JRC Scientific and Technical Reports

Cost Effectiveness Analysis of the Emission Abatement in the Shipping Sector Emissions

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EUR 23715 EN - 2008

JRC
EUROPEAN COMMISSION

Institute for Environment and Sustainability

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JRC 49334

EUR 23715 EN
ISBN 978-92-79-11280-5
ISSN **1018-5593**
DOI 10.2788/77899

Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

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ABBREVIATIONS

CAFE	Clean Air Force Europe Programme
CEERS	Center for Energy and Environmental Research Services
EC	European Commission
ECA	Emission Control Areas
EEB	European Environmental Bureau
EMEP	Northeast Atlantic and Black and Mediterranean Seas
EPA	U.S. Environmental Protection Agency
EU	European Union
EUROSTAT	Statistical Office of the European Communities
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
LMIU	Lloyds Marine Intelligence Unit
MEPC	Marine Environment Protection Committee
MES	Marine Exhaust Solution
NE	Northeast
SECA	Sulphur Emission Control Areas
UNCLOS	UNITED Nations Convention of the Law of the Sea
UNCTAD	United Nation Conference on Trade and Development

AE	Auxiliary Engines
APU	Auxiliary Power Unit
DWI	Direct Water Injection
EGR	Exhaust Gas Recirculation
FBC	Fluidized Bed Combustion
GDP	Gross Domestic Production
GPL	Liquid Petroleum Gas
HAM	Humid Air Motor
HFO	Heavy Fuel Oil
ICR	Inter-cooler recuperative
IEM	Internal Engines Modification
MDO	Marine Diesel Oil

MGO	Marine Gas Oil
MGO	Marine Gas Oil
Mtoe	Million Tons of Oil Equivalent
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
VOC	Volatile Organic Compound

1. INTRODUCTION

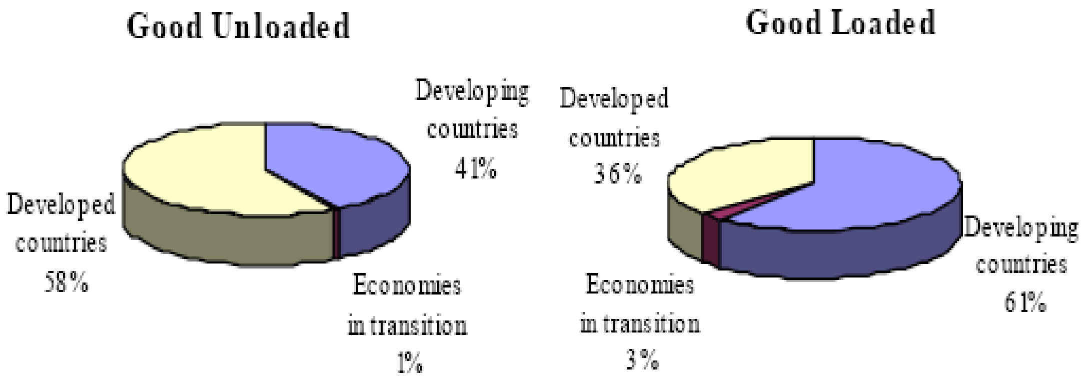
Maritime transport activity is becoming one of the most important topics on sustainability debate. Apart from industrial activity and energy production, maritime transport is the largest contributors to air pollution and the increasing rate of trade make the problem even more worrying.

During the last decades, transport demand is strongly increased, at or above the GDP growth rate, and maritime trade is become the most important way for merchandise transfer. Today, almost 90% of the world goods are carried by sea and maritime transport account for over 90% of European Union external trade and 43% of its internal trade (UNCTAD, 2007).

Economic growth and globalization are driving forces for maritime transport demand. Goods and materials are needed for production and ready access to market is an important factor for economic growth. In 2006, the gross domestic product (GDP) grew by 4%, augmenting seaborne trade by 7% in terms of volume and 10% in terms of value. In the same year the value of goods imported increased by 13.4% and the total freight costs paid for transport services increased by 31.2% (UNCTAD, 2007).

Both developed and developing countries play an important role for international trade but the impact on nominal trade flows differed by region. For Brazil, Chile and Peru sea transport represents the most important mode of transport for trade (over 95% of exports in volume terms and nearly 75% in value terms) and Asia results to be the most dynamic regions for seaborne trade. In 2003, for example, China's imports expanded by 40% in nominal dollar terms while its exports expanded by 35% (OECD, 2004). In general terms, the increasing rate of industrialization makes developing countries the main source of maritime transport and the world trade of commodities is even more sustained by the growing imports demand from China and India. As reported in figure 1, in 2007 the 64% of the total tons are loaded in developing countries and exported to developed countries. On the contrary, the 66% of the total economic value was controlled by developed countries and the 34% by developing countries (UNCTAD, 2007).

Figure 1. World seaborne trade by country group (percentage share in tonnage)



Source: UNCTAD, 2007

On the other side, the movement of goods and people in spaces implies the consumption of resources as time, space, money and energy as well as the production of negative externalities on environment. The increasing resource consumption that supports transportation activities imposes considerable environmental costs, including pollutant emissions, noise and effects on human health. The ships emissions, for example, contribute to eutrophication, acidification and the formation of ground-level ozone, as well as impact on climate change. In order to reduce environmental impact of maritime transport, both international legislation and technological improvements are urgently needed. Legislative actions, regulating the levels of pollutant or implementing market mechanisms, are oriented to reduce emissions at global level. On the contrary, the developments of technologies to reduce emissions or to produce cleaner transportation fuel are an essential step to decrease pollution emitted by marine diesel engines. Analysing the ships emissions abatement technologies, this report is focused on technological side. It considers the most important reduction measures and synthesizes the main results on cost effectiveness analysis.

Objectives

The scope of this study is to provide a summary of the ship emissions abatement technologies and investigate the cost effectiveness of specific emission measures.

Giving an overview of the costs and benefits related to potential emissions reduction, this report provides important information to improve the sustainability of the transport system.

This study is structured as follows. Section 2 provides an overview of the maritime sector. It presents vessels classification and analyses the increasing demand for shipping services. Section 3 focuses on emissions and international legislation. It describes the most important impacts generated by NO_x, SO_x and CO_2 emissions and provides data about quantification. Section 4 presents the main abatement technologies. Section 5 reviews the main results on cost effectiveness of reduction measures. Section 6 concludes.

2. OVERVIEW OF THE MARITIME SECTOR

2a. Ships classification:

Ships are difficult to classify, mainly because a plurality of criteria can be adopt. Excluding the military vessels, the most used classifications for commercial ships generally consider the vessels activities, the engine size and the ages. The first one distinguishes between passengers and cargo. The second one, based on engine size, is related to energy consumption and is generally used to analyze the environmental impacts of maritime transport. The last one considers the ages of the vessels and the distribution ages between developed and developing countries.

Passengers and cargo:

Based on the vessel activity, **Passengers and Cargo** is one of the most important ships classifications for commercial vessels.

Passengers are ships that do not carry cargo but passengers. They include:

- Ferries which transport more than 120 passengers, vehicles and one or more cargo decks for short-sea trips;
- Ocean Liners that transport passengers and cargo for longer-sea trips;
- Cruise ships used for tourism.

Cargo is a more heterogeneous category and includes all the vessels that carry cargo, goods, commodities and materials form one port to another. Usually they are classified by type of cargo and carry (Mäkelä et al., 2002):

- Cargo ferries: they transport less tan 120 passengers and cargo;
- Bulk carriers: they carry bulk solids or unpacked cargo (grains, coal, stones…);
- Container ships: are designed to transport standard-sized containers;
- Tankers: to transport crude oil, chemical or gas;
- Roll on/Roll of (RoRo): considered as cargo ferries, because they carry wheeled cargo (railway carriages, or automobiles);
- Reefers: are designed to transport dairy products that need to be kept cold (vegetables, fish, meat, fruits…);

- Smaller vessels: the include fishing vessels, recreational boats or vessels of sea salvage service.

Dry cargo and container are the most important shipments. Dry cargo account for 63.9% of total goods loaded, increasing by 12.8% in 2004, 8.7% in 2005 and 13.5% in 2006 (UNCTAD, 2007). On the contrary, as reported by the AIS database of the Baltic Marine Environment Protection Commissions (HELCOM), Barge and Icebreaker results to be the smaller category.

Engines size

The 96% of installed engine power is produced by diesel engines and the great majority of ships are powered by slow-speed, two-stroke diesel engines (Eyring et al., 2005). Since pollution and energy consumption are strictly related to vessels size, the classification based on **Engines Size** is generally considered as the most important classification to analyze the environmental impacts of transport activities. In this paragraph two classifications are considered but a classification based on vessels size category and vessels activities is also reported.

The first one, proposed by the U.E. Environmental Protection Agency (EPA, 1999) identifies tree ships categories according to their sizes.

Category 1 considers ships that are similar to land-based of-road engines. They have a rated power at or above 37 kW and have a specific displacement of less than 5 liters per cylinder.

Category 2 considers the water-based counterparts of locomotive engines. They have a specific displacement of 5 to 30 liters per cylinder.

Category 3 considers ships that have very large engines with a specific displacement at or above 30 liters. They are used for propulsion in the large ocean-going vessels and correspond to land-based power plant generations. These ships are designed for maximum fuel efficiency but their emissions levels are very high.

The second classification, strictly related to energy consumption, considers the engines used to produce the power needed on ships. It distinguishes between the auxiliary and the main engines and classifies vessels into small, medium and large:

Small vessels have a main engine size of 3,000 kW and an auxiliary engine size of 500 kW.

Medium vessels have 10,000 kW of main engine and 1,500 kW of auxiliary engine size.

Large vessels have 25,000 kW of main engine size and 4,000 kW of auxiliary engine size.

The main engines are generally used to produce the energy needed for propulsion system. The auxiliary engines produce the energy needed on board for electricity, pumps cooling and hydraulic device (Mäkelä et al., 2002; Klokk, 1995). Based on the Entec report (2005) the small ships are the 60% of the total ships worldwide. The medium are the 30% and the large only the 10%.

Since energy consumption is strictly related to each operating activity (at sea, at berth or maneuvering), a classification based on vessels size category and activity can be useful to estimate the total amount of energy used. Table 1 reports the main results provided by Entec (2005). It estimated the energy consumption on the base of vessel activity, size and engine.

Table 1: Assumed per vessel activity by size and engine (MWh/year)

	Small	**Medium**	**Large**
Main Engine			
At Sea	14,400	48,00	120,000
At Berth	21	70	175
Manoeuvring	12	40	100
Total Main Engine	14,433	48,110	120,275
Auxiliary Engines			
At Sea	1,008	2,664	6,840
At Berth	157	414	1,064
Manoeuring	6	15	38
Total Auxiliary Engines	1,170	3,093	7,942
Total Usage	15,603	51,203	128,217

Source: Entec, 2005

As reported in table 1, if total energy consumption is considered, small vessels use less energy than large vessels. However, in unitary terms, large vessels results to be more efficient than small vessels. According to Shmid and Weisser (2005), in order to reduce the total energy consumption, the use of large ships, like container ship, tankers and bulk carriers, should be promoted.

Ages

Another way to classify the ships is based on **ages**. Tree categories are generally considered: new, young and old. Vessels are **new** if built in the last year, **young** if built in the last fifteen years and **old** if built before 1990 (Entec, 2005).

Assuming an annual renewal rate of 4%, Entec (2005) estimate that the new vessels are the 4% of the total population, young vessels are the 56% and old vessels are the 40% of the total population. According to the Entec report (2005), the main quantity of ships is old or young and only a small part is new.

Really interesting is the classification based on ages for groups of country. Table 2 reports the distribution of vessels by ages and world regions in 2007.

Table 2: Age distribution of the world merchant fleet, by type of vessel in 2007.

