have been derived from IPCC (2006) for CH_4, N_2O, CO_2 and from EMEP CORINAIR (Thomas *et al.*, 2002) for CO, NMVOC, CH_4, N_2O, SO_2, PM_{10}. For NO_x emissions they followed the IMO regulation. It also provides information on other pollutants such as refrigerants (HFCs, CFCs, HFC-22, R717), VOCs and PFCs.

Other sources of emission factors are Cooper (2003), Dalsoren *et al.* (2008) for black and organic carbon, Corbett *et al.* (2009) and IPCC (2006) for a discussion on the CO_2 emission factor.

In addition, for maritime traffic analysis it is very important to know the geographic location of main ports (to be directly imported in a GIS environment) and the distance by sea between them.

Port characteristics datasets may be found at the sources suggested by Wang *et al.* (2007a). Unfortunately, these datasets are no longer available online. A good source can found in shape file format (.shp) on http://www.evs-islands.com/search/label/download which contains World Port Index data.

For a more macroscopic analysis, information on distance along maritime routes can be found on several websites (see for example http://e-ships.net/dist.htm or the sea rates website http://www.searates.com/reference/portdistance/). However, these on-line tools give the port-to-port distance between two specific ports and therefore they are practically of no use when the distances between thousands of ports are required. A more useful system is the NetPas tool (http://www.netpas.net/), which allows multiple queries (unfortunately there is a limit of five queries per day in the free trial version).

Finally, the global fuel sales statistics are usually used to drive the estimation of the global impact of maritime traffic on air emissions. The International Energy Agency (IEA) and the Energy Information Administration (EIA) provide such data (see IMO, 2009). However, the reliability of the figures provided has recently been put into question. For this reason it is not currently recommended that they be used.

2.2. Concluding remarks

The evaluation of the total amount of emissions deriving from current and future shipping activities plays a central role in appraising possible strategies for the sustainability of the maritime transport sector. The analysis carried out in this chapter highlights the limitations of the current methodologies as well as the scarcity and limited availability of data concerning maritime transport activities. These limitations make the design and assessment of air emission reduction strategies a complex task for this sector. A precondition for an effective policy strategy to regulate air emissions is that they be estimated in terms of quantification and localisation. The analysis highlights the fact that the scientific debate is still open on the subject of estimating the air emissions from maritime transport.

A conclusion of this section is that there is at present no optimum source of information, in terms of accuracy, coverage and comprehensiveness. However, and this is key, different data sources may be used together in order to reduce their overall uncertainties. This consideration has received limited attention in the literature, due to the difficulties associated with accessing different types of data. Finally, potential new sources of information, as a result of the introduction of innovative technologies, are expected to provide benefits to the sector in the near future.

3. Reducing air emissions from ships: technological and policy options

The analysis carried out in the previous chapters shows the complexity of the current contribution of the maritime transport sector to global and local air emissions. The increasing environmental impacts of the sector call for the design of sector-based policy strategies to abate global and local air emissions. This task requires the combination of several policy options.

Which policy option is the most suitable depends on the particular circumstances such as the external costs under consideration and the social acceptability of the option in question. With regard to the external costs, in general terms the placing of monetary values on the externalities associated with transport, although not a necessary condition, has a number of distinct benefits for policy formulation.

The variety of policy instruments for reducing environmental impacts are usually classified into a set of broad classes, the most important of which are '*command and control*' instruments and '*economic incentive based*' instruments.

Conventional approaches to regulating the environment are often referred to as "command and control" regulations, since they allow relatively little flexibility in the means of achieving goals. Regulatory instruments (standards, permits, zoning, use restrictions, *etc.*) are policy instruments that governments use to change the behavior of different individuals by issuing acts, rules and directives. These are often, but not always, supported by the threat of sanction. Harmful environmental impacts are largely controlled through environmental legislation prohibiting the use of certain harmful substances, setting limits on emissions, enforcing certain technical standards, making producers responsible for their products such as waste, limiting certain activities in special areas such as nature reserves or car-free areas in cities, and controlling land use planning (Maler, K.,G., Vincent, J., R., 2003).

Economic instruments attempt to encourage individual behavior through market signals rather than through explicit directives regarding pollution control methods. Their main characteristic is, in simple terms, their ability to address the externalities (market failure) by providing a realistic evaluation of environmental services (Turner, K., R., Pearce, D., Bateman, I., 1993). Nevertheless, the policy dilemma on how to select the most appropriate option for the chosen objective can be supported by some selection criteria as shown in Table 4.

Table 4. Criteria for selection of pollution control instruments. Source: Perman (2003: 203).

Criterion	Brief description
Cost- effectiveness	Does the instrument attain the target at least cost?
Long run effects	Does the influence of the instrument strengthen, weaken or remain constant over time?
Dynamic efficiency	Does the instrument create continual incentives to improve products or production processes in pollution reducing ways?
Ancillary benefits	Does the use of the instrument allow a 'double dividend' to be achieved?
Equity	What implications does the use of an instrument have for the distribution of income or wealth?
Dependability	To what extent can the instrument be relied upon to achieve the target?
Flexibility	Is the instrument capable of being adapted quickly and cheaply as new information arises, as condition change, or as targets are altered?
Cost if user under uncertainty	How large are the efficiency losses when the instrument is used with incorrect information?
Information requirements	How much information does the instrument require that the control authority posses, and what are the costs of acquiring it?

The focus of this Report is on the cost effectiveness analysis whose basic criterion is the selection of the option which achieves a specified objective at the least cost. Typically, cost effectiveness analysis involves calculating a cost effectiveness ratio using the least-cost method, which holds the output constant and seeks the cheapest way to achieve it. Within a cost effectiveness analysis the impacts of different technical alternatives can be determined, but a comprehensive weighting is not undertaken. This method of analysis offers a ranking of regulatory options based on a "cost per unit of effectiveness" of each measure. The cost per unit of outcome achieved is usually the decisive criterion and it is only helpful if the benefit can be measured in one single physical unit (such as, for instance, 8% reduction in CO_2).

The literature distinguishes three different perspectives from which to consider the costs: the end users, society (as a whole) and government. The perspective of end users (this category includes companies, institutions, households) takes into account the costs directly related to the different options and distributed over the various actors.

A 'society as a whole' perspective considers the external benefits and implementation costs related to a policy. The cost-effectiveness analysis for climate change abatement options usually opts for the social perspective. The last perspective, the government one, takes into account the costs of implementation or government subsidies. However, all these perspectives have in common the central element of the cost effectiveness analysis, which is the direct expenditure involved in the implementation of the abatement option (Davidson, Van Essen, 2009). The direct expenditures include: capital costs (the sum total of one-off costs associated with the implementation of the abatement option (*Ibidem*); operating costs (the costs of making the option or the technology operational); regulatory costs (the costs of policy estimation, implementation and enforcement). A comprehensive approach should include: (i) the welfare effects of the overall costs of an option, such as the reduction of air pollutants, as ancillary benefits of an option to abate CO_2 emissions; (ii) the indirect effects due to the distortion arising in associated markets (labour or capital markets); (iii) the transaction and information costs.

The current policy actions available to abate air emissions and GHGs from maritime transport mainly concern the quality of fuel used and the technological options available. Market-based instruments such as emissions trading are under discussion at international level within the IMO. Furthermore, the inclusion of the maritime transport sector within the EU Emission Trading Scheme is on the EU strategy to address GHGs.

The following chapters give a detailed description of the technological options, their potential and their costs in abating air emissions from ships (Chapter 5), the international regulatory system in which regional and international environmental policy strategies are integrated, and the current international debate on such strategies (Chapter 6).

4. Abatement technologies: estimated performance and costs

The maritime transport sector has a higher inertia to possible change compared to other sectors. However, an increased awareness of the environmental impacts of the sector may represent the catalyst that leads shipping to move towards increased efficiency. In addition, the current period of economic uncertainty has led to a reduction in the profits of the ship companies' owners. The main driver of this phenomenon has been the unpredictable increase in fuel costs. In fact, the dependency on fossil fuels makes the maritime sector fragile. This is why new strategies and technologies to reduce ships' fuel consumption are now attracting the interest of the entire maritime community, as they attempt to reconcile the environmental and economic objectives related to fuel consumption. New technologies are now available, ready to use, and with proven results. These include air cavity systems, wind power, fuel additives, twin propellers, new propeller blades, recovering the waste gas heat and so on. All of these, together with the use of alternative "greener" fuels, can help reduce emissions of NO_x by up to 80%, PM by up to 90%, SO_x by up to 90% and CO_2 by up to 70% (IMO, 2009). The estimation of the costs of such technologies is fundamental to assessing the feasibility of their application in the sector. However, this task is complex due to the required additional information is. In general terms, the costs related to abatement technologies can be divided into capital (or investment) and operating costs. The capital costs include the construction, the manpower, the license fees, the delivery of the installation and all the expenditures accumulated in preparing the start-up of the installation. The operating costs relate to the annual expenditures. These include fixed expenditures such as the costs of maintenance and administration, and variable costs such as additional labour or increased energy requirements for operating the device. The average annual costs are calculated taking into account the investment costs, the fixed and variable operating costs and the normal technical lifetime of the installation. The unitary costs are calculated by relating the annual costs to the emissions abated. The cost effectiveness is calculated by dividing the annual cost of any measure by the annual emissions reduction attributable to that measure. Moreover, the costs related to abatement technologies vary depending on whether the vessel is new or retrofit.

The tables below (Tables 5 to 8) list the main technologies that could be used to reduce fuel consumption and pollutant emissions from ships. The different technologies are grouped into five categories depending on the specific sector in which they are used. These categories are (Wartsila, 2009): (i) Ship design; (ii) Propulsion; (iii) Machinery; (iv) Operation; and (v) Fuel. All the related possible strategies are included in each category. The main findings reported in IMO (2009) are provided for the estimation of the cost efficiency and the global CO_2 abatement potential of each option. The expected CO_2 abatement potential of options which are not estimated in the IMO report are taken from the Wartsila on-line catalogue[4] (2009) for the specific ship on which they are applied. All the estimates consider 2020 as a base year, a bunker fuel price of US$ 500/tonne and a 4% interest rate.

4 http://www.wartsila.com/. It is worth mentioning that this company is a global leader in complete lifecycle power solutions for the marine and energy markets.

Table 5. Cost efficiency and abatement potential for ship design related options

Ship Design		Cost efficiency (US$/tonne of CO_2)		Maximum CO_2 abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
Efficiency of scale	Max potential*	n.a.	n.a.	n.a.	4*
Reduce ballast	Max potential*	n.a.	n.a.	n.a.	7*
Lightweight construction	Max potential*	n.a.	n.a.	n.a.	7*
Optimum main dimension	Max potential*	n.a.	n.a.	n.a.	9*
Interceptor trip planes	Max potential*	n.a.	n.a.	n.a.	4*
Ducktail waterline extensions	Max potential*	n.a.	n.a.	n.a.	7*
Transverse thrusters openings	Lower potential	-145	-140	10.7	0.90
	Higher potential	-160	-160	53.1	4.20
Air cavity systems	Lower potential	-115	-90	7.5	0.90
	Higher potential	-150	-140	24.4	1.90
Machinery concept	Max potential*	n.a.	n.a.	n.a.	30*

*Source: Our estimations based on IMO (2009), Annex IV, pp. 265-286; *Wartsila (2009) refers to the abatement potential on a single ship on which the system is installed and not on the global emissions. The latter is reported by IMO (2009).*

Table 6. Cost efficiency and abatement potential for propulsion related options

Propulsion		Cost efficiency (US$/tonne of CO_2)		Maximum CO_2 abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
Wing thrusters	Max potential*	n.a.	n.a.	n.a.	8*
CRP propulsion	Max potential*	n.a.	n.a.	n.a.	10*
Propeller performance monitoring	Lower potential	-135	-130	5.4	0.40
	Higher potential	-160	-160	42.5	3.40
Propeller/rudder upgrade	Lower potential	90	120	19.7	1.60
	Higher potential	-80	-70	58.5	4.70
Propeller upgrade (winglet/nozzle)	Lower potential	530	600	1.3	0.10
	Higher potential	-90	-80	11.2	0.90
Propeller boss cap fins	Lower potential	-155	-150	42.9	3.40
	Higher potential	-155	-155	53.1	4.20
Variable speed operation	Max potential*	n.a.	n.a.	n.a.	5*
Towing kyte	Lower potential	-85	-75	37.1	3.00
	Higher potential	-135	-130	100.9	8.00
Pulling thruster	Max potential*	n.a.	n.a.	n.a.	10*
Seawater lubricated stern Tube Bearing System	Max potential*	n.a.	n.a.	n.a.	2*

*Source: Our estimations based on IMO Annex IV, pp. 265-286; *Wartsila (2009) refers to the abatement potential on a single ship on which the system is installed and not on the global emissions. The latter is reported by IMO (2009).*