	Type of vessel	**0 – 4 years**	**5 – 9 years**	**10 – 14 years**	**15 – 19 years**	**20 – + years**	**Average age**
Developed Countries							
	Tankers	36.5	35.4	14.3	6.7	7.1	7.7
	Bulk carriers	19.6	25.5	23.9	6.1	24.9	11.9
	General cargo	14.9	23.9	15.8	12.8	32.6	13.7
	Containerships	30.6	31.6	19.1	8.8	9.9	8.9
	All others	22.4	19.9	15.0	10.7	31.9	13.0
	All ships	28.4	29.9	17.6	7.8	16.3	9.9
Developing Countries							
	Tankers	28.0	21.0	17.7	17.5	15.8	10.8
	Bulk carriers	23.1	18.3	18.6	9.6	30.5	12.8
	General cargo	9.6	10.9	10.7	8.5	60.4	17.9
	Containerships	35.9	24.4	19.3	7.2	13.1	9.1
	All others	17.6	12.9	10.5	7.8	51.2	15.9
	All ships	24.6	18.9	17.1	11.8	27.7	12.4

Source: Compiled by the UNCTAD (2007) on the basis of data supplied by Lloyd's Register – Fairplay.

The results reported in table 2 show that a similar age distribution exists between developed and developing countries: the main quantity of ships is old (more than 20 years) or young (less than 4 years) and the smaller percentage are between 5 and 19 years old. However, the average age for the ships of developing countries is higher than the average age of ships for developed countries (12.4 years for developing countries and 9.9 year for developed countries).

Interesting is the case of containerships. In developing countries, containerships are replacing general cargo vessels. As consequence, the 35.9% of the containerships are younger than five years and the old general cargo (more than 20 years) are the 60.4%. On the contrary, in developed countries containerships have yet replaced general cargo because only the 32.6% of them are more than 20 years old.

2b. Trends

As reported in the previous paragraph, maritime sector results to be largely heterogeneous and many ships categories can be identifies. Moreover, the increasing demand for transport services, generated by globalization and economic growth, contribute to differentiate the maritime supply.

Today, almost 90% of the world goods are carried by sea but maritime trade is expected to increase. Each year more than 30,000 vessels travel through EU water weighing more than 500 gross tones. At global level, maritime transport passed from 10,654 billion of ton-miles in 1970 to 30,686 in 2005, growing by 5,5% in 2006 (UNCTAD, 2007).

During the same period, also the number of new buildings vessels and the average vessel size increased. As reported in table 3, the deliveries of new buildings vessels passes from 786 in 1980 to 2,398 in 2006 and the average size increased from 22,901 dwt to 29,648 dwt. Moreover, since in 2007 the global ships new builder order had reached its highest level, also the prices for all vessel types augmented. The highest increasing rate was for tanker (+39.7% in 2007), followed by general cargo vessels +33.3% in 2007).

Table 3: Quantity and average size of new building vessels

	1980	**1985**	**1990**	**1997**	**2000**	**2004**	**2006**
No. of vessels	786	950	723	1,067	1,544	1,820	2,398
Average size	22,901	26,316	31,812	34,489	28,756	27,143	29,648

Source: Compiled by the UNCTAD (2007) on the basis of data from Fearnleys and Lloyd's Register – Fariplay.

As a consequence, the total energy consumption increased. Between 1970 and 1995, the energy final use in industrial sector augmented by 45%, while it growing by 90% in the transport sector (IEA, 1997; EUROSTAT, 2005; Ruzzenenti and Basosi, 2008). IMO (2007) estimates that annual fuel consumption by the global fleet amount to about 350 million tones a year and predicted marine fuel consumption would increase to 486 million tones by 2020.

Correlated with the trend in the delivery of ships is the trend in the demolition of ships. It is equivalent to only 0.6 per cent of the existing world fleet and, during the lasts decades, the average age at demolition has increased. In 2006, the highest age for demolition was for general cargo (32.3 years) followed by tankers (30 years) and containerships (28.1 years) (UNCTAD, 2007).

The increasing age for demolition and the increasing number in new buildings vessels generated an increasing number of ships.

3. EMISSIONS

Compared to other modes of transports, shipping has several advantages. It has few problems with traffic congestion, noise and use of land and the energy consumption is relatively low per unit of transported goods.

As reported in table 4, shipping is the most efficient mode for moving cargo, both for energy use and pollutant emissions. However, as emissions of air pollutants from land-based sources have diminished over the last decades, those from maritime transports show a continuous increase. Given the increasing rate of shipping activity, without stringent controls, shipping emissions are likely to become an even larger environmental problem in the near future (Corbett and Fishbeck, 1997).

Table 4: Comparative analysis for energy use and emissions

	Tanker	**Rail (diesel)**	**Truck**	**Air (Boeing 74)**
Energy Use (kWh/tkm)	0.01	0.07	0.18	2.00
NOx	0.15	0.35	0.31	5.69
Sox	0.10	0.1	0.01	0.17
PM	0.01	0.1	0.01	n/a
CO2	5	17	50	552

Source: INTERTANKO, 2008

Today, maritime transport account about 10% of total transport fuel consumption and international shipping account for 80% of maritime energy use. However, for the increasing volume of international movement, energy consumptions and air pollution are expected to increase. Since maritime transportation is widely recognized as a highly significant source of the total air pollution, the impact on air quality on sea and land is becoming an important topic for transport sustainability (UNCTAD, 2007).

As known, the combustion of marine fuels results in emissions of many pollutants, and diesel exhaust contains an estimated total of 450 different compound, such as sulphur dioxide (SO_x), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), carbon dioxide (CO_2) emissions and other (Maudley, 1992). In this report $NO_{x,}$ SO_x, and CO_2 emissions are considered.

3a. Emissions classification

Nitrogen Oxides (NO_x)

Nitrogen Oxides (NO_x) is the generic term for a group of highly reactive gases that contain varying amounts of nitrogen and oxygen. They can be divided into nitric oxide (NO) and nitrogen dioxide (NO_2) (Young, 2006).

Contributing to acidification, formation of ozone, nutrient enrichment and to smog formation, NO_x are deemed between the most harmful gases to the environment. They can be transported over long distances and generate problems to areas not confined to areas where NO_x are emitted.

Some of the most important health and environmental impacts generated by NO_x are:

Ground-level Ozone (Smog): Photochemical smog is formed when NO_x and volatile organic compound (VOC) react in the sunlight and unburned hydrocarbons. Ozone can be transported by wind currents and cause health impacts far from original sources. It generates damage to vegetation, crop and affect human health. It can compromise the immune system, generate emphysema, bronchitis and irritation of the eyes. It affects, in particular, children and people with respiratory diseases. Moreover, since particle smog is formed by PM (ultra-fine particles of soot) it can contribute to damage hearth and lungs.

Acid Rain: Acid rain is caused by NO_x and SO_x combining with water in the atmosphere and returning to the ground as mild nitric and sulfuric acid. They can deteriorate vegetation, crops, buildings and water of lakes, affecting freshwaters and terrestrial ecosystems. When acid precipitation becomes chronic in a watershed, it can exceed the buffering capacity of the soil, reducing growth of forests and leading to loss of flora and fauna.

Water Quality Deterioration: The nitrous oxide can lead to eutrophication of costal estuaries that can lead to oxygen depletion and reduce fish and shellfish population. Excess nutrient nitrogen causes species composition changes and biodiversity loss.

Global Warming: The nitrous oxide causes the formation of the ozone that is a greenhouse gas, which accumulates in the atmosphere, can cause a gradual rise in the earth's temperature global warming leads to a rise in the sea level, biodiversity loss, ecosystems changes and risk to human health.

Toxic Chemical: A variety of toxic products, which may cause health effects and biological mutation, can be generated by reaction between NO_x, ozone and common organic chemicals.

Since 1970, EPA has tracked emissions of the six principal air pollutants (carbon monoxide, lead, nitrogen oxides, particulate matter, sulfur dioxide, and volatile organic compounds). Emissions of all of these pollutants have decreased significantly except for NO_x which has increased approximately 10 percent over this period. Shipping is an important source of nitrogen and its share compared to other sources is rapidly increasing. According to information collected in the Baltic Sea, using the Automatic Identification System, the largest contribution is from ship built after the year 2000 and vessels with size above 8000 GRT. However, passenger ships have the highest fuel consumption and second highest NO_x production (Cofala et al., 2007).

Since NO_x emissions are formed during the combustion process, the quantity produced is a function of temperature, oxide concentration and fuel used. For this reason, the best way to reduce NO_x generation is to decrease the combustion temperatures. To do so, many technologies exist and the most important will be presented in the part 4 of this report.

Sulphur Oxides (SO_x)

Sulphur oxides are caused by the oxidation of the sulphur in the fuel into SO_2 and SO_3. They are formed during the combustion process through the reaction: $S+O_2= SO_2$ and are a function of the sulphur content in the fuel (Lyyranen et al., 1999; Flagan and Seinfels, 1998). Acid rain, health effects and climate change are some of the most important effects.

Health effects: They are caused by the exposure to high levels of SO_2 and include breathing problems, respiratory illness, changes in the lung's defenses and worsening respiratory and cardiovascular disease. People with asthma or chronic lung or heart disease are the most sensitive to SO_2. Shipping emissions have been estimated to induce more than 60,000 premature deaths globally, of which about one third in Europe (Corbett et al., 2007a).

Acid Rain: Since SO_x is corrosive, it contributes to damages trees and crops, generates acidification of lakes and streams, accelerate corrosion of buildings and reduce visibility.

Global Warming: SO_x forms aerosol which reflects sunlight and has a direct effect on cooling.

The SO_x emissions from land sources have decreased over the last years, while the SO_x ship emissions have increased (Olivier and Berdowski, 2001). Endresen et al., 2005, estimate that SO_x emission from international marine transportation in 2002 was abut 6.3 Tg. The 95% of this value is generated by the combustion of heavy fuel.

The best way to reduce SO_x is by reducing the sulphur content of the fuel. Unfortunately, low-sulphur fuels are more expensive to purchase (10 to 20% greater cost, when switching from 3.5% to 1% sulphur) and there is a practical lower sulphur limit desired as desulphurisation of fuel lowers the lubricity of the fuel which can lead to increase wear on fuel pumps and injectors. Moreover, the desulphurization of diesel exhaust gases can be achieved by wet scrubbing, but additional costs are incurred in disposing of the scrubbing products.

Today, SO_x regulation is predominately a regional issue. However, international pressure is growing for the oil producers to reduce the sulphur content of all fuels in order to control this problem at the source. The current EU Directive (2005/33/EC), which applies to all gas oil sold on land in the EU, is that the % sulphur content of fuels must remain below 0.2% with the aim of reducing this limit to 0.1% by the year 2010. Presently, most military navies use 1% low-sulphur fuels or lower. Special Areas have been set up, such as the Baltic, where the use of low sulphur fuels will be mandatory when Annex VI is ratified and will be limited to 1.5%.

Carbon Dioxide (CO_2)

CO_2 is one of the basic products of combustion. It is proportional to the content of carbon in fossil fuel. It is not toxic; however it is the main responsible of the “greenhouse effect” and global warming. Due to human activities, such as combustion of fossil fuels and deforestation, the concentration of atmospheric carbon dioxide has increased by about 35% since the beginning of the age of industrialization.

Transport account for the 25% of energy-related CO_2 emissions. Shipping account for approximately 2% of global anthropogenic emissions of CO_2 but the annual grow rate was close to 2.5% during the past decade (IMO, 2000).

Diesel is one of the most efficient engines for the combustion of fossil fuels. However, to reduce CO_2 emissions thermal efficiency should be increased and the amount of fuel burned should be reduced.

3b. Emissions Estimation

As reported above, the 90% of global merchandise is transported by ships and maritime sector is become the most important mode of transport for international trade. However, since diesel engines are generally used for vessels, large pollutants are emitted and maritime transport is becoming one of the most important fractions of air pollutants emissions in Europe. Annually, ships are estimated to emit 4.7-6.5 Tg SO_x, 5-6.9 Tg NO_x and 2-4% or global CO_2 emissions (Corbett et al., 2007). The general observation is that transport atmospheric emissions have increased during the 1990s in developed as well as developing country and are expected to continue to grow through time due to sheer growth in traffic volume. For the year 2020 SO_x and NO_x emissions are expected to amount approximately 30% of land-based emissions (Deakin, 2001). Moreover, since the 85% of ship emissions are discharged within the northern hemisphere, by 2020 the emissions from international shipping around Europe would have surpassed the total emissions from all land-based sources in the European member states (Corbett, 1999; EEB, 2004).