Table 7. Cost efficiency and abatement potential for machinery related options

Machinery		Cost efficiency (US$/tonne of CO_2)		Maximum CO_2 abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
Shore-Side Electricity	Max potential*				20**
Diesel electric machinery	Max potential*	n.a.	n.a.	n.a.	20*
Water Injection	Max potential*	n.a.	n.a.	n.a.	2*
Selective catalytic reduction	Max potential*	n.a.	n.a.	n.a.	n.a.
Waste heat recovery	Max potential*	n.a.	n.a.	n.a.	10*
Main engine tuning	Lower potential	405	470	1	0.10
	Higher potential	-90	-85	7.8	0.60
Common rail upgrade	Lower potential	25	45	1.1	0.10
	Higher potential	-125	-120	5.3	0.40
Shaft power meter	Lower potential	70	115	5.4	0.40
	Higher potential	-105	-95	21.3	1.70
Fuel consumption meter	Lower potential	245	330	5.4	0.40
	Higher potential	-60	-40	21.3	1.70
Low energy/Low-heat lighting	Lower potential	385	440	0.1	0.00
	Higher potential	-95	-85	0.6	0.00
Power management	Lower potential	100	130	0.1	0.00
	Higher potential	-130	-125	0.7	0.10
Speed control pumps and fans	Lower potential	210	250	2.1	0.20
	Higher potential	-90	-80	10.6	0.80
Solar Power	Max potential*	n.a.	n.a.	n.a.	4*

*Source: Our estimations based on IMO (2009), Annex IV, pp. 265-286; *Wartsila (2009) refers to the abatement potential on a single ship on which the system is installed and not on the global emissions. The latter is reported by IMO (2009); ** This percentage refers to the CO_2 abated in the production of electrical energy while the ship is in port (the estimate varies by country).*

Table 8. Cost efficiency and abatement potential for operation related options

Operation		Cost efficiency (US$/tonne of CO_2)		Maximum CO_2 abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
Turnaround time in port	Max potential*	n.a.	n.a.	n.a.	10*
Propeller brushing	Lower potential	-75	-65	25.4	2.00
	Higher potential	-125	-120	62.8	5.00
Increased frequency of propeller brushing	Lower potential	-160	-130	6.2	0.50
	Higher potential	-160	-160	36.7	2.90
Hull coating type 1	Lower potential	-115	-105	6.6	0.50
	Higher potential	-150	-150	26.1	2.10
Hull coating type 1	Lower potential	-40	-15	13.2	1.10
	Higher potential	-140	-130	65.3	5.20
Hull brushing	Lower potential	-95	-65	12.7	1.00
	Higher potential	-155	-150	125.6	10.00
Underwater hydroblasting	Lower potential	-80	-35	12.7	1.00
	Higher potential	-155	-150	125.6	10.00
Dry-dock full blast	Lower potential	-155	-150	8.2	0.60
	Higher potential	-160	-160	16.1	1.30
Hull performance monitoring	Lower potential	-45	-45	6.2	0.50
	Higher potential	-150	-150	61.2	4.90
Weather routeing	Lower potential	-130	-100	1.2	0.10
	Higher potential	-165	-160	46	3.70
10% speed reduction	The entire fleet	80	135	98.7	7.90
Vessel trim	Max potential*	n.a.	n.a.	n.a.	5*
Autopilot upgrade/ adjustment	Lower potential	-140	-140	5.4	0.40
	Higher potential	-160	-160	31.9	2.50
Energy saving operation awareness	Max potential*	n.a.	n.a.	n.a.	n.a.

*Source: Our estimations based on IMO (2009), Annex IV, pp. 265-286; *Wartsila (2009) refers to the abatement potential on a single ship on which the system is installed and not on the global emissions. The latter is reported by IMO (2009).*

A comprehensive and detailed description of the different technologies is provided in Annex A. For each technology/strategy, information is given of the types of ship to which it can be applied (following a rough classification of Tankers, Containers, Ro-Ro, Ferries and Off-Shore Support Vessels), the possibility for existing ships to adopt it, an indication of the amount of time required to recover the starting investment (*i.e.* the payback time) and an estimate of the potential fuel/emission reduction rate.

With regard to the fuel category, marine fuels are generally classified as fuel oil or distillate. Fuel oil refers to residual fuel oil manufactured at the "bottom end" of an oil refining process. The most commonly used term for this kind of fuel is heavy fuel oil (HFO). It is the heaviest of the marine fuels and contains significant amounts of sulphur. Its average sulphur content is 2.7% mass, which is 90% higher than conventional diesel or petrol (Butt, 2007). However, for economic reasons, it is the most widely used (Endresen *et al.*, 2003).

Figure 4 shows that marine fuel has high sulphur content. Distillate fuel can be divided into marine gas oil (MGO) and marine diesel oil (MDO). MGO is a light distillate fuel containing light aromatic hydrocarbons and no residual components. MDO can contain residual fuel oil and is a heavier distillate (Wilde *et al.*, 2007).

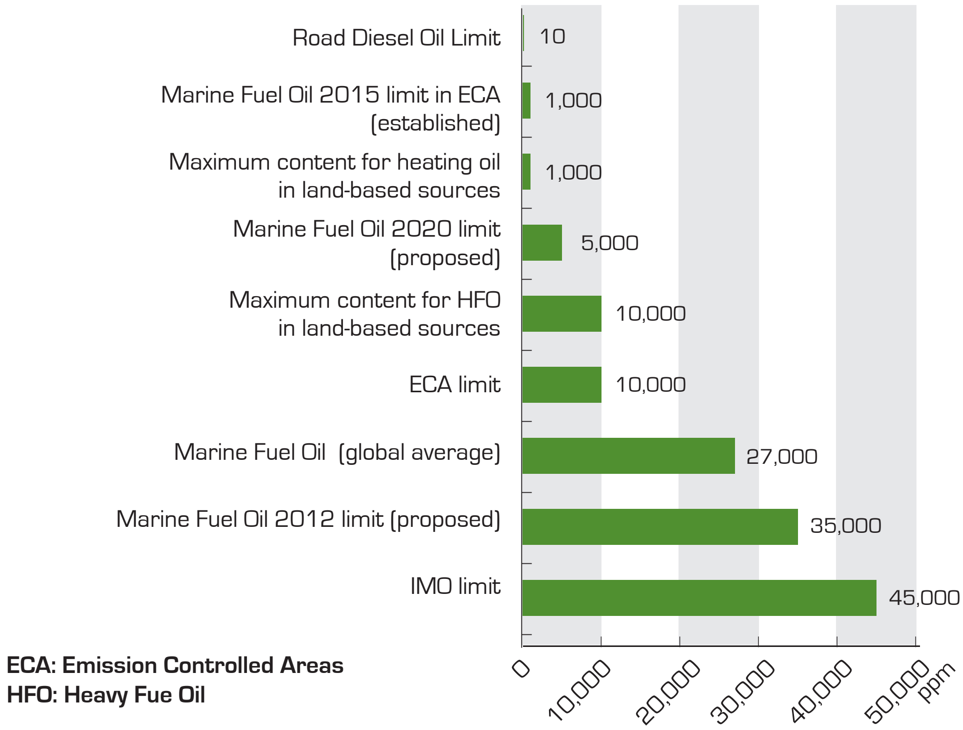

Figure 4. Sulphur content of fuels – Our elaboration on data from EEB (2008)

Since sulphur emissions are proportional to the sulphur content in the fuel, the easiest way to reduce SO_x emissions is to use fuel with lower sulphur content. Three alternatives are available:

(i) Low-sulphur fuels, which contains less than 10,000 parts per million (ppm) of sulphur, 1.0% (or even 5,000 in some cases);

(ii) Ultra-low sulphur fuels, which contains less than 300 ppm sulphur, 0.03%;

(iii) Alternative fuels (biofuels, natural gas and hydrogen);

(iv) Distillate fuel. Distilling fuel reduces its SO_x by 80% and its PM by 35%. It is estimated that the cost of introducing distillates in the market is US$ $250x10^9$ and the time required is about 20 years. Distillate fuels, however, usually lead to an increase in CO_2 emissions (up to 20%);

(v) Water emulsified fuel. The water in fuel is believed to reduce the combustion temperature which reduces the nitrogen dioxide (NO_2) production and alters combustion to inhibit soot, hydrocarbons and PM formation (Armas *et al.*, 2005).

In Wang *et al.* (2007b) a cost-effectiveness analysis was carried out to assess the effect of introducing different SO_2 control strategies on U.S. commercial fleet travelling in the European SO_x Emission Control Areas (SECA), *i.e.* the North and Baltic Seas, and in the hypothetical U.S. West Coast Sea. Three strategies were considered: i) the use of a prescriptive standard for the use of low-sulphur fuel (considered to have 1.5% sulphur content), ii) the application of a performance-based strategy (using scrubbers) and iii) the application of a market-based strategy.

In order to account for uncertainties in the evaluations of the three strategies, seven scenarios were defined. Considering abatement potential, the most convenient strategy appeared to be the market-based one (cost-effectiveness in the range US$ 1,200-1,500/tonne SO_2 abated) in comparison with the performance-based (US$ 1,200-2,900/tonne SO_2 abated) and the prescriptive strategies (US$ 1,300-3,000/tonne SO_2 abated). However, the performance-based strategy was considered the easiest to apply (*e.g.* emission targets were met even when only one out of ten ships used scrubbers on board).

Indeed, the application of a prescriptive standard of low-sulphur fuel requires that the vessels be re-equipped with fuel storage and delivery systems and that special controls be incorporated into distribution schemes. In addition, the different fuel oil grades may require the use of different lubricating oil grades and technical modifications of fuels storage and handling systems on board (Schmid and Weisser, 2005).

In Bosh *et al.* (2009) another study on this topic was carried out. Results are reported in Table 9 in terms of estimated costs of fuel shift per fuel tonne or per energy produced in 2020 (using as a reference a cost of US$420/tonne of fuel with 2.94% sulphur content, as in Avis and Birch, 2009).

In addition, it gives an estimation of the corresponding cost of SO_2 abatement.

Table 9. Cost for fuel shifting in 2020 both with respect to the tonnes of fuel and to the energy produced

Option (%S in fuel)	Low Cost ($/tonne)	High Cost ($/tonne)	Low Cost (k€$_{2005}$/PJ)	High Cost (k€$_{2005}$/PJ)	Low SO_2 abat. (€/tonne)	High SO_2 abat. (€/tonne)
Fuel Shift (2.94→1.5)	20	20	359	359	510	510
Fuel Shift (2.94→1)	30	30	538	538	568	568
Fuel Shift (2.94→0.5)	120	170	2,152	3,049	1,806	2,559
Fuel Shift (2.94→0.1)	280	330	4,510	5,370	3,621	4,268
Fuel Shift (0.5→0.1)	160	160	2,753	2,753	14,692	14,692

Source Bosch et al. (2009), Table 7.2, page 38

Table 10. Cost effectiveness of fuel switching for SO_x reduction measures per €/tonne abated

Technologies	Small Vessel (€/tonne)	Medium Vessel (€/tonne)	Large Vessel (€/tonne)
Fuel Shift: 2.7%→1.5%	1,900	1,900	1,900
Fuel Shift: 2.7%→0.5%	1,300	1,300	1,300

Source: data are in accordance with those reported in EMTEC (2005b), Rahai and Hefazi (2006), Lovblad and Fridell (2006) and IIASA (2007). Note that 2.7% S fuel is the sulphur concentration in the fuel.

4.1. Energy Efficiency Design Index

A specific section is reserved for the **Energy Efficiency Design Index** for new ships (IMO, 2009c).

With its MEPC.1/Circ.683 Circular, the International Maritime Organization (IMO) defined temporary guidelines for the development of a ship's energy efficiency management plan and the calculation of the Energy Efficiency Design Index for new ships.

The definition of a methodology derived from the necessity to establish a reference measure of energy efficiency for new ships which would be capable of stimulating innovation and technical development in this field.

The idea of establishing a mandatory design index was proposed to the IMO for the first time by Denmark at the 57^{th} session of the Marine Environment Protection Committee (MEPC) in 2008.

The definition of a single index for all categories of ships is not straightforward and therefore the methodology defined hitherto is only temporary, and will need to be further refined. In its present form, the methodology takes ten vessel categories into consideration (passenger ships, dry cargo carriers, gas tankers, tankers, container ships, ro-ro cargo ship vehicle carriers, ro-ro cargo ship volume carriers, ro-ro cargo ship weight carriers, general cargo ships and ro-ro passenger ships).

The Energy Efficiency Design Index (EEDI) is defined as a measure of a ship's CO_2 efficiency and is calculated by means of a specific formula (IMO, 2009).

The index allows for the definition of a threshold ($EEDI_{required}$) above which a new ship cannot be approved, and provides an instrument which helps the ship's manufacturer to calculate how and how much the overall efficiency should be increased.