To reduce pollution and plan a sustainable transport activity[1], a reliable emission inventory is urgently needed. By means of engineering calculations, it is the foundation or baseline for other activities such air quality analysis and strategy development. To do so and to identify pollutants emitted by sources in geographic area information about:

1) **emissions sources**,
2) **vessel movement** and **vessel characteristics**
3) **estimation methods**

are needed.

1) **Emission sources**: Table 5 synthesizes the main emission sources for marine sector. Fuel quality and combustion temperature results to be the most important factors for pollutant quantification. However, since many other factors influence the amount of emissions (e.g. the fuel quality, the efficiency engines, the abatement technologies…), plurality of estimations can exists. For these reasons, quantification is a difficult task (Deakin, 2001).

[1] Sustainable transportation is defined as transportation that meets mobility needs while preserving and enhancing human and ecosystem health, economic progress and social justice now and for the future (Deakin, 2001).

Table 5: Air pollutant of marine sector

Emissions	Legislated by IMO	Source
SO_x	Yes	Function of fuel oil sulphur content
NO_x	Yes	Function of peak combustion temperatures, oxygen content and residence time.
CO_2	No	Function of combustion
CO	No	Function of the air excess ratio, combustion temperature and air/fuel mixture.
Smoke/Particulates	No	Originates from unburned fuel, ash content in fuel and oil.

2) **Vessels movement** and **vessels characteristics:** These information are generally provided by the Lloyds Marine Intelligence Unit (LMIU) database, and by the Lloyds Register Fairpaly. The first one includes all vessels above 500 gross registered tones but not the smaller. However, their movements can be estimated assuming to be operating closer to land and using lower sulfur marine fuels. In this case, a "top-down" approach can be adopted, by assuming that additional percentages of emissions are attributable to small vessels (IIASA, 2007).

3) **Estimation methods:** Significant progress in estimating international ship emissions has been made in the past decade and several global, regional and local inventories have been performed. Ship emission estimations are generally developed by a "bottom-up" approach or a "top-down" approach. The "bottom-up" approach estimates emissions for individual vessels combining ship-type specific engine emission modeling, global distribution methods and ship operation data. It multiplies the energy consumption of the ships with a certain emission factor and aggregates the value to estimate the total emissions (Endresen et al., 2003). The "top-down" approach estimates emissions dividing the aggregate numbers for the total EU over the different countries, ships or locations. Endresen et al. (1999), Corbett et al. (1999), Skjølsvik et al. (2000), Olivier and Berdowski (2001), and the Atmospheric Emission Inventory Guidebook (EMEP/CORINAIR, 2002) elaborated some of the most detailed methodologies for constructing fuel-based inventories.

As reported above, since a plurality of data is needed to estimate emissions, different values can be obtained. Table 6 reports some shipping SO_x emission inventory and illustrate variations with respect to emissions factors, calculation methodologies or reference years.

Table 6: Shipping SO_x emission inventory

Area	Source	Base year	Tg SO2
Worldwide	Endresen et al., 2005	2001	6.3
Worldwide	Corbett and Koehler, 2003	2001	13.0
Worldwide	Endresen et al., 2003	2000	6.8
Worldwide	Skjølsvik et al., 2000	1996	5.8
Worldwide	Olivier & Berdowski, 2001	1995	7.3
Worldwide	Corbett et al., 1999	1993	8.5
North sea/Baltic	Whall et al., 2002	2000	0.76
EMEP[2]	Whall et al., 2002	2000	2.58
NE[3] Atlantic	LR, 1995	1990	1.37
Baltic Sea	LR, 1998	1990	0.23
Mediterranean and Black Sea	LR, 1999	1990	1.25
Asia waters	Streets et al., 2000	1995	0.82

Source: Endresen et al., 2005

Within the European monitoring and evaluation programme (EMEP), the European Commission (2002) estimated that the European shipping fleet, using fuels with an average sulphur content of 2.7% m/m, emitted approximately 2,578 thousand tons of SO_x for the year 2000. However, over the past decade other reports have estimated emissions from marine transport sector (Lloyd's Register Engineering Services, 1995; Corbett et al., 1999; Skjolsvik, 2000).

Entec (2005) and IIASA (2007) provided two of the most important report about emissions estimation. They consider the ship movements between ports of the European Community and distinguish emissions for various sea areas, providing estimates for national and international movements. National movements are the movements between ports of the same country. International movements are them between ports of different countries.

Entec (2005) estimated CO_2 emissions of vessels in the EMEP region, which include the North Sea, Irish Sea, English Channel, Baltic Sea, Black Sea and Mediterranean. Based on year 2000, it uses the data collected by Lloyds Marine Intelligence Unit (LMIU) that includes information about vessel type, size and flag and considers all movement of whips world-wide. Emissions were calculated based on vessel specific emission factors. It estimated that, during 2000, 157 Mt of CO_2 has been emitted in the EMEP region.

In 2005 another report elaborated by Entec estimated the total amount of SO_2 and NO_x emissions. It calculated the emissions in EU water considering a distribution of times spent in EU waters and distinguishing between engines, dimensions and operations of vessels. It concluded that marine sources contribute about 14% of worldwide NO_x emissions and 6.5% of all SO_x emitted by fuel. Table 7 reports the main results and shows that the vast portion of emissions occurs while at sea. This report

[2] EMEP: NE Atlantic and Black and Mediterranean Seas
[3] NE: Northeast.

also estimated that the 85% of emissions take place in the northern hemisphere and the 70% within 400 km of land. In North Sea, for example, the 90% of emissions is emitted within 90 km of land (Wahlstrom et al., 2006).

Table 7: Estimated annual NO_x and SO_x emissions per vessel (tonne/year)

	Small		**Medium**		**Large**	
	NO_x	**SO_x**	**NO_x**	**SO_x**	**NO_x**	**SO_x**
Main Engine						
At Sea	216	158	720	528	1,800	1,320
At Berth	0.3	0.2	1.1	0.8	2.6	1.9
Manoeuvring	0.2	0.1	0.6	0.4	1.5	1.1
Total Main Engine	216	159	722	530	1,805	1,323
Auxiliary Engines						
At Sea	15	11	40	29	103	75
At Berth	2.4	1.7	6.2	4.6	16.0	11.7
Manoeuring	0.1	0.1	0.2	0.2	0.6	0.4
Total Auxiliary Engines	18	13	46	34	119	87
Total Usage	234	172	768	564	1,924	1,411

Source: Entec, 2005

To estimate emissions, an alternative approach has been adopted by IIASA, which used the EMEP unified model to compute the atmospheric dispersion of ship emissions. The EMEP model is a multi-layer atmospheric dispersion model for simulating the long-range transport of air pollution over several years (Simpson et al., 2003; Fagerli et al., 2004; Jonson et al., 2006). It includes 70 species and 140 chemical reactions. Moreover, the EMEP Eulerian atmospheric dispersion mode, that describes the atmospheric dispersion of ship emissions, has been used to derive source-receptor relationship. This information is very important in order to perform a cost-effectiveness analysis. To do so, IIASA has used the RAINS/GAINS model.

Tables 8 and 9 report the estimation of CO_2, SO_x and NO_x emissions provided by IIASA. It calculated that, in 2000, SO_x and NO_x emissions from international maritime activities amounted to 30% of the land-based emissions in the EU-25 (IIASA, 2007). However, their contribution is expected to augment for the future increase of ship movements. Table 8 reports emissions from larger vessels (≥ 500 GRT) and table 9 reports emissions from all vessels.

Table 8: Emissions from larger vessels (≥ 500 GRT) by sea region for the year 2000 (kilotons/year)

Sea area	CO_2	SO_x	NO_x
North Sea	29,664	496	693
Black Sea	3,721	62	86
Mediterranean	75,484	1,251	1,781
Baltic Sea	12,727	212	299
NE Atlantic	31,109	522	764
Total	**152,705**	**2,543**	**3,623**

Source: IIASA, 2007

Table 9: Emission from all vessels by sea region for the year 2000 (kilotons/year)

Sea area	CO_2	SO_x	NO_x
North Sea	30,878	516	720
Black Sea	3,852	65	89
Mediterranean	77,140	1,278	1,818
Baltic Sea	13,447	224	315
NE Atlantic	31,673	532	777
Total	**156,989**	**2,615**	**3,719**

Source: IIASA, 2007

This estimation reveals that larger vessels are the main responsible for the air pollution emitted in the considered geographical areas and smaller vessels add between 2 and 6% to total emissions. Since smaller vessels are predominantly part of national fleets they are not involved in international trade.

Another estimation of the proportion of air pollutant emitted from ships has been proposed by Farrel et al., (2003). They provide an intermodal comparison of transport emissions for US case study. They found that, in 2003, large ships generated the 30% of total nitrogen oxides emissions. They estimate that: a single cargo ship coming into harbor can release as much pollution into the sky as 350,000 cars in one hour; 16 container ships in port produce as many emissions as one million cars; a cruise ship, in port, produces as many emissions as 12,400 cars. Table 10 reports the main results of their intermodal comparison analysis.

Table 10: Intermodal comparisons

	Emissions (g/kg fuel)[4] NO_x	CO_2	Carbon intensity[5] ($/tC)	Fraction of CO_2 (%)	Size of fueling station (power)	No. of fueling stations
Marine	71	16	950	6	175 MW	28-40[6]
Autos[7]	14	130	2300	56	2.7 MW	180,000
Aircraft	3	17	2100	8.7	240 MW	72[8]
Heavy trucks	30	17	2800	16	20 MW	5,500
Rail	76	9	3500	2.3		

Source: Farrell et al., 2003.

Sea shipping results to be the most environmental friendly mode of transport for goods, when measured in terms of emissions per ton-km (tones of goods per km). However, for the absence of an emission reduction strategy, the growth rate of maritime shipping, which is expected to continue in the future due to the global supply chain, will be translated in an emissions growth of the same magnitude. Same results have been found by INTERTANKO (2008), as reported in table 4.

Many other reports estimate the amount of pollutant emissions and other calculate the trend for future emissions. The European Commission's Clean Air For Europe (CAFE) (Amann et al., 2004) programme calculate that, between 2000 and 2020, the SO_x emissions from international shipping will double and NO_x emissions are expected to increase by two thirds. Based on this data, NO_x and SO_x emissions from shipping in Europe will be bigger than land-based emissions. Similar results have been obtained by IIASA (2007). It estimates that SO_x and NO_x emissions from international shipping will increase by 42 and 47% respectively.

[4] Computed using estimated actual emissions and fuel use
[5] End user expenditures divided by carbon emissions
[6] Total of companies in the large U.S. ports providing international marine fuels
[7] Includes both automobiles and light trucks.
[8] Large hub airports.

3c. International legislation

As reported in the previous paragraph, the increasing amount of emissions generated by the maritime sector is becoming a serious problem for human and environmental well-being. For this reason, legislative actions oriented to regulate the air pollutant emissions, have been taken on global and national levels.

Currently, the Annex VI Act of the MARPOL 73/78 established by the International Maritime Organization[9] (IMO) and the EU directive (2005/33/EC) are the most important legislations for ship operation. The main difference between the IMO and the EU strategy is that IMO opens for exhaust gas cleaning, which imposes the use of sea water scrubbing. The EU strategy only opens for trials with abatement technologies on scientific basis, and will accept this if the results are satisfactory (European Union, 2002; European Union, 2004).

At international level, the most important international legislations are: the United Nations Convention of the Law of the Sea (UNCLOS) and the MARPOL 73/78 Annex. The UNCLOS provides a universal legal framework for the management of marine resources and their conservation. It was elaborated in 1973 to regulate navigational rights, territorial sea limits and economic jurisdiction but provide also a legal framework for the protection and preservation of the marine environment. The MARPOL 73/78 Annex VI, put into force in May 2005, is a regulation for the prevention of air pollution from ships. It is a part of the "International Convention for the Prevention of Marine Pollution from Ships" elaborated in 1973 and modified by the Protocol of 1978. It regulates the emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), ozone-depleting substances and volatile organic compounds (VOC). It also introduces sulphur emission control areas (SECA) where more stringent control on sulphur emissions has to be applied in order to prevent, reduce and control air pollution from SO_x and its attendant adverse impacts on land and sea areas. Moreover, in 2004 the Marine Environment Protection Committee of IMO adopted the resolution A.963(23), oriented to reduce greenhouse gas emissions from shipping. It considers all new vessels constructed after 1st January 2000 and the engines over 130kW, which undergo major conversion after 1st January 2000. It states that:

- The sulfur content of fuel oil must not exceed 4.5% m/m world wide, or 1.5% m/m for ships operating within SO_x Emission Control Areas (SECA). However, the IMO

[9] International Maritime Organization is the United Nations specialized agency with responsibility for prevention of marine pollution and safety of shipping.

legislation would reduce the maximum sulfur content in fuel from 4.5% to 3.5% beginning January 2012 falling to 0.5% in January 2020.

- For SECA they will be reduced from 1.5% to 1.0% in March 2010 and to 0.1% in January 2015.
- Actually world's only SO_x Emission Control Areas (SECA), that are the most impacted and sensitive maritime areas, are in the Baltic Sea and in the North Sea but other are under consideration. The east and the west coasts of United Stated and Canada, as well as Mediterranean Sea, Hong Kong and Tokyo Bay are some of them.

Moreover, the generation of NO_x will be restricted within the following limits:

- 17.0 g/kWh when the maximum engine speed is less than 130 rpm;
- $45.0*n^{(-0.2)}$ g/kWh when the maximum engine speed (n) is more than 130 but less than 2000 rpm;
- 9.8 g/kWh when the maximum engine speed is greater than 2000 rpm.

As reported above, IMO legislation regulates SO_x and NO_x emissions. However, since many pollutants are emitted by combustion, a more extensive regulation able to consider other emissions, like smoke, particulate and CO_2, should be established. The Marine Environment Protection Committee (MEPC), which is part of IMO, suggested a number of short and long terms measures to reduce CO_2 emissions but no mandatory restrictions have been imposed. Since today targeted reductions of greenhouse gases from shipping are not included in the Kyoto protocol (Endresen et al., 2003). In addition, no international or European regulation is applied to fuel consumption or CO_2 emissions from shipping (Kageson, 2007).

At European level, more stringent regulation to decrease the atmospheric emissions from seagoing ships and reduce the impacts of marine transport on acidification, ground level ozone, eutrophication, climate change and ozone depletion has been developed. The Sulphur Content of Certain Liquid Fuels Directive (1999/32/EC) and the Directive 2005/33/EC are some of the most important. According to this legislation, all ships at berth (exception for short-stay vessels and ships switching off all engines and using shore-side electricity) have to use less than 0.1% sulfur fuel and less than 1.5% sulfur fuels have to be used for ships in English Channel, Baltic Sea and North Sea and for all ferries in EU water. Exhaust gas scrubbing technologies can be use as alternatives. Moreover, to improve air quality around ports and inland waterways, by 2010 ships staying for more than 2 h in port must use shore side electricity or fuel with sulphur content less than 0.1%. The EU is also considering to include ship emissions in the EU emissions trading scheme (ETS), aiming to increase the use of renewable fuels and developing more efficient technologies to reduce emissions.

Table 11: Timetable of maritime emissions regulation

2004	MARPOL Annex VI ratification
2005	14 April 2005: EU Parliament passes Sulphur Directive 1999/32/EC 19 May 2005: Global sulphur limit 4.5%; Scontent on BDN 22 July 2005: Publication of Sulphur Directive 2005/33/EC
2006	19 May 2006: Baltic Sea SECA 1.5% 11 August 2006: EU Member States laws enacted: 1.5% in Baltic SECA; 1.5% for all passenger ships sailing between EU ports; Use of abatement technology as an alternative to 1.5% fuel
2007	11 August 2007: North Sea SECA 1.5% November 2007: North Sea SECA 1.5% Review MARPOL Annex VI
2008	EU commission review on: further restrictions on sulphur in marine fuels possibly down to 0.5%; additional SECAs; alternative measures including proposals on economic instruments
2010	January 2010: 0.1% sulphur limit on all marine fuel used in EU ports

4. ABATEMENT TECHNOLOGIES

As reported in the previous paragraph, the quantities of air pollutant from ships are so high that it is an urgent matter to reduce it. Many methods exist but most of them are at an early stage of development and limited information is available. The combined cycle[10], for example, might be a viable option for the future (Horlock, 2002). However, since it has rarely been used in the past, it is difficult to present a reliable cost figures for marine applications. For these reasons the combined cycle will not be considered in this report.

This report investigates some of the most important reduction measures on ships. In general terms, they can be divided into NO_x, SO_x and CO_2 abatement technologies and can be oriented to reduce pollutants on fuels or to reduce emissions after combustion. Other alternatives are the Shore Side Electricity, the ships' design (Sorgard et al., 2001) or a change in the whole transport system (Shmid and Weisser, 2005).

In the next paragraphs, the shore side electricity and the main NO_x, SO_x and CO_2 abatement technologies are considered. Beside a technical description, estimations about mid range values of emissions reduction efficiencies are reported.

4a. Shore side electricity

Generally, when ships are in port, they produce electricity using their Auxiliary Engines (AE). Since marine fuel oil is used, large quantities of emissions are generated. Shore-connected electricity can be used to replace the burning of marine fuel oil in ships' auxiliary engines while berthed at quay. Providing electricity from the national grid, it contributes to reduce emissions and noise. The stringent emissions control imposed on land based power plants and the alternative type of electricity production process, base on renewable energies, allows reducing the emission factors. The advantages of shore-side electricity are recognized by the European Commission, which in its Communication from November 2002, on an EU strategy to reduce atmospheric emissions from seagoing ships, urges port authorities "to require, incentivize or facilitate ships' use of land-based electricity or clean onboard

[10] Combined cycle is generally used for power production and is a plant in which higher thermodynamic cycle produces power, but all or part of its heat rejection goes to supply heat to a lower cycle. However, since it needs to be fairly larger in order to attain a high efficiency it can be applied only on large ships.

power while hotelling in port" (COM(2002)595final). Moreover, EU ports welcomed the Commission's recommendation of May 2006 on the use of shore side electricity (2006/339/EC) (Entec, 2005a).

In order to provide shore side electricity a connection to the national grid is needed and technical requirement have to be installed on ports and ships. Flexible cables have to be provided between the quay and the ship and high voltage electricity have to be available nearby the port. Actually there are no existing standard for shore-side electricity supply systems, but the general principles for modern high voltage systems would anyway be the same (Agren, C., 2004).

There are examples of shore-side electricity being used in various parts of the world. However, only very few ports have applied this system, and consequently there is an urgent need for action. Coordinate measurement should be applied to ensure the development of uniform systems between ships and ports.

A recent study on shore-side electricity from ships, produced on behalf of the North Sea Commission, investigated its practicalities, costs and benefits. It shows that health and the environmental benefit are achieved, however they depends on a number of factors, such as the time the vessel is berthed at quay, the fuels used the engines etc… From an economic point of view, a comparison shows that direct generation costs are higher for shore-side power than for onboard power. That is because energy taxes are paid for land-based electricity and no taxation is applied on marine fuel oil. However, if externalities are taken into account, the outcome is completely the opposite (MariTermAB, 2004).

4b. NO_x

To reduce NO_x emissions technological improvement can be applied. However, the type of fuel used is determinant in the composition of the emissions. Generally, marine fuels are classified as fuel oil and distillate. Fuel oil refers to residual fuel oil manufactured at the "bottom end" of an oil refining process. The most commonly term used for this fuel is the heavy fuel oil (HFO). It is the heaviest of marine fuels and contains significant amounts of sulphur. Its average sulphur content is 2.7% mass, 90% higher than conventional diesel or petrol (Butt, 2007). However, for economical reason, it is the largest used (Endresen, 2003). Distillate fuel can be divided into marine gas oil (MGO) and marine diesel oil (MDO). MGO is a light distillate fuel containing no residual components and light aromatic hydrocarbons. MDO can contain residual fuel oil and is a heavier distillate (Wilde et al., 2007).

To reduce pollution, the denitration, oriented to remove some of the nitrogen from the fuel, can be a useful solution (Beicip-Franlab, 2002). However temperature and engine speed has been found to be important factors to determine pollutant emissions, which are one of the main by-products of the combustion process. For this reason, one of the most successful approaches to lower NO_x emissions is to reduce the peak temperature during combustion. To do so, many methods exist. However, some of them are at an early stage of development and limited information is available.

In general terms, abatement technologies can be divided into dry and wet methods. Dry methods involve of optimum shape of the combustion chamber, high compression ratio, fuel injection equipment, optimized turbo-charging system for correct air to fuel ratio and internal cooling of the cylinder by earlier closing of the air intake valves. The wet methods introduce water into the combustion chamber. They can be directly includes on new ships or incorporated to existing engines. Improving the existing design and making the combustion process more efficient, they reduce the waste gases and the associated pollutants (Wartsila Corporation, 2004).
The main technologies can be divided into three methods: **pre-treatment**, **primary** (or internal methods) and **secondary** (or after-treatment methods). However, not every one of them can be applied to every ship design.

Pre-treatment methods go to modify the fuel in order to reduce its quantity of pollutants. Since diesel fuel contains environmentally damaging matter, once the fuel is consumed SO_x, NO_x, CO_2 and PM are vented through the exhaust system to the atmosphere. By decreasing the amount of harmful agents within the fuel, fewer pollutants are generated. Three methodologies are generally used:

1. **Denitratio of fuel**: It is oriented to remove some of the nitrogen from the fuel in order to reduce NO_x emissions. Generally, for each 0.1% nitrogen in the fuel, 0.6 g/K Wh of NO_x is produced. Unfortunately, since today there is no practical method of removing nitrogen from the fuel available within reach of industry.

2. **Using alternative fuels**: Diesel fuel contains environmentally damaging matter and the major pollutants in diesel exhaust emissions are a direct result of the diesel combustion process itself. Two are the main alternative fuels that can be use for ships. One is the methanol and the other is the liquid petroleum gas (GPL). If methanol is combined to Exhaust Gas Recirculation, NO_x can be reduced as much as 50%. However, methanol is a more expensive fuel than distillate and its use requires modification to engine injection system and fuel storage. Liquid petroleum gas is a low sulfur fuel that combined with the use of pilot injection can reduce the NO_x emissions by 60%. The main problem is the storage that can compromise safety on board (Sudiro and Bertucco, 2008).

3. **Emulsified fuel**: It reduces pollutant emissions by adding water on fuel. Producing a more complete combustion with lower fuel consumption it cut the amount of NO_x, CO and PM. It has been in use since 1984 on stationary low speed diesel engine plants. However, smaller ships could have spatial problem, because additional equipments are needed for generating the water/fuel mixture. Larger fuel pumps and water tank are some example. Moreover, since the water used for emulsification must be clean and without salts, a water distiller system is needed (Sorgard et al., 2001). In theory, large reduction of NO_x is possible, but the reduction rate is proportional to the amount of water added to the fuel. MAN B&W reports that for each 10% of water added a 10% NO_x reduction can be achieved (MAN B&W, 2004).

Primary methods: They involve changes to the combustion process within the engine. Generally, they are defined “Internal Engine Modification” (IEM) and are oriented to optimize combustion, improve air charge characteristics or alter the fuel injection systems thank to engine modification. Since many parameters influence the combustion efficiency and emission formation, many technological changes has been proposed. Large parts of them aim to cut NO_x emissions reducing peak temperature and pressure in the cylinder The Internal Engine Modification (IEM) can be divided in two main categories and in five sub-categories. The main categories are the Basic and the Advanced (Entec, 2005b).

Basic IEM: It changes the conventional fuel valves with low-NO_x slide valves. The purpose is to optimize spray distribution in the combustion chamber without compromising on component temperatures and engine reliability. Currently, the Basic IEM is only applicable for slow-speed 2 stroke engines. Since all cylinders can be changes simultaneously, installation can take a day per engine and is not require being in dry dock. However, all new engines of this type are though to have these valves fitted as standard. Slide valves provide a reduction in NO_x, VOC and PM emissions (Aabo, 2003).

Advanced IEM: They are optimized combinations of a number of IEMs developed for particular engine families. They include: retard injection, higher compression ratio, increased turbo efficiency, common rain injection, etc. The most common combination used is increased compression ratio, adapted fuel injection, valve timing and different nozzles (EPA, 2003). A reduction rate of 30-40% in NO_x emissions is generally achieved. Wartsila, Caterpillar and FMC are the main manufactures. However, advanced IEM for ships are generally still in the development phase (Wartsila Corporation, 2004).