The IMO Energy Efficiency Design Index is an example of the international system which regulates maritime transport and of how the environment issue is integrated within this framework. Indeed, a legislative intervention to control air emissions from international maritime transport must be integrated into a complex international regulatory system that governs this sector[5].

The next chapter gives an overview of this system and provides the main elements of its legal and political structure.

5 For additional information see the paragraph 5.1

5. The international framework for regulating air emissions from ships

The International Convention for the Prevention of Pollution from Ships (MARPOL 1973/1978) represents the main IMO Convention currently in force regarding the protection of the marine environment.

The Convention's principle articles deal mainly with jurisdiction and powers of enforcement and inspection. More detailed anti-pollution regulations are given in the annexes, which can be adopted or amended by the Marine Environment Protection Committee (MEPC) of the IMO with the acceptance of a number of parties representing 50% of the GT of the world's merchant fleet[6].

Six annexes of the Convention cover the various sources of pollution from ships and provide an overarching framework for international objectives but, without ratification and implementation by sovereign states, they are not sufficient to protect the marine environment from waste discharges[7].

A State that becomes party to MARPOL must accept Annexes I and II. Acceptance of Annexes III-VI is voluntary.

All six have been ratified by the requisite number of nations.

Each signatory nation is responsible for enacting domestic laws to implement the Convention and effectively pledges to comply with the Convention, its annexes, and the related laws of other nations[8].

The MARPOL 1973/1978 Convention represents the most relevant regulation on marine pollution.

In 1997, air pollution was included in Annex VI, setting limits on sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions from ship exhausts and prohibiting deliberate emissions of ozone-depleting substances.

Annex VI was ratified by 60 contracting States with 84.04% of the world's merchant shipping tonnage[9]. It entered into force on 19 May 2005[10].

In 2008 Annex VI was amended (MEPC 58/23/Add.1). The revised text, which establishes more stringent emission requirements for ships that operate in designated coastal areas where air quality problems are acute, entered into force on 1 July 2010.

Amendments are normally adopted within MEPC's sessions or by a Conference of the Parties to MARPOL[11]. Annex VI amendments became effective following the tacit acceptance procedure[12], which is defined by Article 16(2)(d) of the 1973 Convention.

The IMO emission standards are commonly referred to as Tier I-III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by the Annex VI amendments adopted in 2008, as follows: 1997 standards applied retroactively to new engines

6 Annex I deals with regulations for the prevention of pollution by oil. Annex II details the discharge criteria and measures for the control of pollution by noxious liquid substances carried in bulk. Annex III contains general requirements for issuing standards on packing, marking, labelling, and notifications for preventing pollution by harmful substances. Annex IV contains requirements to control pollution of the sea by sewage. Annex V deals with different types of garbage, including plastics, and specifies the distances from land and the manner in which they may be disposed of. Annex VI sets limits on sulphur oxide, nitrogen oxide, and other emissions from marine vessel operations and prohibits deliberate emitting of ozone-depleting substances.

7 Annex I – Oil; Annex II - Noxious Liquid Substances carried in Bulk; Annex III - Harmful Substances carried in Packaged Form; Annex IV – Sewage; Annex V – Garbage; Annex VI - Air Pollution

8 For further information on this topic see A.K. Tan, Vessel-source Marine Pollution: The Law and Politics of International Regulation (Cambridge Studies In International and Comparative Law), Cambridge University Press, 2006, pp. 107-75.

9 Updates about the Status of the Convention are available on http://www.imo.org/conventions/mainframe.asp?topic_id=247

10 The "1997 Protocol" to MARPOL, which includes Annex VI, was going to become effective 12 months after being accepted by 15 States with not less than 50% of world merchant shipping tonnage. On 18 May 2004, Samoa deposited its ratification as the 15th State (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden and Vanuatu). On that date, Annex VI was ratified by States with 54.57% of world merchant shipping tonnage. Accordingly, Annex VI entered into force on 19 May 2005.

11 See http://www.imo.org/Conventions/contents.asp?doc_id=678&topic_id=258.

12 The amendments entered into force six months after the deemed acceptance date, 1 January 2010. This process would have not been concluded if, within the acceptance period, an objection had been communicated to the Organization by not less than one third of the Parties or by the Parties the combined merchant fleets of which constitute not less than 50% of the GT of the world's merchant fleet.

greater than 130kW installed on vessels constructed on or after 1 January 2000, or which underwent a major conversion after that date. This regulation also applied to fixed and floating rigs and to drilling platforms[13]. Annex VI amendments adopted in October 2008 introduced: 1) new fuel quality requirements starting from July 2010; 2) Tier II and III NO_x emission standards for new engines; 3) Tier I NO_x requirements for pre-2000 engines.

Annex VI defines two sets of emission and fuel quality requirements: 1) global requirements, and 2) more stringent requirements applicable to ships in Emission Control Areas (ECA).

An Emission Control Area can be designated for SO_x and PM, for NO_x, or for all three types of emissions from ships, subject to a proposal from a Party to Annex VI.

According to Regulation 12 of MEPC 58/22 "an Emission Control Area shall be any sea area, including any port area, designated by the Organization", in which stringent international emission standards will apply to ships. Existing Emission Control Areas include:

- The Baltic Sea (for SO_x; adopted in 1997 and entered into force on 19 May 2006);
- The North Sea, which also includes the English Channel (for SO_x; adopted in 2005 and entered into force on 22 November 2007);
- The North American ECA, including most of the US and Canadian coast (for NO_x & SO_x; adopted in 2010 and to entered into force in 2011).

The first two areas, designated for SO_x only, are commonly known as SECAs. The North American ECA was approved by the IMO during the MPEC 60 (MEPC 60/22, Annex 11) on 26 March 2010 and will enter into force on 1 August 2011.

The revised MARPOL Annex VI should guarantee a progressive reduction in SO_x emissions from ships on a global scale as well as within SECAs. The global sulphur cap shall be initially reduced to 3.5% (from the current 4.5%), effective from 1 January 2012, then progressively to 0.5%, effective from 1 January 2020[14] (in the meantime a feasibility review should be finalised by 2018[15]).

Since 1 July 2010 limits have been reduced to 1.0% in SECAs (from the current 1.5 %) and they will be further reduced to 0.1 %, effective from 1 January 2015[16].

The IMO also agreed on a progressive reduction in NO_x emissions from marine engines, defining the most stringent controls on Tier III marine diesel engines installed on ships constructed on or after 1 January 2016, operating in ECAs[17].

It also has to be briefly mentioned that Regulation 12 of Annex VI prohibits deliberate emissions of ozone depleting substances, including halons and chlorofluorocarbons (CFCs). New installations containing ozone-depleting substances are prohibited on all ships. But new installations containing hydro-chlorofluorocarbons (HCFCs) are permitted until 1 January 2020.

According to the 2008 amendments, as of 1 July 2010 vessels should also keep on board a list of equipment containing ozone depleting substances and a Record Book in which ozone depleting substances resulting from certain operations are instantly recorded, including, for example, the full or partial recharging of equipment containing ozone depleting substances[18].

13 Except for emissions directly related to exploration and/or handling of sea-bed minerals.

14 MEPC 58/23/Add. 1 Annex 13, Regulation 14, paragraph 1.

15 MEPC 58/23/Add. 1 Annex 13, Regulation 14, paragraph 8.

16 MEPC 58/23/Add. 1 Annex 13, Regulation 14, paragraph 4.

17 MEPC 58/23/Add. 1 Annex 13, Regulation 14, paragraph 5.1.

18 According to MEPC 58/23/Add. 1 Annex 13, Regulation 12, paragraph 7:"Entries in the Ozone Depleting Substances Record Book shall be recorded in terms of mass (kg) of substance and shall be completed without delay on each occasion, in respect of the following: 1 recharge, full or partial, of equipment containing ozone depleting substances; 2 repair or maintenance of equipment containing ozone depleting substances; 3 discharge of ozone depleting substances to the atmosphere: 3.1 deliberate; and 3.2 non-deliberate; 4 discharge of ozone depleting substances to land-based reception facilities; and 5 supply of ozone depleting substances to the ship."

5.1. International mechanisms for reducing maritime transport emissions: the current debate

In order to fully deliver its mandate as stipulated in Article 2.2 of the Kyoto Protocol to the UNFCCC[19], the MEPC also analysed the potential constraints of a new legally binding instrument addressing GHG emissions from international shipping[20]. In particular, the Committee voiced concerns about the compatibility between the Kyoto Protocol's "common but differentiated responsibilities" approach, according to which legally binding emissions reduction commitments should apply only to Annex I Parties, and the Paris MoU's "no more favorable treatment" concept, according to which relevant legal instruments (conventions) should apply also to ships which fly the flag of a State which is not a Party to that convention[21]. To ascertain whether there is a potential conflict between two different international treaties it has to be established whether or not they somehow regulate the same subject in a contradictory way.

In the Copenhagen discussions the conflict between these two principles was highlighted. In a statement by the Executive Secretary of the UNFCCC Secretariat, Mr. Yvo de Boer, a solution was proposed: "[…] A global cap on bunker fuels would be in line with the "equal treatment" principle of the IMO". Using the obtained revenues to assist developing countries in addressing climate change would be in line with the provisions of the United Nations Framework Convention on Climate Change. The amounts that could be generated by maritime transport in reducing its carbon footprint are substantial with estimates over four billion US dollars per year" (Buhaug *et al.,* 2009). A second way of combining both principles is to differentiate commitments for Annex I and non-Annex I countries without relying on the nationality of ships.

A solution could be to differentiate responsibilities according to the route of the vessels or the ship size (Faber and Rensema, 2008). A justification for differentiated responsibilities in maritime policy is that the policy should not interfere with the growth potential of developing countries.

As some countries are dependent on maritime transport for their exports, and countries are thought to develop by periods of export-led economic growth, global coverage of the described policies could lead to lower economic growth (Faber and Rensema, 2008). Kågeson (2008) highlights that it may not be possible to achieve complete global coverage of an international maritime emission trading scheme, as support from developing countries might be limited. He therefore envisages three possible stages of implementation: Firstly the set-up of a scheme by the IMO and the UNFCCC that is open for voluntary participation by States and ports, and secondly, a scheme that covers all traffic in the ports of Annex I countries, which can finally be extended to a scheme covering all maritime traffic on a global level.

The same could be applied on the basis of a tax or a levy system, although careful analysis of the effects is needed as a major threat to the environmental effectiveness of these systems is carbon leakage due to incomplete coverage. For the voluntary sectoral crediting option, this is not an issue.

The debate is still open. However, within the evaluation of the best possible IMO regulatory framework on GHG emissions from ships, in particular CO_2, Parties already agreed on a list of principles[22] to be adhered to:

1. Effective contribution to the reduction of total GHGs;
2. Binding and equally applicable to all Flag States in order to avoid evasion;
3. Cost-effectiveness;

19 Art. 2.2 of the Kyoto Protocol to the UNFCCC: "The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively".

20 This discussion has been pushed forward by the publication of the "Second IMO GHG Study 2009" (update of the 2000 IMO GHG Study) which has been prepared on behalf of the IMO by an international consortium led by MARTINEK. This study set out a comprehensive overview of policy options for the reduction of emissions, including a Maritime Emissions Trading Scheme, seen as "cost-effective policy instruments with high environmental effectiveness".

21 http://www.parismou.org/upload/pdf/MOU,%20incl.%2031st%20%20Amendment%20editorial%20revised.pdf

22 MEPC 57/WP.8

4. Limitation, or at least, effective minimisation of competitive distortion;

5. Sustainable environmental development without penalising global trade and growth;

6. Goal-based approach and not a prescriptive specific method;

7. Supportive of promoting and facilitating technical innovation and R&D in the entire shipping sector;

8. Accommodating to leading technologies in the field of energy efficiency;

9. Practical, transparent, fraud-free and easy to administer

The MEPC has been invited by the Parties to take concrete action and to deliver its mandate, as stipulated in Article 2.2 of the Kyoto Protocol, by preparing a legal framework to be adopted in the immediate future. However, the absence of new legally binding commitments as a result of COP15 has prolonged the abovementioned discussion until MEPC 60 and 61. Even though important steps forward have been made by the Parties for the adoption of a final text amending Annex VI, the process is still pending.

At present, the option which meets with most Parties' approval is the establishment, within Annex VI, of a mandatory **Energy Efficiency Design Index (EEDI**). Within MEPC 58 and 59, Parties adopted a list of guidelines for calculation and trial purposes and agreed on the fact that EEDI should be comprised of the following three components for better enforcement and compliance: (i) requirements (the EEDI should be calculated for each new ship following IMO guidelines), (ii) verification and certification (ships should be subject to surveys for verification of their compliance with the EEDI's requirements), and (iii) State Port control (ships may be subject to inspection by the Authority of the Parties when entering their ports or offshore terminals).

However, no amendment has so far been approved and the EEDI can currently only be adopted on a voluntary basis. During the latest MEPC 61, Parties debated about whether to get the Secretary-General to circulate proposed amendments to MARPOL Annex VI in order to make the EEDI mandatory, but no consensus about how to proceed on this issue was reached. However, progress on this is expected to be made in the Committee's next session.

One of the reasons for which this option was not unanimously approved is that, according to some of the Parties, this solution might not cover all the aspects required for a future IMO GHG regulatory framework.

To address GHG emissions from ships, Market-Based Measures (MBM) are also currently under discussion within the IMO. The discussion centres on several options.

At the MEPC60 it has been established an Expert Group to evaluate the several proposals of possible MBM presented to the Committee. The Expert Group has analysed ten proposals: 1) An International Fund for GHG from ships (GHG Fund) proposed by Cyprus, Denmark, the Marshall Islands, Nigeria and IPTA; 2) Leveraged Incentive Scheme (LIS) to improve the energy efficiency of ships based on the international GHG fund proposed by Japan; 3) Achieving reduction in GHG from ships through Port State arrangements utilizing the ship traffic, energy and environment model, STEEM proposal by Jamaica; 4) the United States proposal to reduce GHG emissions from shipping, the Ship Efficiency and Credit Trading (SECT); 5) the Vessel Efficiency System (VES) proposal by World Shipping Council; 6) the Global emission trading System (ETS) for international shipping proposal by Norway; 7) Global Emission Trading System (ETS) for international shipping proposal by the United Kingdom; 8) further elements for the development of an Emission Trading System (ETS) for international Shipping proposal by France; 9) Market-Based Instruments: a penalty on trade and development proposal by Bahamas; 10) A rebate Mechanism for A market Based instruments for international shipping proposal by IUCN (IMO, 2010).

Each proposal has been assessed considering nine criteria: (i) environmental effectiveness; (ii) the cost effectiveness of the proposed MBM and impacts on trade and sustainable development; (iii) potential impacts on innovation and technological change; (iv) practical feasibility of implementing the proposed MBM; (v) the need of technology transfer to, and capacity building within , developing countries; (vi) the MBM proposal's relation with other relevant conventions; (vii) potential additional burdens, and the legal aspects for the national Administrations by implementing the proposed

MBM; (viii) the potential additional workload, economic burden , and operational impact for individual ships, the shipping industry and the maritime sector; (ix) the MBM's compatibility with the existing enforcement and control provisions under the IMO legal framework (IMO, 2010). The results of this analysis was discussed during the last MEPC 61 and the Committee set out the Terms of Reference for an inter-session Meeting of the Working Group on GHG Emissions from Ships, to be held in March 2011. The outcomes of the meeting will be presented and discussed at the next MEPC 62 in July 2011.

In conclusion, although the sector has a significant abatement potential, meaning that environmental gains can be realised, there are some challenges that need to be overcome in order to make such a policy successful. These challenges include deciding on a method to allocate ship emissions to countries, diminishing the risk of carbon leakage, and designing a policy that is administratively and politically feasible with respect to allowance distribution and treatment of the great variety in ship type, size and usage. A global policy could overcome most of the above-mentioned challenges.

6. The EU policy on air and GHG emissions from international shipping

An EU strategy to reduce and regulate atmospheric emissions from ships was available in November 2002, covering emissions leading to both air pollution and climate change[23]. However, only the strategy related to air pollution from ships became a concrete action with, for example, a directive regulating the sulphur content of marine fuel which came into force in August 2005[24].

Indeed, European Union legislation establishes a set of rules which aim to reduce sulphur oxide emissions from maritime transport. In particular, Directive 1999/32/EC[25], which relates to a reduction in the sulphur content of certain liquid fuels, has set the first sulphur limits for marine distillate oil used in EU territorial waters.

This Directive extended the scope of the previous Directive 93/12/EEC on the reduction of sulphur dioxide emissions to cover certain liquid fuels derived from petroleum and used by seagoing ships. Recently, Directive 2005/33/EC[26] extended the scope of Directive 1999/32/EC to all petroleum-derived liquid fuels used by ships operating within Member States' waters.

It provides for innovative measures such as the abolition of existing derogations for marine gas oils, the enforcement of a 1.5% limit on sulphur content in Emission Control Areas as defined by the International Maritime Organization, the application of the same limit to all passenger ships operating on scheduled services to or from any Community port, the requirement for all ships at berth in Community ports to use a fuel with a sulphur content not exceeding 0.1%, and the permission to use approved emission abatement technologies as an alternative to using low-sulphur marine fuels.

With regard to GHG emissions, the European Commission Communication towards Copenhagen COP15[27] sets out the core legislative actions which have been taken on a European scale in order to address emissions from maritime transport.

23 http://ec.europa.eu/environment/air/transport/index.htm
24 EU (2005) Directive 2005/33/EC of the European Parliament and of the Council.
25 OJ L 121, 11.5.1999
26 OJ L 191, 22.7.2005
27 COM(2009) 39 final, Brussels, 28.1.2009, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *Towards a comprehensive climate change agreement in Copenhagen.*

In this document the Commission set out concrete proposals on how to achieve successful results within international climate change negotiations in Copenhagen and beyond.

In particular, this Communication identified three core challenges, namely targets and actions, financing, and the building of an effective global carbon market. Within the definition of new commitments and practical solutions for achieving them, the Commission stated that "*to have a reasonable chance of staying below the 2°C threshold, global GHG emissions must be reduced to less than 50% of 1990 levels by 2050…Developed countries must lead in meeting this global goal and demonstrate that a low-carbon economy is possible and affordable*".

Concerning emissions from international aviation and maritime transport, the Commission expected a global settlement to be agreed in Copenhagen for reducing the climate impact of these sectors below 2005 levels by 2020 and below 1990 levels by 2050.

Market-based measures, including emissions trading, are seen as a possible solution that could ensure emission reduction.

The Commission stressed that both the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) have the responsibility to conclude the process by the end of 2010. The Commission agreed on the fact that, if no agreement is reached between the ICAO and the IMO after this deadline, "*emissions from international aviation and maritime transport will be counted towards national totals under the Copenhagen agreement which will ensure comparable action by all developed countries.*" The EU has included CO_2 emissions from aviation within the EU ETS[28].

Regarding maritime transport, the Commission asserted: "*several market-based measures are currently being examined. If no effective global rules to reduce GHG emissions from this sector can be agreed upon, the EU should agree its own measures.*" (COM(2009) 39 final).

The above-mentioned communication was published on 28 January 2009 following the approval of the EU Climate Change package, which was

28 Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009, No L 140.

adopted by the European Parliament in December 2008. This package has been designed to achieve the EU's overall environmental target of a 20% reduction in greenhouse gases and a 20% share of renewable energy in the EU's total energy consumption by 2020[29].

Regarding the EU's 20% unilateral commitment it should be mentioned that, in December 2008, the European Council expressed its intention to increase this target to 30% within the framework of a global agreement to be reached in Copenhagen[30].

Analysing the post-Copenhagen international climate policy, the European Commission has recently confirmed its ambition to increase its reduction commitment to 30% provided that other developed countries do the same and developing countries start contributing in proportion to their responsibility and capability[31]. However, according to the Commission, "*at present the conditions set for stepping to 30% have not been met*"[32]. Therefore the option for moving to 30% should be suspended in anticipation of the right conditions.

In addition, on 26 May 2010 the European Commission published the Communication COM(2010) 265 final "Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage" in which it confirms that *"the EU will continue to pursue an international agreement through the IMO and the UNFCCC. As agreed under the climate and energy package, the EU will take steps to move forward if no such agreement has been agreed by 31 December 2011"*.

29 COM(2008) 30 final, Brussels, 23.1.2008, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 20 20 by 2020. *Europe's climate change opportunity*.

30 Presidency conclusions, Brussels European Council, 11 and 12 December 2008, 17271/1/08 REV 1, CONL 5

31 See COM(2010) 265 final, Brussels, 26.5.2010, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage*.

32 COM(2010) 86 final, Brussels, 9.3.2010, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *International climate policy post-Copenhagen: Acting now to reinvigorate global action on climate change*.

With regard to the inclusion of maritime transport in the EU ETS, in order for the maritime transport sector to become more environmentally friendly, the flexible nature of the EU ETS provides a definite window of opportunity, without placing an unnecessarily heavy burden on the sector (as can be expected from traditional command-and-control measures).[33]

Reducing GHG emissions from the maritime transport sector by means of inclusion in the EU ETS is interesting mainly because of the opportunities that the scheme offers to reduce emissions from the maritime sector, while allowing for flexibility in how to achieve this goal.

It has to be taken into account that trading and other transaction costs could place a large burden on small emitters such as single ships, making trading inefficient. Another threat to the functioning of the EU ETS is that of incomplete information or insecurity about future policy decisions, which can lead to volatility and investment risk in the carbon market.

A threat for the maritime sector is loss of competitiveness for companies that don't fall under the scheme.

In contrast to the conclusions drawn from the external features of the EU ETS, the internal features of the maritime shipping sector do not lend themselves favourably to inclusion in the scheme.

Although the sector has a significant abatement potential, meaning that environmental gains can be realised, and large ships are already obliged to hold bunker notes with information about bunker fuel sold, there are some challenges that need to be overcome in order to make membership of the scheme a success.

First and foremost, the participating countries need to decide on an allocation method, which raises political issues and has been the major bottleneck for over a decade in the international debate.

33 A number of studies comparing market-based and command-and-control instruments for different pollutants found that, in all cases, the cost of achieving the same reduction in pollution are between 1.72 and 22 times higher for command-and-control instruments (Tietenberg, 2003). The previous chapter provides a thorough comparison of market-based and command-and-control policy instruments.

The mobile nature of the sector creates a risk of carbon leakage, which is a major concern for the environmental effectiveness of the policy and needs to be addressed with great care.

In addition, there are administrative difficulties due to the fact that the ships vary considerably in size, type and use. This means that deciding on the specific policy design, mainly with respect to the distribution of allowances (grandfathering based on an historic or benchmark approach, or auctioning), will face the challenge of getting all stakeholders to agree while still coming up with an ambitious policy.

6.1. Legal constraints on EU environmental policy regulation of air emissions from ships

Developing a regional (European) Emission Trading Scheme for international shipping is a challenging task given the constraints which regulate the international legal framework of the maritime sector. Indeed, any EU environmental policy regulating air emissions from maritime transport has to comply with the International Law of the Sea and, in particular, with the United Nations Convention on the Law of the Sea 1982 (UNCLOS) to which the EU is signatory.

The EU, as any other signatory State having a coastline, is entitled under international law to take certain limited steps to protect its own interests within the world's oceans. UNCLOS recognises four main zones of varying Coastal States' jurisdiction: (i) internal waters – bays, ports and similar enclosed areas of the sea; (ii) territorial waters - extending 12 miles seaward of defined "baselines" along the shore; (iii) a contiguous zone - covering the territorial waters and a further 12 miles seaward; and (iv) the exclusive economic zone (EEZ) - extending to 200 miles.

A State's powers range from full sovereign powers within internal waters to rights limited to the exploitation of natural resources in and beyond the EEZ. UNCLOS Article 86 states that all parts of the sea which are not included in the abovementioned zones form the high seas. Within these zones, according to UNCLOS Article 92, ships "shall sail under the flag of one State only and...shall be subject to its exclusive jurisdiction". According to customary law, as stated by the Permanent Court of International Justice in the Lotus Case, only Flag States, namely those of which vessels possess the nationality and whose flag the vessel is entitled to fly, can enforce regulations applicable to vessels on the high seas (Birnie, P. 2009). This principle can also be indirectly read by analysing the combined provisions of UNCLOS Article 218 and 228 regulating pollution from ships.

Whilst under Article 218 a port State may take legal proceedings for discharge violation, Article 228 states that for discharges occurred on the high seas Flag States are empowered to intervene and suspend those proceedings. This could cause a severe limitation of the EU's jurisdiction to charge taxes or implement emissions standards outside EU waters. In fact, even though Article 218 would allow member Port States to exercise their enforcement jurisdiction over foreign ships which are voluntarily within their ports, for any violation that occurred in the high seas, Flag States could still request to take action restricting Port States' jurisdiction (Bang, H.S., 2009).

Flag States can adopt laws and regulations for the prevention, reduction and control of pollution and shall exercise full jurisdiction and control in administrative, technical and social matters over vessels flying their flag.

This provision would empower the EU to impose environmental requirements on ships flying EU Member States' flags. However, the majority of vessels worldwide currently fly "convenience" non-EU flags.

According to UNCLOS Art. 25.2, Coastal States are entitled to refuse the admission of a vessel into their internal waters if the vessel does not comply with the State's entry conditions but, by so doing, Port States also have to avoid contravening Article 227 which states that "States shall not discriminate in form or in fact against vessels of any other State".