Since today, the most used Internal Engine Modification (IEM) includes (EPA, 2003; Sarvi, 2004):

1. **Modification of combustion:** To modify combustion many methods exists.

   Injection timing retardation: By retarding the fuel injection timing, it reduces temperature and the maximum combustion pressure. Combined with other technology oriented to reduce HC and PM, it allows reducing 30% of NO_x emissions (EPA, 2003; Trozzi and Vaccaro, 1998). However an engine redesign may be required because engine efficiency can be reduced.

   Increase of Injection Pressure: It is generally known as the "Common Rail Technology". It 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). Optimizing the fuel injection it allows reduces NO_x, particulate and CO_2 leading to better atomization of the fuel. From an economic point of view, total costs can increase because stronger injection equipments, as fuel pumps, accumulators, injectors and control unit, are needed.

   Modification of compression ratio: It is the Miller Cycle Technology that reduces the compression ration, high pressure turbo-changing, variable air inlet valve timing and charge-air cooling. Reducing the temperature in the combustion chamber, it allows cutting down NO_x

emissions. Wartsila has applied this technology reaching 35% reduction of NO_x emissions (Wartsila, 2004a).

Optimization of Induction Swirl: It improves the combustion process by assisting air/fuel mixing. However, there is presently a great debate as to the benefits of swirl with respect to NO_x reduction. Since it will not in itself reduce NO_x, other techniques have to be combined.

Modification of Injector Specification: NO_x can be reduced optimizing the spray pattern of the fuel within the combustion space. Changing the fuel nozzle design, mini-sac type nozzles and slide valve, can reduce NO_x emissions by 30%, achieving also a reduction of smoke and particulate matter.

Change in Number of Injectors: The combustion process can be made more efficient increasing the number of injectors per cylinder. This can reduce NO_x emissions from 30%. However increasing costs are generated by additional injectors, piping, associated equipment and maintenance.

Modification of Air Intake System: It is generally knows as “Turbo-Charging” and “Charge-Air After-Cooling” technologies. It can take the form of either the modification of the scavenge/charge-air cooling or the modification of the scavenge/charge air pressure.

Scavenge/Charge Air Cooling: This technology reduces NO_x formation by reducing temperatures in the combustion chamber. To do so, cool compressed air is used. Lowering the scavenge temperature from 40 to 25 ^{o}C it reduces the 40% of NO_x generated during combustion. Since today this method is available only for high-speed diesel and its success is strictly dependent on atmospheric and seawater conditions. Moreover, the additional water supply and the cooler requirement increase the cost of engine.

Increasing the Scavenge/Charge Air Pressure: It reduces PM emissions because enables particles to oxide more efficiently. Combined with other methods, such as injection retardation, this method can reduce NO_x emissions of 10 to 40% (Karila et al., 2004). Since it has to be combined with other techniques, the engine cost can increase.

2. **Water injection:** It is a promising approach for NO_x reduction, because reduce the combustion temperature adding of water to the combustion process. 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 of the modes 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. Problems can exist for higher engine costs and for potential corrosion problem. A cost reduction can be reached injecting water using the same injector as the fuel. However this technique is still in development phase. Wartsila and Man B&W are the main producer of Water Injection technologies. In 2005 it was commercially installed on 23 ships. In these cases, water to fuel ratio of the 40-70% is required to achieve a 50-60% NO_x reduction. Water Injection can also be applied in combination with internal exhaust gas recirculation (EGR). In this case up to 70% reduction in NO_x emissions below the IMO limit might be obtain. Two particular methods of water injection are:

Direct Water Injection: It injects the water into the engine cylinders right after fuel injection (Sarvi, 2004).

Direct High Pressure Water Injection: injects the water during the fuel injection. The main advantages are: the water is close to the flame and away from the wall and the fuel-water percentage can be changed for various operating systems (Sarvi, 2004).

Unfortunately, they increase the fuel consumption and smoke emissions and, considering the elevated costs, they have a short lifetime (Eilts and Borchsenius, 2001).

3. **Exhaust Gas Recirculation (EGR):** Thanks to recirculation process, a portion of exhaust gases is filter, cooled and circulated back to the engine charge air. Decreasing the peak cylinder temperature, it reduces the formation of NO_x during the combustion process. Entec reports the reduction of 35% in NO_x emissions (Entec, 2005b). On the contrary, smoke and PM tend to increase because of the reduced amount of oxygen and longer burning time. Moreover, since exhaust gases contain gaseous sulfur species, a corrosion problem from sulfuric 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. At the present, the EGR is available only for ships using 0.2% sulfur marine distillate. Other limitations are: the long installation time, the large space required and the accelerate deterioration of the combustion chamber (Entec, 2005b; Klokk, 1995).

4. **Humid Air Motor (HAM):** It is an alternative to water injection that uses seawater to add water vapour to the combustion air. Based on decrease of combustion temperature it reduces the NO_x formation up to 80% (Eyring, et al., 2005). From an economic point of view, high

initial costs have to be sustained to install the humidifier, which also require large surface and volume. However, the low consumption of fuel and lubricating oil consumption allows reducing the operating costs of the engine. The University of Lund in Sweden conducted many installations research and development. The first installation has been tested on 1999 and today, the MAN B&W has applied this technology in the Baltic Sea ferry Viking Line's MS Mariella. SAM and Wetpac are similar techniques. Mariella use the HAM method in daily operation and emissions has been reduced from 17 to between 2.2 and 2.6 g/k Wh. According to Mariella's experience also fuel consumption has decreased (2-3%) (Det Norske Veritas, 2005).

Secondary methods: These methods are centered on treating the engine exhaust gas itself either by re-burning the exhaust gas or passing it through a catalyst or plasma system.

1. **Re-burning:** This method reduce the NO_x emissions reintroducing the fuel into the exhaust gas. It is then re-heated in a boiler but at significant less temperature than the combustion within the diesel itself. The main drawbacks are that the thermal efficiency is reduced and that a significant increase in cost and space requirements occurs (IIASA, 1998).

2. **Selective Catalytic Reduction (SCR):** It uses catalyst to covert NO_x emissions into nitrogen and water by reaction reducing agents such ammonia (NH_3) or urea ($CO(NH_2)_2$).

   $NO_x + NH_3 \rightarrow N_2 + H_2O$

   $NO_x + CO\ (NH_2)_2 \rightarrow N2 + H_2O + CO_2$

   It is based on a reaction between urea – decomposed to ammonia (NH_3) - and NO_x in the flue gas over a catalyst. NO_x is then reduced to nitrogen (N_2). Urea solution is injected into the hot flue gas after the combustion. The urea injection is automatically tuned to power changes in the engine. The catalyst is made from titanium oxide and vanadium oxide and consists of small exchangeable units (monolites of extruded ceramics). Urea can be delivered with a road tanker directly to the ship; however the transport costs can be significant (Entec, 2005b). SCR is one of the very few established techniques to achieve significant NO_x reductions and also particle emissions may be reduced but this is not well documented. No limitations exist about the ships types. Actually it is installed on both low and medium speed diesel engines and allows reducing NO_x emission up to 90-95%. To reach 90% NO_x reduction 15 g of urea are approximately needed per kWh energy from the engine (EEB et al., 2004). Moreover, lower fuel consumption can be combined with low

NO_x emissions because the engine may be fuel-optimized. The most critical problems are the space requirement for the catalyst elements and storage of ammonia or urea and also the investment and operational costs are appreciable. Time of installation may vary between 1 and 3 weeks. Its lifetime is relatively long but depends on the fuel. A low sulphur (max 0.2%) system has been in operation for 14 years and heavy fuel oil can reach 40,000 hours of operation. Clean fuel will prolong the life of the catalyst and decrease the maintenance necessary. Once installed it is in most cases operating nearly 100% of the time (Trozzi and Vaccaro, 1998; Sorgard et al., 2001). It has been in commercial use since 1989 and actually it is installed on more than 300 engines world-wide (Munters web site).

3. **Selective Non-Catalytic Reduction (SNCR):** It works similarly to Selective Catalytic Reduction but without use of catalyst. A reducing agent (ammonia or urea) injected during the combustion process, transform the nitrogen oxides to nitrogen and water, reducing a 50% of NO_x emissions (Sorgard et al., 2001; Marintek, 1999). The drawback of the system is that it is less efficient that the Selective Catalytic Reduction, because only 10-12% of ammonia react 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 engine, the SNCR don't seems to be competitive.

4. **Plasma Reduction Systems:** Plasma is a partially ionized gas comprised of a charge of neutral mixture of atoms, molecules, free radicals, ions and electrons. Electrical power is converted into electron energy and the electrons create free radicals, which destruct pollutants in exhaust emissions. Experiments have shown that NO_x can be reduced 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 development phase.

5. **WiFE on Demand:** It is a system that reduces NO_x emissions providing water in fuel emulsion "on demand". It is really useful in environmental and legislative hot spots. It is a fuel emulsion technology for marine vessels that recycles oily waste water from on board for safe use in the combustion process, eliminating the need for costly disposal of oily waste on shore. It can work with a variety of water to fuel ratios, from 0% to 50%, on the base of the water available on the vessel and in proportion that is appropriate to specific operating conditions. A 30% of water in fuel emulsion can reduce NO_x emissions by 30% and particulate matter (PM) by 60-90%. The lower temperature and greater combustion from the water in fuel emulsification result in a reduction in nitrogen oxides in a one-to-one relationship with the emulsion's water content and

a reduction of particulate matter equal to 2 to 3 times the emulsion's water content. It is one of the few technologies that decrease NO_x and PM simultaneously. It is retrofitted to a variety of vessel types and fuel system and its unit's size is determined by the engine size and configuration. However, in old ships a greater emission reduction is achieved. It works particularly well in the greatest polluters, built prior to the new engine emissions standard for new builds in 2000. From an economic point of view, it seems to be a cost-effective pollution solution. The equipment cost is about $250,000 and the cost to reduce emissions is $78 per ton of NO_x reduction and $271 per ton of PM reduction (Sea to Sky web site).

As reported above, some of these methods are at an early stage of development. Today, the most useful technologies are:

- Internal Engine Modifications (IEM)
- Direct Water Injection (DWI)
- Humid Air Motors (HAM)
- Exhaust Gas Recirculation (EGR)
- Selective Catalytic Reduction (SCR)

Table 12 summarizes the main NO_x abatement technologies and the average value of emission reduction.

Table 12. Technical solution and NO_x emissions reduction

Measure	% NO_x emissions reduction
Pre-treatment Methods	Related to the nitrogen content of fuels.
Primary Methods	
Modification of combustion	
- Injection retardation	30%
- Increase of Injection Pressure	N/A
- Modification of compression ratio	35%
- Optimization of Induction Swirl	N/A
- Modification of Injector Specification	30%
- Change in Number of Injector	30%
- Scavenge/Charge Air Cooling	40%
- Increasing the Scavenge/Change Air Pressure	10 – 40%
Water Injection	
- Water Injection	50 – 60%
- Water Injection + EGR	70%
Exhaust Gas Recirculation	35%
Humid Air Motor	80%
Secondary Methods	
Re-burning	N/A
Selective Catalytic Reduction	90 – 95%
Selective Non-Catalytic Reduction	50%
Plasma Reduction Systems	97%
WiFE on Demand	30%

4c. SO_x

Sulphur oxide is a pollutant emissions 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 (Cooper, 2004). In 2005, the European Commissions established that, from January 2010, the marine fuels used at berth shall not exceed 0.1% sulphur content. However, to reduce sulphur oxide emissions abatement technologies can also be used and literature documents several dozen of them (Rentz et al., 1996; Takeshita, 1995).

In this report six of the main abatement technologies are considered.

They are:

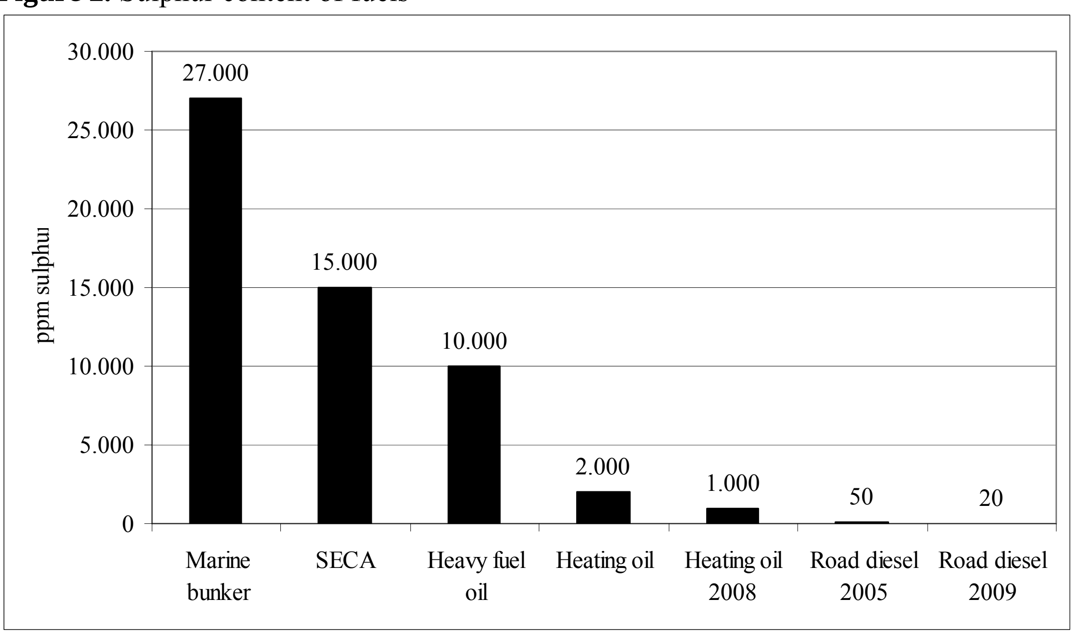
1. Combustion modification
2. Fuel switching

3. Desulphurization
4. Changes in energy system
5. Sea Water Scrubbing
6. Fresh Water Scrubbing

1. **Combustion modification:** It uses the addition of limestone ($CaCO_3$) or dolomite ($CaCO_3$*$MgCO_3$) into conventional boilers. Usually, the process injects limestone into pulverized coal-fired boiler, which achieves emission reduction rated 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 is the large amounts of waste that are produces. This can be a problem for the increasing difficulties with waste disposal and costs.

2. **Fuel switching:** Maritime transports generally use bad quality fuels with high contents of sulphur. As reported in Fig. 2 a comparison between sulphur content of various fuels shows that marine bunker has the highest share. That is because diesel engines usually run on heavy fuel oil that is a residual fuel oil manufactured at the "bottom end" of the oil refining process.

Figure 2. Sulphur content of fuels



Source: UNCTAD, 2007

Since the sulphur emissions are proportional to the sulphur content on the fuel, the easiest method for reducing sulphur oxide emissions is to use fuel with lower sulphur content. Three alternatives are available: the use low-sulphur fuels, the use of ultra-low sulphur fuels and the use of alternative fuels.

Low Sulphur diesel fuel: It is the fuel that contains fewer than 500 parts per million sulphur (0.5%). It reduces sulphur emissions and has a decreasing effect on particulate matter emissions (EEB et al., 2004). A study of Ritchie et al., (2005) shows that a switch from 2.7% to 1.5% sulphur content on fuel will reduce PM emissions by 18% and a switch to fuel with 0.5% sulphur content will decrease PM emissions by more than 20%. At the moment, low sulphur marine gas oil (MGO), which possesses 0.2% sulphur content, is available. However, in order to use this fuel, a capital investment is required. The vessels have to be re-equip with fuel storage and delivery systems and special controls must be incorporated into distribution schemes. In addition, the different fuel oil grades may require use a different lubricating oil grades and technical modification for fuels storage and handling system on board (Schmid and Weisser, 2005).

Ultra-Low Sulphur diesel fuel: It is the fuel that contains fewer than 30 parts per million sulphur (0.03%). Also in this case, capital investments are needed to re-equip the vessel's fuel storage and the delivery system. Moreover, since the ultra low sulphur fuel doesn't contain enough sulphur to provide lubrication, a synthetic lubricant additive have to be mixed with the fuel prior to use (Schmid and Weisser, 2005).

Alternative fuels: Other fuels can be used to replay diesel fuels. Biofuels, natural gas and hydrogen are some of them. Generally, for fuel switching techniques, vessels have the option of either entirely switching to alternative fuels or operating on dual-fuel mode, with separate fuel storage tanks for each fuel. The European Commision's White Paper (1997) on renewable energy sources estimated the bioenergy potential on EU15 in 2010 at 135 Mtoe compared to 55 Mtoe in 1998. The EU has set a goal of replacing 20% of the fuels used in transport with alternative fuels by 2020.

Biofuels are produced from animal or vegetable fat base (palm oil, coconut oil, etc…). Glycerol and fatty acids are removed during the refining process and the residue of methyl or ethyl ester is used as a combustion fuel source. Using biofuels many advantages can be reached. Beside to reduce the emissions of SO_x and particulate matter (-50%) they allow reducing the dependence on fossil-based and non-renewable fuel sources. However, the level of NO_x content in exhaust gases seems increase (+10%). Moreover, the availability of this fuel is limited and the costs remain an issue (Karila et al., 2004).

Natural gas is generally methane. Since it burns slowly, its combustion in the diesel engines generate low levels of CO_2 and particulate emissions (Karila et al., 2004). Wartsila produce a dual-fuel four-stroke engine, which during operation can switch between natural gas and light fuel oil. Its energy consumption increases a bit, but the production of SO_x and NO_x is only a few per cent of the amount produced in a conventional two stroke engine (Wartsila, 2004).

Hydrogen technology requires the application of fuel cells on ship. Few commercial installations for small ships (15 kW) already exist. However, for larger vessels with a big power demand (60 MW) the application of the fuel cells is still not possible. Moreover, a larger tankage volume to cover the same energy need provided by diesel fuels is needed (Eyring et al., 2005). From an economic point of view, the fuel cell application is still not competitive with the internal combustion engines (Keith et al., 2000).

3. **Desulphurization:** Generally, low-sulphur fuels go to substitute fuels of the same category having higher sulphur content. However, a desulphurization process can also be applied. Based on a purification process of fuel during combustion, it requires measures and investments at the plant site.

4. **Changes in energy system:** Changes in energy system lead to a lower consumption of sulphur by energy conservation or fuel substitution. Influencing the energy consumption structure, they allow reducing SO_x emissions. However, environmental, economic and political aspects are also involved. Greenhouse gas emissions, trade balance and energy supply security are some example. In this case, a full assessment of cost-effectiveness has to consider a detailed analysis of these elements.

5. **Sea Water Scrubbing:** It is an extremely efficient method used to reduce sulphur and particulate matter concentration in exhaust gases. It uses alkaline compounds to neutralize sulphur oxides in the scrubber and transfer them into the water in the form of sulphates (Trozzi

and Vaccaro, 1998). Seawater is an ideal scrubbing agent because it has an adequate level of alkalinity and already contains 900mg per liter of sulphur as a natural constituent, thus it makes it perfect for removing acid gases from the exhaust emissions. After this process, the water is filtered to remove particulates and re-circulated back into the sea (EEB et al., 2004). The solid particles removed from the gases are trapped in a settling or sludge tank and collected for disposal. It has been calculated that, using a filter with a pore size of 0.47 micron, an 80% of particulates by weight is removed. It is estimated that this process can cut SO_x emissions by up to 95% and particles by up 80% but no removal of NO_x was observed (MES, 2005). The first prototype was installed in 1991 on a passenger ferry serving the Oslo-Kiel route. Its removal efficiency of SO_x was about the 92%. Today the Pride of Kent EcoSilencer trials represent the most up-to date assessment of Sea Water Scrubbing. Operating with a 2.5% sulphur fuels, the SO_x reduction rates is between 68 and 94% (MES, 2005). However, uncertainty exists about the effects of waste water on sea. It still remains to be demonstrated if this cleaning technology is environmentally suitable in all types of 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 the seawater naturally contains (Trozzi and Vaccaro, 1998). However, based on precautionary principle, the Annex VI of the MARPOL forbids discharging waste into estuaries and enclosed ports (EEB et al., 2004).

6. **Fresh Water Scrubbing:** It is an alternative to sea water scrubbing if high efficiency cleaning is needed, because his cleaning efficiency is higher then 90%. Generally, it uses a caustic soda (NaOH) solution for neutralizing 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.

Table 13 summarizes the main technical solution and the average value of emissions reduction.

Table 13. Technical solution and SO_x emissions reduction

Measure	% SO_x emissions reduction
Combustion modification	50 – 60%
Fuel switching	Related to the sulphur content of fuels
Change of fuel from 2.7 to 1.5% S	44%
Change of fuel from 2.7 to 0.5% S	81%
Desulphurization	N/A
Change in energy system	N/A
Sea water scrubbing	95%
Fresh water scrubbing	90%

4d. CO_2

Carbon Dioxide emissions from maritime transports are increasing fast, becoming an important topic and a difficult task. Due to the high share of total transport demand, in spite of being one of the most efficient modes of freight transport (together with the railways) sea shipping generates substantial quantities of greenhouse gas emissions. Actually they are double those of aviation. The Institute for Physics and Atmosphere in Wessling, Germany, reveal that CO_2 emissions of maritime transport range between 600 and 800 Mt, accounting for the 5% of the global total. CE Delf (2006) estimates that sea shipping account for 1.8% to 3.5% of global greenhouse gas emissions and IEA (2006) estimates that in 2005 international maritime activity accounted for 543,3 Mt of CO_2 emissions from fuel combustion[11]. This value represent the 3,9% of the global carbon dioxide emissions and IMO (2007) calculated that CO_2 emissions from the global fleet would rising to 1,475 million mt in the next 20 years as globalization leads to increased demand for bigger and faster ships. Since international shipping increase of 3% or more per year, improve engine efficiency is ever more important to reduce CO_2 emissions (IMO, 2007).

As reported above, in spite of a general agreement about the growing trends of future emissions, large uncertainty exists about quantification. Generally, CO_2 emissions are calculated by the seal of fuel to vessels and CO_2 efficiency is estimated by index. One of the most important index has been proposed by IMO. Based on the relation between the fuel consumption and the transport work, it is calculated by multiplying cargo unit by the distance. It expresses the CO_2 efficiency in terms of CO_2 emissions per unit transport work (tonn-km). In alternative, the INTERTANK index can also be used. It calculates the transport work multiplying the cargo mass by the distance sailed. Monitoring performance and collecting data for environmental accounting, these indexes can be use for reporting purposes or to plan reduction policies.

Unfortunately, to reduce greenhouse gas emissions few technologies exist. Since CO_2 emissions are proportional to the content of carbon in fossil fuel, increase energy efficiency and use alternative fuels are key means for reducing CO_2 emissions. For this reason, the main abatement technologies generally involve the efficiency of the engine and the switching toward alternative fuels (Ship and Ocean Foundation, 2000).

1. **Energy efficiency:** The amount of CO_2 produced is proportional to the fuel combustion, which is governed by the engine efficiency. In larger diesel engine, the energy efficiency can be

increased by the use of high efficiency gas turbine engines. Based on intercooler recuperative (ICR) gas turbine, they can reduce fuel consumption by 25-30% (IEA, 2008). Alternatively, the steam turbines driven by exhaust gas heat[12] can be used. Based on oxidation method, they use a reactor to oxides CO and HC pollutants into CO_2 and H_2O. The potential of reduction is about the 70% for the HC emissions and the 90-95% for the CO emissions (Sorgard et al., 2001).

To increase energy efficiency, also the new ship design can be a solution. The Ecoship, developed by several Swedish companies, is an example. Reducing the water resistance by 10-15% it will reduce the fuel consumption and the CO_2 emissions. In 2000, IMO estimates that technical measures and new ships design could reduce fuel consumption by 5-30%. The specific fuel efficiency of most types of vessels has improved significantly in the past few decades and this trend is expected to continue (European Commission, 1999). Moreover, stern flaps and wedges, extending the bottom surface of the hull, can reduce energy consumption and related CO_2 emissions by 4% to 10% depending on ships (Breslin and Wang, 2004). However, in the long term even more options are expected to become available.