Indeed, there is currently no strong legal basis for the EU to exercise extra-territorial jurisdiction, and this is likely to give non-EU states and industry bodies grounds for challenging carbon emissions reduction measures adopted by the EU for maritime transport. Two further arguments could also be brought by non-EU countries against such measures (Bang, H.S., 2009).

The challenge could be based on the violation of the right to innocent passage through territorial waters. Coastal States are required by UNCLOS Art 24 not to hamper the innocent passage of foreign ships through the territorial sea.

The right to innocent passage represents a cornerstone of the International Law of the Sea. Under UNCLOS Articles 18 and 19, ships are deemed to be 'passing' when they simply navigate through territorial waters without "entering internal waters or calling at a roadstead or port facility", and their passage is considered to be innocent when it is not "prejudicial to the peace, good order or security of the coastal State". Within this right, parties are free to navigate setting out the parameters of Coastal States' jurisdiction. Non-EU States could also claim a violation of UNCLOS Art. 26 which states that "no charge may be levied upon foreign ships by reason only of their passage through territorial sea" and that "charges may be levied upon a foreign ship passing through the territorial sea as payment only for specific services rendered to the ship", without discrimination. An EU decision to impose an extra-territorial charge on ships requiring vessels to surrender allowances at EU entry ports not only due to services provided to the ships but to their emissions outside the EU EEZ could be considered a violation of the abovementioned Article (Boyle, A. 2002).

7. Conclusion

Regulating air emissions and GHGs from ships is part of the broader debate on the sustainability of the transport system and the environmental impacts of transport activities.

The complexity of air pollution and climate change policies for the international maritime transport sector calls for a wide range of considerations to be taken into account (Montgomery, 1972; Tietenberg, 2003) requiring policymakers: 1) to set binding long-term emission reduction goals, 2) to take action in a flexible manner, 3) to ensure knowledge and technology sharing of innovative practices, and 4) transparency, administrative feasibility.

Our analysis has sketched the state of the art concerning the main methodological aspects that have to be considered when designing policy measures to regulate air emissions and GHGs from international maritime transport. In particular, the Report provides a review of certain tasks of this process (in particular, the estimation of emissions caused by maritime activities and the identification of technological and policy options to abate air emissions from ships).

Our results show that, because of the high level of uncertainty in air emissions estimations, further research is required in this field. In fact, a scientific debate is still open on the most appropriate way to estimate air emissions. The scarce or limited availability of data concerning maritime transport activities has resulted in the widespread use of different calculation methodologies. In addition, the application of new technologies which enable more detailed traffic data acquisition puts further into question the usefulness of the methodologies proposed so far.

The Report also analyses the international regulatory system in which the policy regulation should be included and the current international and European debate on developing an environmental policy strategy for this sector.

The current policy actions to abate air emissions and GHGs from maritime transport relate mainly to the quality of fuel used and to the technological options available.

Market based instruments such as emissions trading are under discussion at international level within the IMO. Furthermore, the inclusion of the maritime transport sector within the EU Emission Trading Scheme is on the EU strategy to address GHGs.

Moreover, the environmental impacts of maritime transport are also related to the growth rate of trade, which makes the problem even more pressing. This aspect is related to the intensive nature of production and consumption of goods and services, which have been stimulated by several factors such as the new global dimension of modern production and consumption which has re-shaped European and world trade, and the use of *just-in-time* techniques which allow manufacturers and wholesalers/retailers to dispense with warehouses (OECD, 2002). These issues call for the integration of any environmental strategy to regulate air emissions from ships into a broader framework which includes all the pillars of sustainable transport.

In conclusion, this Report identifies the methodological aspects of designing an environmental strategy to regulate air emissions from ships and shows how to integrate such a strategy in an international framework.

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Annex A. The main technological options for abating air emissions from ships

A.1. Ship design

Efficiency of scale (fuel consumption)

Usually, the larger a ship is, the more efficient it becomes. This can be reflected in both the construction of new ships and the optimised use of existing ones. Ports, machineries and infrastructures need to be adapted. Optimising the ship's size will result in a 4-5% increase in transport efficiency. This strategy can be applied to tankers, containers, ro-ro ships and ferries and can be considered to have a short payback time after its implementation (Wartsila, 2009).

Reduce ballast (fuel consumption)

In order to increase its stability, a ship is usually provided with additional weight in the lowest part of the hull. This weight (usually obtained using water), called ballast, is stored in a particular tank of the ship. It causes a higher resistance to the ship's displacement and thus a higher consumption of fuel. Reducing the ballast to the minimum feasible level can save up to 7% of fuel consumption. In addition, in new ships, a further ballast reduction can be made without reducing the stability of the ship by increasing the beam by 0.25m. This strategy can be applied to all vessel categories and is considered to have a short payback time (Wartsila, 2009).

Lightweight construction (fuel consumption)

An alternative strategy for reducing the weight of a ship is the use of lightweight structures. This can be applied only to new ships (of all the types) and should have a short payback time (Wartsila, 2009). A maximum 7% increase in efficiency is expected.

Optimum main dimension (fuel consumption).

A big impact on the ship's resistance is also made by the hull fullness ratio (the ratio between the hull volume and the product of its maximum length, breadth and draft). Reducing this fullness ratio will result in a more efficient ship (an increase of up to 9% in efficiency). This can be achieved by increasing the ship's length. This strategy usually has a longer payback time. According to the data presented in Sames (2009), the increase in efficiency of *e.g.* a Baby Post-Panamax vessel would be about 30% higher than that of the traditional Panamax vessel.

Interceptor trim planes (fuel consumption)

Interceptor trim planes can be applied to both new and existing ferries and ro-ro ships and consists of positioning a vertical metal plate on the transom of the ship covering most of its breadth. Due to the great pressure that is usually exerted in that area, the interceptor has a great stabilisation capability, leading to an increase in efficiency of up to 4%. Its payback time is typically short (Wartsila, 2009).

Ducktail waterline extension (fuel consumption)

This operates on a similar principle as that of the interceptor, but in this case the aft of the ship is lengthened. The best results are obtained when coupled with the interceptor. It has been applied to containers, ro-ro ships and ferries. The ducktail waterline extension has a short payback time. A 7% increase in efficiency is expected.

Minimising resistance of hull openings (fuel consumption)

Openings on the ship's hull are usually created as bow thruster tunnels. Bow thrusters are very important for increasing the manoeuvrability of big vessels. However if the openings are not designed properly they can significantly contribute to motion resistance. Optimising their design will therefore result in an increased efficiency. It can be applied to all kinds of new and existing ships. The payback period is usually short.

Air lubrication (fuel consumption)

Air pumped under the ship's hull creates a cushion between the water and the ship itself and leads to substantially reduced friction. An example of air lubrication is provided by the Air Cavity System (ACS), which was first implemented by the DK Group, the Netherlands. Motion resistance is considerably reduced. Depending on the type of ship, it results in different levels of reduced fuel consumption. This reduction ranges from a minimum of 3.5% for ferries to a maximum of 15% for tankers. The payback period is quite short for most ships (Wartsila, 2009; it is assumed the system has an average working life of 30 years).

Since the minimal length of the vessels to which this strategy can be applied is 225m, in IMO (2009) the following ship categories have been considered:

- Tankers (crude oil and bulk > 60,000 dwt, LPG > 50,000 m^3 capacity and all LNG tankers)
- Container Vessels > 2,000 TEU

The analyses carried out in IMO (2009) consider half of the fuel reduction assumed by the technology suppliers (i.e. 5% for tankers and 3% for containers). The cost efficiency data reported in Table 5 (IMO, 2009, Annex IV, page 275) was obtained using the cost of new ships reported in UNCTAD (2008) (with a 0.7 correction factor) and assuming that the ACS system should have a 2-3% impact on the price of a new ship. It is worth noting that, according to IMO (2009), the smoothness of the hull has a big influence on the effectiveness of this measure. This of course leads to extra maintenance costs.

Tailoring machinery concept for operation (fuel consumption)

The efficiency of new-build ferries and OSV's can be improved by tailoring the machinery concept to the operation required. As an example, the high propulsion efficiency of a single skeg hull form is combined with the manoeuvring performance of steerable thrusters. The concept is limited to new-build ferries and OSVs. It has a short payback time and can increase the ship's efficiency by up to 35%.

A.2. Propulsion

Wing thrusters (fuel consumption)

Wing thrusters present an innovative propulsion concept which can increase efficiency by 8-10%. It can only be adopted by new ro-ro ships, ferries and OSVs. It is considered to have a quite short payback period (Wartsila, 2009).

CRP propulsion (fuel consumption)

In this propulsion concept, a single propeller is substituted by two propellers, one behind the other, that rotate in opposite directions. It can be adopted by all new-build ships. The efficiency gain is around 10-15%. The implementation costs seem to be quite a lot higher than those of the other solutions, resulting in a longer payback time (Wartsila, 2009).

Propeller design and monitoring (fuel consumption)

The propeller(s) of a ship plays an important role in the consumption of fuel. Several strategies can be adopted to increase its efficiency, such as introducing: i) optimised interaction between propeller and hull, ii) propeller-rudder combinations, iii) advanced propeller blade section, iv) propeller tip winglets, v) propeller nozzle and vi) propeller monitoring. Almost all these strategies can be applied to both new and existing ships (all can be applied to tankers and containers, while only some of them can be applied to the other ship types). The payback period is generally short. Overall, these strategies can contribute to a 15% increase in efficiency. In IMO (2009) the cost effectiveness of propeller performance monitoring, propeller/rudder combination and upgrading, and propeller upgrading (with winglet, nozzle and boss cap fins) has been evaluated. The results are reported in Table 6 (taken from IMO (2009) Annex IV, pages 279-280). The latter has been estimated assuming a capital cost of €20,000 for a 735kW engine and of €146,000 for 22,050kW engine (the cost varies linearly with the power between the two extreme values), a 10-year lifespan and that the strategy can be applied to all vessels.

Constant versus variable speed operation (fuel consumption)

Reducing the number of revolutions of the propellers with the speed would save up to 5% of fuel.

Wind Power (fuel consumption)

A very promising option for increasing a vessel's efficiency is to use wind energy. Different possibilities for harnessing this energy exist. One option would be to install sails on the deck or to attach a kite to the bow of the ship (leading to an increase in efficiency of up to 20% for all kind of ships, apart from OSVs), while another would be to use vertical rotors which can convert wind power into thrust, exploiting the so-called Magnus effect (Magnus, 1852). The latter, which can only be applied to tankers and ro-ro ships, can potentially improve efficiency by 30%. A medium payback time characterises both options. According to Faber *et al.* (2009), rotors placed on ship decks can help to reduce fuel consumption by between

3.6% (for a crude oil tanker with deadweight (dwt) < 200,000 tonnes) and 12.4% (for a bulk carrier with dwt < 99,000 tonnes). In the scenario of using a towing kite to use the wind energy, the optimal configuration is achievable only with vessels of a minimum 30m in length and a minimum speed of 16 knots. Therefore, only tankers and bulk carriers are considered as potential users (IMO, 2009). The IMO report (IMO, 2009) also attempts to evaluate the 2020 cost efficiency of this kind of application. Starting from the available towing kites (up to 640m²) and assuming that kites of up to 50,000m² will be available by 2020 to be used in the largest vessels, the report provides results as given in Table 6 on Cost efficiency and abatement potential (see IMO, 2009, Annex IV, page 272). This table considers two scenarios based on the number of days at sea for which the kite can be used (33 or 67%).

Pulling thrusters (fuel consumption)

Another technological option dedicated to new ferries, ro-ro and OSV ships is the pulling thruster. Different configurations can be chosen leading to a potential 10% reduction in fuel consumption. This option is characterised by a quite short payback period, according to Wartsila (2009).

Seawater Lubricated Stern Tube Bearing System (fuel consumption+ oil waste reduction)

Apart from atmospheric emissions, maritime transport also impacts the environment through the discharge of waste oil into the sea. A source of this oil is that contained in the stern tube. This oil is needed to allow the seal of the propulsion system to work properly. The problem is that, in some cases, slight damage to the system makes the oil flow directly into the sea. Considering that typical stern tubes contain 1,500 litres of oil, it is possible to imagine how significant the problem is. Recently, the possibility of substituting the oil with seawater has been evaluated (Carter, 2009). The first outcomes of this strategy are the environmental and economic benefits connected with avoiding oil use. Furthermore, as shown in Lavini *et al.* (2007), the use of seawater also allows an efficiency increase of around 2%.

A.3. Machinery

Hybrid auxiliary power generation (fuel consumption)

A hybrid system that uses the electric energy produced by a fuel cell and stored in batteries can maximise energy efficiency by balancing the loading of each component. Despite the fact that the overall increase in efficiency is less than 2%, the use of the fuel cell can lead to a reduction of NO_x and PM by more than 60% and a reduction of CO_2 by about 30% (Wartsila, 2009). It can be implemented on all types of new ships and has a short payback period.

When in ports, it would be advisable for ships to use shore-side electricity instead of producing it. This is likely to generate considerable emission reductions since the average efficiency of power stations is much higher than that of ships' power generators. In addition, the pollution generated by power plants (including noise and vibrations) is likely to be produced in less densely populated areas (with respect to the areas surrounding the biggest ports) and thus its external cost should be lower. In Hall (2009), an analysis of the efficiency of shore-side as opposed to onboard power generation was carried out. The following table gives a comparison of emissions generated by the production of shore-side and onboard electricity for the UK.

Table 11. Potential emissions reduction using shore-side electricity for the UK

Pollutant	Ships power generator emissions (g/kWhe)	Power station emissions (g/kWhe)	Reduction (%)
NO_x	14.1	1.2	91.6
CO	0.9	0.2	75.6
SO_2	2.2	1.2	45.8
CO_2	718.6	542.6	24.5

Source: Hall (2009) Table I, page 3

However, the situation is not positive everywhere. In China, Indonesia, Russia, and the United Arab Emirates, replacing onboard with shore-side power production facilities would lead to an increase in pollutant emissions. On the other hand, the situation is more favourable in countries such as Norway, France, Belgium, Brazil, Japan, Spain and Italy than in the UK, due to a more extensive use of renewable sources of energy.

In Entec (2005a), an attempt was made to provide an estimation of the cost of using shore-side electricity. Results are reported in the following table.

Table 12. Shore-Side electricity costs (€/tonne) (ENTEC, 2005A, Table 5.2, Page 39)

Emission	Ship type	Small Vessel €/tonne	Medium Vessel €/tonne	Large Vessel €/tonne
NO_x	New	9,662	5,371	3,847
	Retrofit	12,086	6,631	4,704
SO_2	New	9,889	5,498	3,937
	Retrofit	12,370	6,788	4,815

Source: ENTEC (2005A), Table 5.2, Page 39

Diesel electric machinery (fuel consumption)

A similar concept can also be applied to the main engines of a ship. The use of diesel electric machinery in normal operations can provide great benefits to the ship's overall efficiency. The system can be applied to new-build ro-ro ships, ferries and OSVs. The payback period is relatively short. The situation would be even better in the case of a fully electric main engine (see Hansen, 2009). Up to 20% savings in fuel are estimated.

Internal Engine Modification (IEM) (NOx, VOC, PM)

Internal Engine Modifications involve changes to the combustion process within the engine and are designed to optimise combustion, improve air charge characteristics or alter the fuel injection systems. Since many parameters influence the combustion efficiency and emission formation, a number of technological changes have been proposed. Many of these aim to cut NO*x* emissions by reducing peak temperatures and pressures in the cylinder. IEMs can be divided into two main categories: Basic and the Advanced (Entec, 2005b). Basic IEMs change the conventional fuel valves with low-NO*x* slide valves. The purpose is to optimise spray distribution in the combustion chamber without compromising on component temperatures or engine reliability. Currently, the Basic IEM is only applicable for slow-speed 2 stroke engines. Since all cylinders can be changed simultaneously, installation can take a day per engine and does not require being in dry dock. However, all new engines of this type are thought to have these valves fitted as standard. Slide valves lead to a reduction in NO_x, VOC and PM emissions (Aabo, 2003).

Advanced IEMs are optimised combinations of a number of IEMs developed for particular engine families. They include: retard injection (30% reduction estimation of NO_x, EPA, 2003, but also risk of reduced efficiency), higher compression ratio (up to 35% NOx reduction, Wartsila 2004a), increased turbo efficiency, common rail injection, *etc*. The most common combination used is that of increased compression ratio, adapted fuel injection, valve timing and different nozzles (EPA, 2003). A reduction of 30-40% in NO*x* emissions is generally achieved. Wartsila, Caterpillar and FMC are the main manufactures. However, Advanced IEMs for ships are generally still in the development phase (Wartsila Corporation, 2004).

Water Injection (NOx)

Water injection is used to reduce the combustion temperature. Using a valve, it cools the combustion chamber during or before combustion, by injecting water directly into the cylinder (Wartsila, 2004a). The engines with water injection are equipped with a combined injection valve and nozzle that allows injection of water and fuel oil into the cylinder. Since the water and the fuel system are separated, neither will affect the operation of the engine. However, separate pumps for the fuel and water are needed, and storage and bunkering of freshwater is necessary. Wartsila and Man B&W are the main producers of water injection technologies. In order to achieve a 50-60% NO_x reduction, a 40-70% water/fuel ratio is required (Sarvi, 2004). Unfortunately, this leads to an increase in fuel consumption and smoke emissions and, considering the elevated costs, has a short lifetime (Eilts and Borchsenius, 2001). Alternatively, the Humid Air Motor (HAM) uses seawater to add water vapour to the combustion air. Based on decreasing the combustion temperature it reduces NO*x* formation by up to 80% (Eyring *et al.*, 2005b). From an economic point of view, high initial costs have to be sustained to install the humidifier, which also occupies a large surface and volume. However, the low consumption of fuel and lubricating oil consumption reduces the operating costs of the engine. The experiment carried out on the Viking Line's MS Mariella has shown a NO*x* emission reduction from 17 to between 2.2 and 2.6 g/kWh, and a decrease in fuel consumption of 2-3% (Det Norske Veritas, 2005).

NOx control methods (NOx, fuel consumption, particulate matter)

These methods are based on treating the engine exhaust gas either by re-burning the exhaust gas (Exhaust Gas Recirculation, EGR) or passing it through a catalyst or plasma system.

Thanks to the recirculation process, a portion of exhaust gases is filtered, cooled and circulated back into the engine's charge air. Decreasing the peak cylinder temperature, it reduces the formation of NO*x* during the combustion process. A reduction of 35% in NO*x* emissions is expected (Entec, 2005b). On the other hand, smoke and PM tend to increase because of the reduced amount of oxygen and longer burning time. Moreover, since exhaust gases contain gaseous sulphur species, a corrosion problem from sulphuric acid formation is generated (EPA, 1999). For this reason it is difficult to use EGR for marine diesel engines using heavy fuel oils on a fully commercial scale. EGR can also be applied in combination with water. In this case up to a 70% reduction in NO*x* emissions below the IMO limit could be obtained. The main drawbacks are that the thermal efficiency is reduced and that cost and space requirements increase significantly.

Selective Catalytic Reduction (SCR) uses a catalyst to convert NO_x emissions into nitrogen and water by using reaction reducing agents such ammonia (NH_3) or urea ($CO(NH_2)2$). No limitations exist regarding the ship types and it can lead to a reduction in NO*x* emissions of up to 90-95%. To reach 90% NO_x reduction, approximately 15g of urea are needed per kWh energy from the engine (EEB, 2004). Moreover, lower fuel consumption can be combined with low NO*x* emissions because the engine may be fuel-optimised. The most critical problems are the space requirement for the catalyst elements and storage of ammonia or urea, and the significant investment and operational costs. Clean fuel will prolong the life of the catalyst and decrease the maintenance necessary. Once installed, it will generally operate nearly 100% of the time (Trozzi and Vaccaro, 1998; Sorgard *et al.*, 2001). Another option is Selective Non-Catalytic Reduction (SNCR), which works in a similar way to Selective Catalytic Reduction but without the use of a catalyst. A reducing agent (ammonia or urea) injected during the combustion process converts the nitrogen oxides into nitrogen and water, reducing NO_x emissions by 50% (Sorgard *et al.*, 2001; Marintek, 1999). The drawback of this system is that it is less efficient than the SCR method, because only 10-12% of ammonia reacts with NO*x*. Since the cost of ammonia is about the same as the cost of heavy fuel oil (Trozzi and Vaccaro, 1998) and since the system requires extensive modification to the engine, the SNCR option does not appear to be competitive.

Plasma Reduction Systems are based on the use of plasma. This is a partially ionised gas comprised of a charge of a neutral mixture of atoms, molecules, free radicals, ions and electrons. Electrical power is converted into electron energy and the electrons create free radicals, which destroy pollutants in exhaust emissions. Experiments have shown that Plasma Reduction Systems can reduce NO*x* by up to 97%. It seems to be flexible in terms of size and shape and should be relatively low cost. However, for marine use, it is still in the development phase.

Table 13. Costs used in Bosch *et al.* (2009) for NO_x control methods (Table 6.4, page 33)

Technologies	Ship type	Investment (k€)	Lifetime (Years)	Operation and Maintenance (k€)	Fuel cost (k€)	Annual Cost (k€)	Cost per NO_x tonne (€/tonne)
Basic IEM	Retrofit	9	2.5	0	0	4	8
Advanced IEM	New	129	25	0	0	8	18
EGR+WIFE (0.1% S)	New	743	25	15	103	166	340
EGR+WIF	New	743	25	22	103	173	350
EGR+WIF	New	743	25	39	103	190	390
EGR+WIF	New	743	25	65	103	215	440
SCR	New	949	25	169	0	297	600

Source: Bosch et al. (2009) (Table 7.8, page 42)

WiFE on Demand is a system that reduces NO_x emissions by providing water in fuel emulsion (WiFE) "on demand". It can be very effective in environmental and legislative hot spots. It is a fuel emulsion technology for marine vessels that recycles onboard oily waste water for safe use in the combustion process, eliminating the need for the costly disposal of oily waste on land. It can work with a variety of water-to-fuel ratios, from 0% to 50%, on the basis of the water available on the vessel and in proportions that are appropriate to specific operating conditions. 30% of water in fuel emulsion can reduce NO_x emissions by 30% and particulate matter by 60-90%. It can be retrofitted to a variety of vessel types and fuel systems. From an economic point of view, it seems to be a cost-effective anti-pollution solution.

Table 13 presents the, the costs used in Bosch *et al.* (2009) for analysing the cost-effectiveness of NO_x reduction techniques.

Table 14 presents an estimation of the cost/effectiveness of the previous technologies as an elaboration of the estimates provided in Entec (2005b), Rehai and Hefazi (2006), Lovblad and Fridell (2006) and IIASA (2007).

Table 14. Cost effectiveness of NO_x reduction measures per €/tonne

Technologies	Ship type	Small Vessel €/tonne	Medium Vessel €/tonne	Large Vessel €/tonne
Basic IEM	New	11	9	9
Basic IEM	Retrofit	35	16	12
Advanced IEM	New	93	36	18
Direct water injection	New	391	353	328
Humid air motors	New	255	222	188
Humid air motors	Retrofit	291	274	250
SCR outside SO_2 ECA	New	704	558	501
SCR outside SO_2 ECA	Retrofit	770	607	543
SCR inside SO_2 ECA	New	517	419	379
SCR inside SO_2 ECA	Retrofit	583	469	422
SCR ships using MD	New	393	411	207
SCR ships using MD	Retrofit	460	473	341

Source: data are in accordance with those reported in ENTEC (2005b), Rahai and Hefazi (2006), Lovblad and Fridell (2006) and IIASA (2007). Note that ECA stands for Emission Control Area and MD for marine distillates.

SOx control methods (SOx, NOx, fuel consumption, particulate matter)

Sulphur oxide is a pollutant emission produced during the combustion process. Since it is directly proportional to the content of sulphur in fuel, the main method to reduce sulphur oxide emissions is to reduce the quantity of sulphur in fuel. In 2005, the European Commission established that, from January 2010, the marine fuels used at berth shall not exceed 0.1% sulphur content. However, abatement technologies can also be used to reduce sulphur oxide emissions, and the literature documents a large number of these (Rentz *et al.*, 1996; Takeshita, 1995). Combustion modification represents a first option. It uses the addition of limestone ($CaCO_3$) or dolomite ($CaCO_3$*$MgCO_3$) into conventional boilers. Usually, the process injects limestone into a pulverised coal-fired boiler, which achieves emission reduction rates from 50 to 60%. Another method is the Fluidized Bed Combustion (FBC) that removes SO*x* and NO*x* emissions with high efficiencies but is still expensive. One of the main problems of the combustion modification process is the large amount of waste that is produced. This can be a problem due to the increasing difficulties with waste disposal and costs.

Scrubbers (NOx, SOx, particulate matter)

Scrubbers deserve a separate section since they are able to effectively abate different kinds of pollutants. They use alkaline compounds to neutralise sulphur oxides in the scrubber and transfer them into the water in the form of sulphates (Trozzi and Vaccaro, 1998). They can reduce SO*x* by 99% and NO*x* and particulate matter by 85% without increasing CO_2 emissions. Retrofitting the existing commercial fleet of over 25,000 dwt would take 5 years and would cost US$ 250 billion, five time more rapidly and less costly than, for example, distilling the fuel. Winkler (2009, page 87) provides the prices of scrubbers, as reported here in Table 15.

Table 15. Indicative scrubber costs for different ship categories

Vessel Type and average fuel usage per year (with total vessel power)	Indicative Scrubber Cost ($)
Ferry 23,850 tonnes (34MW)	3,400,000
Tanker 28,000 tonnes (30MW)	2,400,000
Cruise 40,000 tonnes (40MW)	3,200,000

Source: Winkler, 2009, page 87

Two scrubbing methodologies exist: Sea Water Scrubbing and Fresh Water Scrubbing.