Moreover, several options for fuel saving are available. Since fuel consumption is related to the square of speed a 20% reduction in speed results in a fuel saving of up to 40%. Moreover, route optimization software, taking sea condition and weather into account, can save a few % (Zuidema, 2008). In addition, non conventional options, as “kite-like sails” and air bubbles screen, are being developed to reduce friction and reduce up to 15% of fuel consumption (Sky Sails, 2008, Møller, 2008).

2. **Switching toward alternative fuels:** Significant reduction in carbon dioxide emissions can be also achieved using alternative fuels. Natural gas, for example, is the fossil fuel with the lowest CO_2 emissions per unit of energy, and biodiesel can reduce CO_2 emissions up to 40-45%. Other energy supply solutions can be: methan gas (biogas), alcohols (methanol, ethanol), Fisher-Tropsch liquids (synthetic paraffines, more clean-burning diesel substitutes) and battery systems. The main drawbacks are the high price of alternative fuel and the low efficiency of combustion, compared to diesel engines (Eyring et al., 2005).

   Another alternative could also be the hydrogen power for fuel cells. A development project in Västra Götaland, Stenungsund (Sweden) has tested the use of on board fuel cells as an

[11] Calculated by the seal of fuel to vessels.

Auxiliary Power Unit (APU) for ships in port. To power the fuel cells the hydrogen produced as by-product from the petrochemical industry has been used but in the future hydrogen should be produced form renewable sources.

[12] This solution is currently not competitive in economic terms. However, it can become cost effective for the increasing fuel price.

5. COST ESTIMATION

This paragraph investigates the costs of specific NO_x, SO_x and CO_2 reduction measures on ships. Some costs estimations are reported in this work but many other values can be found in the literature. Since the costs assessment is depended on the measure, large uncertainty exists and many costs estimation have been provided. In this report only monetary value are considered and the issue of externalities is not taken into account. However, the estimation of health and environmental costs related to pollution is become an important topic for transport sustainability.

In general terms, the costs related to abatement technologies can be divided into capital (or investments) or operating costs. The capital costs include the construction, the work, the license fees, the delivery of the installation and all the expenditures accumulated until the start-up of the installation. The operating costs are related to the annual expenditures. They include fixed expenditures, as the costs of maintenance and administrative overhead, and variable costs, as the additional labor demand or the increased energy demand for operating the device. The average annul costs, is calculated taking into accounts the investments 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 abatement emissions. The cost effectiveness is calculated dividing the annual cost of any measure for the annual emissions reduction of that measure. Moreover, the costs related to abatement technologies are different between new or retrofit vessels.

In this paragraph, some costs estimations for Shore-Side Electricity, NO_x, SO_x and CO_2 abatement technologies are reported.

5a. Shore side electricity

To estimate the cost of shore-side electricity large uncertainty exists. Strongly dependent by port and electricity infrastructures, the average expenditures can varies from port to port. In general terms, the total costs depend on three factors:

- The size of the ships engines;
- Whether the technology is introduced (to a new or an old vessel);
- The marine fuel and the electricity costs.

This means that the cost-effectiveness needs to be studied on a case-by-case basis. However, the overall costs results to be much lower for ship with large auxiliary engines and where shore-side electricity is installed in newly built ships. For ships with larger engines switching to shore-side electricity is preferable to using 0.1% sulphur fuel, both environmentally and economically. Moreover, for new-built ships shore-side electricity generate savings compared to low sulphur fuel, especially in the case of electricity tax reductions. Generally, the costs for the power supply for high-voltage at the quay side can vary largely, depending on the distance to the nearest high voltage supply and the local conditions. Moreover, the cost for electricity will vary between the European countries (Agren, 2004).

Table 14 shows the costs estimated by Entec (2005a). It considers small, medium and large vessels and calculates mid range values of cost per tonne of emissions reduced. It considers that the total costs for onboard generation of electricity will depend on the design of the ship's power supply system, on the fuel used, on the costs for investments and maintenance and on the type of the running hours per year.

Table 14. Shore-side electricity costs (€/tonne pollutant)

Emission	Ship type	Small	Medium	Large
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

As reported by Entec (2005a), shore-side electricity becomes attractive, in monetary terms, for fuel prices above €450/tonne. Another study, prepared for the North Sea Commission (MariTermAB, 2004) estimated that the direct cost for shore-side electricity in the port of Gothenburg is 2-4 times higher than the direct costs of generating electricity onboard by auxiliary engines running on heavy fuel oil. Large parts of this cost consist of energy taxes paid for electricity. However, lowering taxation on electricity supplied to ships at berth increases the attractiveness of shore-side electricity.

5b. NO_x

As reported in the introduction, a plurality of methods can be use to estimate the cost of abatement technologies and a plurality of value can been obtained. This paragraph synthesizes the results obtained by four of the most important studies on the cost assessment of NO_x abatement technologies.

1. ENTEC (2005)

In 2005, Entec published a report about cost of NO_x abatement techniques for ships. Considering the capital costs and the operational costs, it estimates the average costs for small, medium and large vessels, distinguishing between new and old engines (Entec, 2005b). A synthesis of the results is reported in tables 15 and 16 that refer to effectiveness per tonne NO_x pollutant abated (table 15) and cost measure per tonne fuel used (table 16).

Table 15. Cost effectiveness of NO_x reduction measures per €/tonne fuel used

Technologies	New/Retrofit	Small ship €/tonne	Medium ship €/tonne	Large ship €/tonne
Basic IEM (Two stroke, low speed, young engines)	Retrofit	0.17	0.13	0.12
Basic IEM (Two stroke, low speed, old engines)	Retrofit	0.90	0.34	0.20
Advanced IEM	New	2	0.7	0.4
Direct Water Injection	New	15	14	13
Humid Air Motors	New	14	12	10
Humid Air Motors	Retrofit	16	15	14
SCR outside SO_2 ECA (ships using 2.7% S resid. Oil)	New	50	38	35
SCR outside SO_2 ECA (ships using 2.7% resid. Oil)	Retrofit	55	41	39
SCR inside SO_2 ECA (ships using fuel 1.5% S)	New	37	29	27
SCR inside SO_2 ECA (ships using fuel 1.5% S)	Retrofit	41	32	30
SCR, ships using MD	New	29	23	22
SCR, ships using MD	Retrofit	34	27	25

Source: Entec, 2005b

Table 16. Cost effectiveness of NO_x reduction measures per €/tonne abated

Technologies	New/Retrofit	Small ship €/tonne	Medium ship €/tonne	Large ship €/tonne
Basic IEM (Two stroke, low speed engine)	New	12	9	9
Basic IEM (Two stroke, low speed, young engines)	Retrofit	12	9	9
Basic IEM (Two stroke, low speed, old engines)	Retrofit	60	24	15
Advanced IEM	New	98	33	19
Direct Water Injection	New	411	360	345
Humid Air Motors	New	268	230	198
Humid Air Motors	Retrofit	306	282	263
SCR outside SO_2 ECA ships using 2.7% S resid. Oil	New	740	563	526
SCR outside SO_2 ECA ships using 2.7% resid. Oil	Retrofit	809	612	571
SCR inside SO_2 ECA ships using fuel 1.5% S	New	543	424	398
SCR inside SO_2 ECA ships using fuel 1.5% S	Retrofit	613	473	443
SCR, ships using MD	New	413	332	131
SCR, ships using MD	Retrofit	483	381	358

Source: Entec, 2005b

As reported in tables 15 and 16 Internal Engine Modification seems to be the best technology to reduce NO_x emissions and the large vessels results to be the most cost effective both in terms of fuel and in term of pollutant abated. This is because a bigger ship has a lower specific consumption per unit of grow weigh than a lighter one. The “size factor” is important on cost efficiency evaluation.

2. CEERS (2006)

Table 17 reports the results of cost estimation elaborated in 2006 by the Center for Energy and Environmental Research and Services (CEERS). Considering the NO_x abatement technologies, it distinguishes between new and retrofit ships and small, medium and large vessels. To estimate the average costs, it considers the capital cost distributed over the life spam of the equipment and ongoing operation and maintenance costs.

Table 17. Cost effectiveness of NO_x abatement technologies

Technologies	**Ship type**	**Small Vessel $/tonne**	**Medium Vessel $/tonne**	**Large Vessel $/tonne**
Direct water injection	New	371.31	325.23	311.68
Humid air motors	New	242.12	207.79	178.88
Humid air motors	Retrofit	276.45	254.77	237.60
Basic IEM	New	10.84	8.13	8.13
Basic IEM	Retrofit	10.84	8.13	8.13
Advanced IEM	New	88.54	29.81	17.17
Direct water injection	New	371.31	325.23	311.68
Humid air motors	New	242.12	207.79	178.88
Humid air motors	Retrofit	276.45	254.77	237.60
SCR outside SO_2 ECA	New	668.53	508.63	475.20
SCR outside SO_2 ECA	Retrofit	730.87	552.90	515.86
SCR inside SO_2 ECA	New	490.56	383.05	359.56
SCR inside SO_2 ECA	Retrofit	553.80	427.32	400.22
SCR ships using MD	New	373.11	299.94	282.77
SCR ships using MD	Retrofit	436.35	344.20	323.43

Source: Rahai and Hefazi, 2006.

Reducing the 90-95% of emissions, the Selective Catalytic Reduction seems to be the most efficient technology in environmental terms, but the costliest in economic terms. On the contrary, the Internal Engine Modification results to be the most cost effectiveness technology both in retrofit and in new ships technology.

3. **IIASA (2007)**

In April 2007, the International Institute for Applied Systems Analysis published a report about the policy measures to reduce ship emissions and estimated the capital, operating cost for technological emission control. It uses the costs data elaborated by Entec (2005b) and derived the weighted value from an average vessel based on the proportion of total installed engine capacity. The results are reported in table 18. However, since the cost-efficiency of a specific measure depends heavily on the spatial proximity of the emission source to the environment receptor, these results are expected to be subject to 30-40% uncertainty range.

Table 18. Technological emission control measures and costs

Technology	**Annualised capital investment (€/MWh)**	**Average operating/ maintenance costs (€/MWh)**	**Average cost effectiveness (€/t NO_x)**
Basic IEM (slide valves, 2-stroke slow speed only)	0.03	0.0	9
Average IEM	0.2	0.0	40
Direct water injection	0.6	2 .1	363
Humid air motors (new build)	2.2	0.2	225
Humid air motors (retrofit)	2.8	0.2	279
Selective catalytic reduction (Residual oil outside ECA – New build)	1.0	6.9	580
Selective catalytic reduction (Residual oil outside ECA – Retrofit)	1.7	6.9	631
Selective catalytic reduction (Residual oil inside ECA – New build)	1.0	4.9	435
Selective catalytic reduction (Residual oil inside ECA – Retrofit)	1.7	4.9	487
Selective catalytic reduction (Marine distillates – New build)	1.0	3.6	506
Selective catalytic reduction (Marine distillates – Retrofit)	1.7	3.6	584

Source: IIASA, 2007

Also in this report, the Internal Engine Modification results to be the most cost effectiveness technology to reduce NO_x emissions. A comparative analysis between the costs of NO_x abatement technologies for ships against the cost of other sources (industries, fuel production, other transport, etc…) is also provided. The results show that shipping sector is one of the most cost effective sectors for achieving NO_x emissions reduction (IIASA, 2007). For this reason, reducing the emissions from shipping provides cost saving in improving the air quality in Europe.

4. **Lövblad and Fridell (2006)**

Another study, oriented to estimate the costs involved with NO_x emissions reduction from ships, has been elaborated by Lovblad and Fridell in 2006. It considers the capital costs, the operating costs and the life spam of technology. The main results are reported in table 19.