Seawater is an ideal scrubbing agent because it has an adequate level of alkalinity and already naturally contains 900mg per litre of sulphur, thus it is perfect for removing acid gases from exhaust emissions. After this process, the water is filtered to remove particulate matter and circulated back into the sea (EEB, 2004). The solid particles removed from the gases are trapped in a settling or sludge tank and collected for disposal. On the other hand, fresh water scrubbing uses a caustic soda (NaOH) solution for neutralising the sulphur. This washing solution is pumped from the process tank through a system cooler to the scrubber. From the scrubber the washing solution returns to the process tanks by gravity. In both cases, uncertainty exists about the effects of waste water on the sea. It still remains to be demonstrated whether scrubbing is environmentally suitable for all parts of the environment (shallow water, brackish waters and enclosed port areas).

Generally, the amount of sulphur discharged seems to be insignificant compared to the quantity of sulphate that seawater naturally contains (Trozzi and Vaccaro, 1998).

However, based on the precautionary principle, Annex VI of the MARPOL Convention forbids discharging waste into estuaries and enclosed ports (EEB, 2004).

Table 16. Scrubber Costs used in Bosch *et al.* (2009)

Technologies	Ship type	Investment (k€)	Lifetime (Years)	Operation and Maintenance (k€)
Scrubber 1.5-open	New	1,148	15	23
Scrubber 1.5-closed	New	2,296	15	193
Scrubber 1.5-open	Retrofit	2,296	12.5	23
Scrubber 1.5-closed	Retrofit	4,592	12.5	193
Scrubber 0.5-open	New	1,148	15	23
Scrubber 0.5-closed	New	2,296	15	296
Scrubber 0.5-open	Retrofit	2,296	12.5	23
Scrubber 0.5-closed	Retrofit	4,592	12.5	296
Scrubber 0.1-open	New	1,148	15	23
Scrubber 0.1-closed	New	2,296	15	347
Scrubber 0.1-open	Retrofit	2,296	12.5	23
Scrubber 0.1-closed	Retrofit	4,592	12.5	347

Source: Bosch et al. (2009) (Table 7.6, page 40)

In the Bosch *et al.* (2009) evaluation of the cost/effectiveness of scrubbers, a cost of 0.2$€_{2005}$/l for urea, 0.5$€_{2005}$/l for NaOH and the additional cost parameters were considered.

Table 17 shows the cost/effectiveness ratio of the abovementioned technologies as an elaboration of the estimates provided in Entec (2005c), Rehai and Hefazi (2006) and IIASA (2007).

Main Engine Tuning/Delta Tuning (fuel consumption)

IMO (2009) provided the estimates (Annex IV, page 285) as reported in this Report in Table 7.

Table 17 Cost effectiveness of SO*x* reduction measures per €/tonne abated

Technologies	Ship type	Small Vessel €/tonne	Medium Vessel €/tonne	Large Vessel €/tonne
Sea water scrubbing	New	370	340	310
Sea water scrubbing	Retrofit	550	520	490

Source: data are in accordance with those reported in EMTEC (2005b), Rahai and Hefazi (2006), Lovblad and Fridell (2006) and IIASA (2007). Note that the sulphur concentration in the fuel is 2.7% S.

Waste heat recovery (fuel consumption)

It is possible to recover the thermal energy from the exhaust gas and convert it into electrical energy to power other systems of the ship. The potential energy and emissions savings is between 10 and 20% (for new systems). It can be applied to all new and existing ships (apart from OSVs). The payback period seems to be quite short.

Common rail (fuel consumption, NOx)

Common rail is an advanced fuel injection technology which reduces emissions and improves engine performance by maintaining a high and constant injection pressure at all engine loads (Sarvi, 2004). By optimising the fuel injection it helps reduce NO*x*, particulate matter and CO_2, leading to better atomisation of the fuel. From an economic point of view, total costs can increase because this method requires stronger fuel injection equipment such as fuel pumps, accumulators, injectors and control unit. IMO (2009, Annex IV, page 285) provided the cost estimates as reported here in Table 7.

Power management and automation (fuel consumption)

Correct power management can contribute to a 5% increase in the efficiency of a ship's operations. It can be applied to all types of ship with a quite short payback period. The increase in efficiency can be also higher if it is perpetrated automatically.

Two possible strategies belonging to this category have been analysed in IMO (2009), *i.e.* the shaft power meter and the fuel consumption meter.

The shaft power meter strategy assumes that costs are constant for each ship type and fall within the range US$ 26,000-31,200, an expected lifetime of 10 years, and a reduction potential in the range of 0.5-2% with the benefits due to optimisation of ballast, load and trim. The same assumptions hold for the fuel consumption meter strategy except for the costs, which are considered in the range of US$ 46,000-55,200. In addition, further reductions can be obtained by energy saving lighting and power management. The analysis results taken from IMO (2009, Annex IV, page 284, 286) are reported in Table 7 of this Report.

Speed control pumps and fans (fuel consumption)

The engine cooling water system contains a considerable number of pumps which are major energy consumers. Controlling their speed could considerably reduce consumption, and can be applied to all new and existing ships. The estimates reported here in Table 7 are taken from IMO (2009) (Annex IV, page 286).

Solar power (fuel consumption)

Depending on the available deck space, solar panels can help reduce the energy consumption of a ship. The expected efficiency is around 4%. This strategy cannot be applied to containers and OSVs. The payback period seems to be relatively short (according to Wartsila, 2009).

A.4. Operation

Turnaround time in port (fuel consumption)

All possible strategies which aim to reduce the port turnaround time can have a big impact on a ship's efficiency. The time saved could be spent on a longer trip with a reduced speed. Strategies can be found for every type of new and existing ship. The expected increase in efficiency is around 10%.

Propeller surface finish/polishing (fuel consumption)

As they are always below sea-level, organic material growth and waste deposits often gather on propellers. This strongly impacts the propellers' efficiency. Regular in-service polishing can therefore help in restoring energy efficiency. Divers can also help avoid the interruption of service.

In IMO (2009) two types of strategies are considered, namely propeller brushing and increased frequency of propeller brushing. For this latter case the following assumptions are made: the cost ranges in the interval US$ 3,000-4,500 applied every 5 years; costs do not vary with ship type (the measure can be applied to all the ship types); the abatement potential ranges between 0.5 and 3%. The results of the analyses carried out in IMO (2009, Annex IV, page 280) are given in Table 8.

Hull cleaning and coating (fuel consumption)

The growth of algae and organic material on the hull can significantly contribute to the ship's resistance. Decisive factors for hull performance are the age of the ship, the time spent in port, service speed, water temperature, and the changes in the draft and duration of loading conditions. Options that are readily available to help improve the ship's performance include maintenance, surface pre-treatment, coating and repeated dry-dock interventions (Kane, 2009). Frequent cleaning can help improve efficiency by about 3%. Alternative modern coatings with smoother and harder hull surfaces, when clean, can offer lower resistance and are prone to less fouling, resulting in a much better overall performance of the ship.

As anticipated, hull cleaning is also important for the performance of the ACS system. Coating can be used specifically to prevent/reduce the build up of waste deposits. In IMO (2009), two types of coatings and three types of cleaning were considered.

The two types of coating that were considered had an approximate cost of US$ 45,000 and US$ 250,000 respectively. For the first type of coating a fuel/CO_2 saving of 0.5-2% was estimated, while for the other, the percentage was estimated to be in the range 1-5% (depending on the ship type). Results of the cost efficiency estimation of IMO (2009, Annex IV, page 278) are reported here in Table 8.

Hull cleaning can be carried out by means of hull brushing, underwater hull hydroblasting or dry-dock full blasting. IMO (2009) also estimates the cost effectiveness of these. For the first type (brushing) the cost estimation ranges between US$ 26,000 and US$ 39,000 (to be repeated every 5 years). The same assumptions made for the coating were made for differentiating the cost among the different ship types. A potential reduction of 1-10% was considered. For the second type (hydroblasting) the same hypotheses were made apart from the costs, which were assumed to range in the interval US$ 33,000-50,000. For the third type (dry-dock full blasting), the cost ranges between US$ 68,000 and US$ 81,500, the process has to be repeated every 25 years and the abatement potential is estimated to be in the interval 5-10%. The results obtained (IMO, 2009, Annex IV, page 282, 283) are reported in Table 8.

Another methodology for increasing ship efficiency is based on hull performance monitoring. In this case, the average cost is estimated to be about US$ 45,000 every 5 years, plus US$ 5,000 each year. It can be applied to all ship types and the reduction potential is considered to be in the interval 0.5-5%. The results are reported in Table 8.

Ship speed reduction (fuel consumption)

Emissions from a vessel are roughly related to the square of the vessel's speed. Therefore, reducing ship speed is an effective way of cutting energy consumption and thus emissions. Given the same distance, a reduction in speed of 1 knot will result in an 11% increase in efficiency. According to Corbet *et al*. (2009), this strategy might be preferred by ship operators in the event of the introduction of CO_2 trading schemes. Indeed, by halving the ship's average speed, its CO_2 emissions would be abated by around 70%. The problem is the type of strategy adopted to preserve the scheduled frequency. Should the time lost be recovered through reduced in-port turnaround time, then the abatement of CO_2 emissions is likely to be even higher. On the other hand, should additional ships have to be added, the reduction will be less significant (in this case this option would lead to a dramatic increase in operating costs and thus it is unlikely that ship operators would accept it).

IMO (2009) made a cost efficiency evaluation considering that, for a given speed reduction percentage (v_r), the number of vessels that would need to be purchased is $\left(\frac{1}{1-v_r} - 1\right)\left(\frac{1}{1-v_r} - 1\right)$.

For the cost of the vessels, the analysis used the costs reported by UNCTAD (2008) reduced by 70% in order to account for price volatility. Without considering fuel costs, the operational costs were estimated to be in the range US$ 6,000-8,000/day. Ferries and cruise vessels were not considered in the analysis (being in a route/time scheme), nor were ro-ro and vehicle carriers, whose prices are uncertain. Results are reported in Table 8.

Weather routing (fuel consumption)

The shortest path is not always the most convenient. Indeed, under bad weather conditions a longer, but smoother path could result in lower fuel consumption. Planning the voyage in this way can lead to considerable benefits in terms of efficiency. In IMO (2009, Annex IV, page 285) a cost effectiveness analysis of this option was performed with the following hypotheses: cost estimated to be in the range US$ 800-1,600, reduction potential in the range 0.1-4% and applicability extended to all vessels with route flexibility (no ferries or cruise ships). Results are reported in Table 8.

Vessels trim (fuel consumption)

By regulating the sailing conditions in order to find the optimum trim, it is possible to increase energy efficiency by about 5%. However, it is not always easy to find the optimum trim and thus this strategy can be very complicated. The payback period seems to be relatively short (Wartsila, 2009).

Autopilot adjustment (fuel consumption)

A better autopilot can help to save on energy consumption since it offers higher stability to the ship. IMO (2009, Annex IV, page 285) has provided the estimations reported in Table 8.

Energy saving operation awareness (fuel consumption)

A culture of fuel saving supported by incentives or bonuses to the crew of a ship can help the company to save a big percentage of its energy consumption. Training and a measuring system are indispensable to the implementation of this strategy.

Annex B - The Law of the Sea: Introductory summary

The process of the law of the sea developed from an initial approach based on separate *ad hoc* attempts to regulate specific problems, such as dumping or pollution from ships, to a more comprehensive legislative action. It was formally established in the 1982 UN Convention of the Law of the Sea (UNCLOS). In its Preamble, UNCLOS defines itself as a "*legal order for the seas and oceans which will facilitate international communication, and will promote the peaceful uses of the seas and oceans, the equitable and efficient utilization of their resources, the conservation of their living resources, and the study, protection and preservation of the marine environment*".

Providing a global framework to guarantee freedom of navigation while regulating environmental protection and the use and conservation of the sea's resources, UNCLOS can be seen as innovative framework in the field of international environmental law. To set limits on national jurisdiction over ocean space, access to the sea, navigation, protection and preservation of the maritime environment, UNCLOS distinguishes three levels of enforcement jurisdiction:

- by Flag States;
- by Coastal States;
- by Port States.

These levels of distinction are further broken down by UNCLOS depending on whether they relate to States' legislative or exclusive jurisdiction. The first defines the extent to which States may adopt legally binding provisions and rules, while the latter circumscribes States' power to take measures to ensure the observation of the same provisions[34].

Flag States, namely those States of which vessels possess the nationality and whose flags vessels are entitled to fly, exercise primary jurisdiction over ships. Flag State jurisdiction can be seen as an extension of the jurisdiction of a State to their ships. Regardless of where it is operating, a ship must therefore comply with the laws of their own flag. However, a Flag State's jurisdiction is exclusive when its vessel is sailing in the Flag State's own waters. Flag States are responsible for regulating safety at sea, preventing collisions, manning the ships and the competence of their crews, complying with labor laws and setting standards of construction, design, equipment and seaworthiness[35].

UNCLOS Art 94.5 requires Flag States to take any steps which may be necessary to secure observance with generally accepted international regulations, procedures and practices. The obligation is repeated in relation to oil pollution in Art 217.

A State having a coastline is entitled under international law to take certain limited steps to protect its own interests. UNCLOS recognises four main zones of different Coastal States' jurisdiction: (i) internal waters – bays, ports and similar enclosed areas of the sea; (ii) territorial waters - extending 12 miles seaward of defined "baselines" along the shore; (iii) a contiguous zone - covering the territorial waters and a further 12 miles seaward; and (iv) the exclusive economic zone (EEZ)- extending to 200 miles. A State's powers range from full sovereign powers within internal waters to rights limited to the exploitation of natural resources in and above the EEZ. According to UNCLOS Article 86, all parts of the sea which are not included in the abovementioned zones form the high seas. Within these zones ships "*shall sail under the flag of one State only and…shall be subject to its exclusive jurisdiction*"[36].

According to customary law, only Flag States can enforce regulations applicable to vessels on the high seas[37]. This principle can also be indirectly read by analysing the combined provisions of Articles 218 and 228 which regulate pollution from ships. Whilst under Article 218 a Port State may take legal proceedings for discharge violation, Article 228 stipulates that Flag States are empowered to intervene and suspend those proceedings for discharges occurring on the high seas [38].

34 See *The law of the sea: obligations of states parties under the United Nations Convention on the law of the sea and complementary instruments*, United Nations Publications, 2004, pp. 35-41.

35 1982 UNCLOS, Articles 94, 211. On this topic see P. Birnie, A. Boyle, C. Redgwell, *International Law and the Environment*, Oxford University Press 2009, pp. 400-405.

36 1982 UNCLOS, Article 92

37 The Permanent Court of International Justice, in the *Lotus Case* (PCJ, 1927, Ser. A, No 10, 169), referred to the principle that no State may exercise any kind of jurisdiction over foreign vessels on the high seas, meaning only that foreign vessels could not be arrested or detained while on the high seas, not that regulations could not be enforced by other States once a ship had voluntarily entered port.

38 See Ho-Sam Bang, Port State Jurisdiction and Article 218 of the UN Convention on the Law of the Sea, *Journal of Maritime Law and Commerce*, Vol. 40, No. 2, April 2009.

Going back to Coastal State jurisdiction, UNCLOS sets three core limitations to this power.

- Under Article 94.5 "*each State is required to conform to generally accepted international regulations, procedures and practices and to take any steps which maybe necessary to secure their observance*".
- Under Article 227, States shall not adopt any measure which could create discrimination in form or in fact against vessels of any other State.
- In their territorial sea, the sovereignty of the Coastal State is subject to the right of innocent passage by foreign ships: Coastal States are required by UNCLOS Art 24 not to hamper the innocent passage of foreign ships through their territorial sea.

The right of innocent passage represents a cornerstone of the international Law of the Sea: under Articles 18 and 19, ships are deemed to be passing when they simply navigate through territorial waters without "*entering internal waters or calling at a roadstead or port facility*"[39], and their passage is considered to be innocent when it is not "*prejudicial to the peace, good order or security of the Coastal State*".

However, according to UNCLOS Article 21, Coastal States have specific powers to adopt laws and regulations which limit the right of innocent passage through their territorial sea in conformity with international laws. Such powers do not exceed their territorial sea, and States may adopt laws and regulations only in respect of Article 21.1 conditions. For example, States may adopt laws and regulations to regulate maritime traffic, protect navigational aids, cables and pipelines, conserve living resources and protect the environment generally, prevent, reduce or control pollution, and prevent the infringement of customs, fiscal, immigration or sanitary laws[40].

39 1982 UNCLOS, Article 18.1 (a). Article 18.2 also states that passage should be continuous and expeditious, which includes stopping and anchoring which is incidental to ordinary navigation or necessary due to unpredictable distress.

40 However, 1982 UNCLOS Article 21 specifically states that the legislation of Coastal States *"shall not apply to the design, construction, manning or equipment of foreign ships, unless they are giving effect to generally accepted international rules or standards"*.

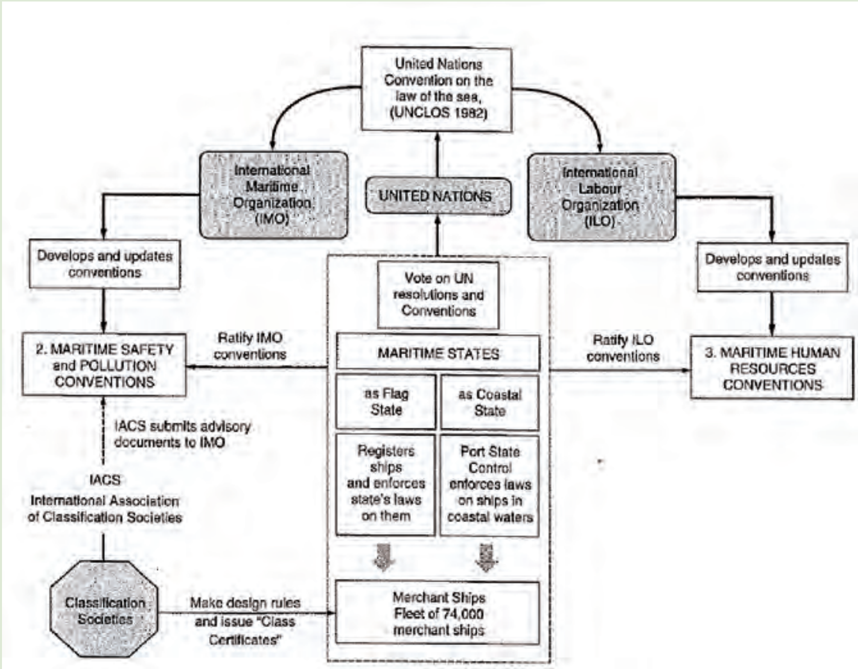
Concerning marine pollution from ships, UNCLOS Article 211 strengthens Coastal States' authority: in the exercise of their sovereignty within their territorial sea, Coastal States may adopt laws and regulations for the prevention, reduction and control of pollution, provided that these do not hamper the innocent passage of foreign vessels. They may include the EEZ in these measures, provided they conform to generally accepted international rules and standards.

States exercise Port State jurisdiction over the ships calling at their ports or inland waters. Article 218 stipulates that "*when a vessel is voluntarily within a port or at the off-shore terminal of a State, that State may undertake investigations and, where the evidence so warrants, institute proceedings in respect of any discharge from that vessel outside the internal waters, territorial sea or exclusive economic zone of that State in violation of applicable international rules and standards established through the competent international organization or general diplomatic conference*"[41]. In order to prevent damage to the marine environment by substandard ships, according to Article 219 Port States can also take administrative measures to prevent vessels from sailing, allowing them to proceed only as far as the nearest repair yard or upon removal of the causes of the violation.

41 As has already been mentioned, Port State jurisdiction can be limited by Flag State jurisdiction when discharges have occurred on the high seas. See footnote n. 4.

Box 1: The maritime regulatory system

The maritime regulatory system showing the role of the 166 maritime states (Stopford, 2009). Figure 16.1, page 657. By courtesy of Cengage Learning EMEA Ltd, @2009Martin Stopford.



The maritime regulatory system does not have a supreme legislative body that makes a single set of international laws. Currently the United Nations Convention on the Law of the Sea (UNCLOS 1982) sets a broad framework including the core principles and rules of the International Law of the Sea, whilst the task of setting and issuing specific regulations consistent with UNCLOS is delegated to two UN agencies, namely the International Maritime Organization (IMO) and the International Labour Organization (ILO). The latter is responsible for the laws governing people working on board vessels while the IMO's main remit includes safety, environmental concerns, legal matters, technical cooperation, maritime security and the efficiency of shipping. At present, 166 countries worldwide are involved in the shipping sector, which are members of the IMO and have to enact its conventions. The IMO's governing body is the Assembly. It gathers every two years and elects a Council, consisting of 32 member states, which acts as a governing body in between its meetings. The IMO structure includes five technical and legal committees: Maritime Safety, Marine Environment Protection, Technical Co-operation, Legal and Facilitation. The IMO started operating in 1958 mainly with the aim of drafting conventions (especially to cover safety, pollution prevention, liability and compensation). However, from 1981 the Assembly decided (Resolution A500 XII) to focus the IMO's efforts not only on drafting but also on the effective implementation of the conventions. In fact, the level of effectiveness of maritime conventions depends mostly on the percentage of countries that actually decide to enact them, and whether they are accepted by countries whose combined merchant fleets correspond to 99% of the world total.

These provisions were issued following the so called "Port State control" movement which arose within the international community to limit the registration of ships under flags of convenience in order to avoid enforcing international maritime regulations[42]. To get a complete picture, the above-mentioned articles should be read together with the 1982 Paris Memorandum of Understanding (MoU), in which 14 European States agreed to cooperate in order to increase the standards of ships visiting their ports and waters and to restrict or even ban ships that do not comply with international conventions that set standards on safety and pollution[43]. Such a MoU has been signed on a regional basis to establish a high degree of control over such vessels. The Paris MoU, as well as other similar agreements in other regions of the world[44], sets out that authorities are entitled to carry out inspections on foreign vessels and their documents to ensure their compliance with the abovementioned Conventions, and to detain non-complying ships until all detected deficiencies have been rectified[45].

Within this framework, the International Law of the Sea finds its highest authority in the International Maritime Organization (IMO), which is a body of the United Nations appointed to set international standards for safety and pollution. It consists of representatives from 152 major maritime nations, including the US. The purpose of the IMO's agreement is to set internationally accepted common standards for Flag States and Coastal States, and to reduce the threat to the marine environment posed by maritime accidents or discharge of pollutants and invasive species. Therefore, the IMO could be seen as the main regulatory and supervisory authority concerning maritime law[46]

42 See Martin Stopford, *Maritime Economics*, Taylor & Francis, 2009, pp.686-7.

43 *Ibidem*. The Port State control movement started in 1978 when eight European States around the North Sea agreed informally to inspect ships entering their internal waters and to share information about possible deficiencies. The following is a non-exhaustive list of International Conventions that set standards on safety and pollution: International Convention on Load Lines 1966 and Protocol of 1988; International Convention for the Safety of Life at Sea 1974 and Protocols of 1978 and 1988; International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 1978; Merchant Shipping (Minimum Standards) Convention 1976 and Protocol of 1996; International Convention on the Control of Harmful Anti-Fouling Systems on Ships 2001.

44 In particular Asia Pacific (Tokyo MoU), the Caribbean, Black Sea and Indian Ocean.

45 Under the Paris MoU, each participating Party's administration should inspect at least 25% of foreign vessels calling at its ports annually. This means that every year roughly 14,000 vessels sailing to Europe are inspected to ensure compliance with MARPOL. For further information on this topic see Birnie, P., Boyle, A., Redgwell, C. (2009). International Law and the Environment, *Oxford University Press*, p. 407.

46 See Copeland, C. (2008). *CRS Report for Congress, Cruise Ship Control: Background, Laws and Regulation and Key Issues*, pp. 7-22.

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Title: **Regulating air emissions from ships: the state of the art on methodologies, technologies and policy options**

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Abstract
In recent years public concerns regarding the environmental impacts of maritime transport have increased. This is because maritime transport is the fifth largest contributor to air pollution and carbon emissions, and the growth rate of trade makes the problem even more pressing. However, considerable environmental improvements can be obtained by changing shipping practices. Current policy actions targeting issues such as emissions relate mainly to the quality of fuel used and to the available technological options. Market based instruments such as emissions trading are under discussion at international level within the IMO. Furthermore, the inclusion of the maritime transport sector within the EU Emission Trading Scheme is on the agenda of the EU strategy to address GHGs. The complexity of air pollution and climate change policies for the international maritime transport sector calls for a wide range of considerations to be taken into account requiring policymakers: **1)** to set binding long-term emission reduction goals, **2)** to take action in a flexible manner, **3)** to ensure knowledge and technology sharing of innovative practices, and **4)** transparency, administrative feasibility. This Reference Report summarises the main findings of a research activity carried out over several years and provides a reference framework of the analytical tools for regulating air emissions from ships. It sketches the 'state of the art' with regard to the main methodological aspects of designing policy measures to regulate air emissions from maritime transport. These are: identification of the impacts; estimation of emissions, and identification and selection of technological and policy options to abate air emissions from ships. The overall aim of this Report is to provide analytical tools to help define a policy strategy to regulate air emissions from ships, by providing various insights into how to design and apply policy efficient and equitable instruments.

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