Table 19. Costs of NO_x abatement technologies

Technologies	Capital cost	Operating cost	Life spam
Basic internal engine modification: new and retrofit of slide valves in young engines is estimated to 9-12 €/ton NO_x depending on the ship size.	Related to valves. Generally there are two valves per cylinder and the additional cost in relation to conventional valves is around 200€	No estimation are available	Fuel valves life spam is around 5 years
Advances IEM technique: Total cost equal to capital cost for new engines is 19-98 €/ton NO_x for 30% below IMO standard	Capital costs vary from one ship to another	No operating cost but benefits, related to decreased lubricating oil	Life span is the life of the engine
Direct water injection (DWI): Installed on new ships is estimated to cost 345 - 411 €/ton NOx	Cost of retrofitting is described as relative high, due to expected need of new cylinder heads which is around ¼ of the cost of a new engine (around € 50/kW)	High water quality is necessary, 90 g/kWh (45% water injection rate). Entec calculated with a distilled water cost estimated € 15/m³. In mwny cases, drinking water is used to a lower cost.	DWI life span is estimated to around 4 years. Rest of the equipment is estimated to have a life time of 25 years.
Humid air motor (HAM): Installed on new ships is estimated to cost 198-268 €/ton NO_x. As a retrofit 263-306 €/ton NO_x.	90-130 €/kW for new built engines and 110-130 €/kW for retrofit.	Maintenance cost is 4000 €/year for a 5.7 MW engine, around 0.15 €/MWh.	Life span if durable non-corrosive or galvanized material is used 25 years
Selective catalytic	40-60 €/kW for new	Urea solution	The catalyst is

reduction (SCR): For a new ship using MD the cost is estimated to 313-413 €/ton NO_x and for a new ship using high sulphur residual oil ≥1,5% S the estimated cost is 526-740 €/ton NO_x.	built engines and 60-100 for retrofit.	€170/ton. Transport of urea can be a considerable part of the urea cost. Maintenance of equipment is needed. Entec estimates that € 8 000 per year and ships are required to cleaning. However, the need for maintenance depends on the fuel used. An estimate of operating cost given for one ship is around € 10 000 per year	estimated to require a rebuild every 20 000 hours of operation, when using residual oil.

Source: Lövblad and Fridell, 2006.

As reported in table 19, the Internal Engine Modification is the most cost effective technology to reduce NO_x emissions. Generally, it results more expensive to install reduction technique on existing ships, compared with installation at old vessels. Moreover, also for this study, the costs for emission reduction on maritime sector are lower than those for reducing the emissions from land-based sources.

5c. SO_x

To reduce SO_x emissions many technologies exist and a plurality of cost estimations have been proposed. However, since future legislation will impose additional restrictions on the sulphur content of fuel, the total price for abatement technologies is expected to change. In this paragraph I report the results of recent studies about the costs of SO_x abatement technologies.

1. ENTEC (2005)

This report investigates the cost effectiveness of three measures to reduce SO_x emissions:

- Sea water scrubbing;
- Fuel switching from 2.5% S fuel to 1.5% S fuel

- Fuel switching from 2.5% S fuel to 0.5% S fuel.

Considering the capital costs and the operational costs, it estimates the average costs for small, medium and large vessels, distinguishing between new and old engines (Entec, 2005c). Table 20 and table 21 report the data about cost effectiveness of SO_x reduction measures in terms of €/tonne fuel used and in terms of €/tonne abated.

Table 20. Cost effectiveness of SO_x reduction measures per €/tonne fuel used

Technologies	New/Retrofit	Small Vessel €/ton	Medium Vessel €/ton	Large Vessel €/ton
Sea water scrubbing	New	390	351	320
Sea water scrubbing	Retrofit	576	535	504
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	2,053	2,050	2,045
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	2,053	2,050	2,045
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	1,439	1,438	1,434
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	1,439	1,438	1,434

Source: Entec (2005c)

Table 21. Cost effectiveness of SO_x reduction measures per €/tonne abated

Technologies	New/Retrofit	Small Vessel €/ton	Medium Vessel €/ton	Large Vessel €/ton
Sea water scrubbing	New	390	351	320
Sea water scrubbing	Retrofit	576	535	504
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	2,053	2,050	2,045
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	2,053	2,050	2,045
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	1,439	1,438	1,434
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	1,439	1,438	1,434

Source: Entec (2005c)

As reported in table 20 and 21 Sea Water Scrubbing for new and retrofit vessels results to be the best technology, in terms of cost-effectiveness, to reduce SO_x emissions. However, the cost of fuel switching is strongly dependent on the quantity required of low-sulphuric fuel. A low quantity of low-sulphuric fuel, for example, can be produced by re-blending distillate fuels. On the contrary a large quantity of low-sulphuric fuel would require refinery investments. Generally, three different ways can be used to provide low sulphur diesel. The cheapest option is the re-blending. The second one is the processing of low-sulphur crude oil. The last one is the desulphurization of the HFO that is the most expensive (EEB, 2004).

2. CEERS (2006)

In 2006, the Center for Energy and Environmental Research and Services (CEERS) published a report about the costs of SO_x abatement technologies. It considers new and retrofit vessels and distributes the capital and operational costs over the life span of the equipment. Table 22 reports the result of the cost effectiveness analysis in terms of $/ton abated.

Table 22. Cost effectiveness of SO_x abatement technologies

Technologies	**Ship type**	**Small Vessel $/ton**	**Medium Vessel $/ton**	**Large Vessel $/ton**
Sea water scrubbing	New	352.34	317.10	289.10
Sea water scrubbing	Retrofit	520.37	483.33	483.33
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	1,854.73	1,852.02	1,847.50
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	1,854.73	1,852.02	1,847.50
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	1,300.03	1,299.12	1,295.51
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	1,300.03	1,299.12	1,295.51

Source: Rahai and Hefazi, 2006.

Also for this study, the Sea Water Scrubbing results to be the best technology to abate emissions both in economics and environmental terms.

3. IIASA (2007)

The IIASA report (2007) estimates the cost of Sea Water Scrubbing for new build and retrofit vessels. Table 23 shows the annualized capital investment and the average operating costs in terms of €/MWh. According to the previous studies reported in this report, the average value for Sea Water Scrubbing range between 350 and 550 Euro per ton abated. However, this report assumes a 30-40% uncertainty range for the cost-effectiveness values.

Table 23. Technological emission control measures and costs

Technology	**Annualized capital investment (€/MWh)**	**Average operating/ maintenance costs (€/MWh)**	**Average cost effectiveness (€/tSOx)**
Sea water scrubbing (New build)	2.4	0.5	347
Sea water scrubbing (Retrofit)	3.9	0.5	531

Source: IIASA, 2007

4. Lövblad and Fridell (2006)

Another study, elaborated by Lövblad, Fridell (2006), estimates the costs involved with SO_x emissions reduction from ships. It considers the capital costs, the operating costs and the life spam of technology. Table 24 reports the main results.

Table 24. Costs of SO_x abatement technologies

Method	**New/Retrofit**	**Small ship €/tonne**	**Medium size ship €/tonne**	**Large ship €/tonne**
Salt water scrubber	New	390	351	320
Salt water scrubber	Retrofit	576	535	504
Change of fuel from 2.7% to 1.5% sulphur	New/Retrofit	2053	2050	2045
Change of fuel from 2.7% to 0.5% sulphur	New/Retrofit	1439	1438	1434

Source: Lövblad, Fridell, 2006.

As reported in table 24, Salt Water Scrubber is the best abatement technology in terms of cost-effectiveness. Moreover, according to Entec report (2005c), Salt Water Scrubbing applied to new and large vessels results to be the most cost effective.

5d. CO_2

As reported above, to reduce greenhouse gas emissions few technologies exists. Since CO_2 emissions are proportional to the carbon content in fuel, increase energy efficiency and use alternative fuels results to be the most effective way for reduce the greenhouse gas emissions from ships. However, in economic terms, the high price of alternative fuels is an important drawback. On the other side, since bunker price represent up to one third of vessel operating costs, the increasing price of oil, make energy efficiency a major concern to vessel owners and operators. As reported by OECD (2008), the sharp increases in fuel prices (+950% from 1970 to 1985) spurred the uptake of more fuel efficient vessels.

From an economic point of view, the cost estimation of energy efficiency and alternative fuels is still a difficult task. Strictly dependant on oil price and market mechanisms, large uncertainty exists. Moreover, since the oil price is now quickly changing, also every cost estimation should be revised at any time. For these reasons, this study not considers the cost assessment of CO_2 reduction technologies for ships.

6. CONCLUDING REMARKS

When measured in terms of emissions per tones of goods per km, ships transportation results to be environmental friendly compared with other transportation means. Nevertheless, air pollution from ocean going vessel represent a significant contribution to the global anthropogenic emissions and is an important source of damage to environment and human health (Corbett et al., 1999; Endresen et al., 2003; Corbett and Koehler, 2003).

Contrary to land based sources, which have achieved an enormous reduction in air pollution over the last decades, shipping emissions have substantially increased over the same time span, along with the gradual growth of marine transport (Hammingh et al., 2007). As reported by IIASA (2007), in 2000, ship emissions accounted to 30% of the land-based emissions in the EU-25 and Entec (2005) calculated that international maritime activities contribute about 14% of worldwide NO_x emissions, 6.5% of all SO_x emitted by fuel and 2% of global anthropogenic CO_2 emissions (IMO, 2000). In spite of the recent financial crisis, that can generate a temporary reduction of the world trade, the rapid increase in the number of ships and the growing demand for maritime transport will probably increase the trend for future emissions. The European Commission's Clean Air For Europe (CAFE) (Amann et al., 2004), for example, estimated that between 2000 and 2020, the SO_x emissions from international shipping will double, the NO_x emissions are expected to increase by two thirds and the annual grow rate of CO_2 is almost close to 2.5% (IMO, 2000).

Today, ships emissions are recognize as a growing problem for both policy makers and scientists, which expect a high potential of reduction through technological improvements, alternative fuels and ship modifications. In this study, a summary of the ship emissions abatement technologies has been reported and an overview of the costs and benefits related to potential emissions reduction has been provided. As highlighted in this report, to reduce NO_x and SO_x emissions many methods are available. However, most of them are at an early stage of development and limited information about costs and efficiency are available. On the contrary, to reduce CO_2 emissions few technologies exist.

This study summarizes the results obtained by some of the most important reports on the cost assessment of NOx, SO_x and CO_2 abatement technologies. In general terms, since a bigger ship has a lower specific consumption per unit of grow weight than a lighter one, the "size factor" results to be an important aspect on cost efficiency evaluation. Moreover, in spite of the large uncertainty associated to cost estimation, a general agreement exists about the cost efficiency results. The Internal Engine

Modification and the Sea Water Scrubbing result to be the most cost effective technologies to reduce NO_x and SO_x emissions, both in economics and environmental terms. On the contrary, since emissions are proportional to the content of pollutants in fuel, energy efficiency and switching toward alternative fuels are key means for reducing CO_2 emissions. In addition, speed reduction, route optimisation and operational changes to the existing fleets can contribute to increase the energy saving potential.

As reported in this study, to reduce the environmental impacts of maritime transport, finding novel technologies that offer improvements in fuel quality and pollutant emissions is essential. However, breaking and decoupling the connection between the environmentally negative impacts from ships and economic growth looks difficult to achieve. For this reason, both technological improvements and international legislation are urgently needed. Great reductions potential in emissions from ships exists but stricter emission regulations and powerful economic instruments are needed to encourage technological investment and switch toward alternative fuels.

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European Commission

EUR 23715 EN– Joint Research Centre – Institute for Environment and Sustainability
Title: **Cost Effectiveness Analysis of the Emission Abatement in the Shipping Sector**
Author(s): V. Andreoni, A. Miola, A., Perujo
Luxembourg: Office for Official Publications of the European Communities
2008 – 72 pp. –21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-11280-5
DOI 10.2788/77899

Abstract
Maritime transport is generally considered environmental friendly compared with other transportation means. Nevertheless, shipping emissions give an important contribution to the global anthropogenic pollution and are a significant source of damage to environment and human health. Contrary to land bases sources, few regulations exist and shipping emissions are expected to grow as a consequence of increasing transport volume. For this reason, both technological improvement and international legislation are urgently needed.

This report summarizes the NO_x SO_x *and* CO_2 *abated technologies and provide an overview of the costs and benefits related to potential emissions reductions. Investigating the cost effectiveness of specific emission measure, this report provides important information for transport sustainability. However, to break the connection between maritime transport and environmental damage, stricter emission regulation and powerful economic instruments are also needed.*

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LB-NA-23715-EN-C

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ISBN 978-92-79-11280-5