European Commission Directorate General Environment

Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments

Task 2b – NO_X Abatement

Final Report

August 2005

Entec UK Limited

Report for

European Commission
Directorate-General-Environment
Directorate C - Unit C1

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European Commission Directorate General Environment

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Task 2b – NOx Abatement

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Certificate No. EMS 69090

Certificate No. FS 13881

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Executive Summary

Introduction

This report forms part of the deliverables under Task 2 of the European Commission contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments.

Task 2 requires an investigation of the costs, emission reduction potential and practicalities of ship emissions abatement technologies. The technologies to be considered are:

- Task 2a: The use of shore-side electricity (see separate report on shore-side electricity);
- Task 2b: NO_x abatement techniques (this report);
- Task 2c: SO_2 abatement techniques with focus on sea water scrubbing (see separate report on SO_2 techniques).

This is the report for Task 2b on NO_x abatement techniques.

This report investigates the costs, emissions reductions and cost effectiveness of specific NO_x reduction measures on ships. The following measures are investigated:

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

Most of these measures are at an early stage of development for application to ships and therefore there is currently only a limited quantity of consistent information available. Due to the limited information basis and lack of long term experience with most of the measures the uncertainty of the derived results is high. The presented results can be regarded as best estimates for average conditions based on the existing literature and information gathered, however for specific applications major variations have to be expected.

Details of NOx abatement techniques

Each of the techniques considered in this report are briefly summarised below.

Internal Engine Modifications (IEM)

There is a large range of methods by which engines can be modified to reduce NOx emissions. These methods aim to either optimise combustion, improve air charge characteristics or alter the fuel injection system. Research and development is required to determine the correct combination of modifications appropriate for each engine type. This study has chosen to represent the large range of IEMs available with two categories:

- 'Basic IEM' (slide valves); and
- 'Advanced IEM'.

Basic IEM
The most widespread IEM is the exchange of conventional fuel valves with low-NO_x slide valves. Slide valves are designed to optimise spray distribution in the combustion chamber without compromising on component temperatures and thereby engine reliability. This measure is currently only applicable for slow-speed 2 stroke engines, and virtually all new engines of this type are thought to have these valves fitted as standard, as a means of meeting the IMO NOx standard.

Retrofit installations are considered to be easy to undertake. The retrofit simply entails removing the old valves, and enlarging the fuel injector holes in the cylinder covers. In addition, some engines may require stronger spring housings for securing the fuel valves to the cylinder cover. Changes are normally made on all cylinders simultaneously, and consequently installation can take a few hours work by the ship's crew per cylinder, totalling around a day per engine, and not requiring the ship to be in dry dock.

Retrofitting of slide valves is likely to be technically possible for all 2 stroke engines, but development work is required to fully test the application of slide valves to these engines.

Advanced IEM
Optimised combinations of a number of IEMs developed for particular engine families are referred to in this report as 'Advanced IEM'. For this technique, it is important to note that the NOx reductions quoted are targets which the manufacturers have set, and that advanced IEMs for ships are generally still in the development phase. Examples of particular techniques include:

- Retard injection/Miller cycle valve timing;
- Higher compression ratio/Adjustable compression;
- Increased turbo efficiency/Two stage turbocharger;
- Common rail injection/Flexible injection system/Two stage injection;
- Higher cylinder pressure;
- Low intake temperature;
- etc

Direct Water Injection (DWI)
With this technique, freshwater is injected through a valve to cool the combustion chamber before combustion commences, thereby reducing NOx formation. At the time of writing it is believed that only one manufacturer has undertaken the research and development required to apply DWI to ship engines. This company has tested engines running on fuels with sulphur contents less than 3%, which should encompass typical current fuel use in European waters.

Storage and bunkering of freshwater is necessary, and installation can be carried out while the ship is in normal operation.

Humid Air Motors (HAM)
The Humid Air Motor (HAM) concept uses heated charge air enriched with evaporated seawater to reduce NO_x formation during the combustion process. HAM can be considered an integrated part of the engine since it replaces the conventional engine air inter-cooler. The technique utilises sea water and spill heat from the engine as consumables. As engine waste heat is also used for generation of hot water for other onboard uses, installation of HAM could lead to capacity problems calling for additional boiler capacity. Although, at the time of writing, only four retrofit installations exist on one ship, one can summarise the experiences thus far as very positive. The main drawbacks of HAM are the high initial costs and the need for integration with the engine.

The central part of the HAM system is a humidification tower, which requires space close to the engine.

The first installation (in July 1999) was largely carried out during the daytime stops. The other three installations were made during the ship's routine dry-dock week in May 2001.

In contrast to SCR, no warm-up time is necessary with HAM and NO_x reduction commences more or less once the motor is engaged. Although the ship with HAM operates using a low sulphur heavy fuel oil, an additional claimed advantage over SCR is that HAM is suitable for residual oils with higher sulphur contents.

Exhaust Gas Recirculation (EGR)
Exhaust gas re-circulation relies on a fraction of the exhaust gases being filtered, cooled and re-routed back to the engine charge air. Since the specific heat capacities of the principal exhaust components are higher than air, the process results in a reduced combustion temperature and thereby less NO_x formation. Also as a secondary effect, a shortage of oxygen in the chamber means that there is less available to combine with nitrogen to form NO_x.

The major obstacle and limitation in EGR however, is that it is very difficult to remove all particulate matter before the exhaust re-mixes with the combustion air. Consequently, particulates will deposit on cylinder walls in the engine and thereby contaminate the lubrication oil increasing its viscosity. The deterioration and wear of the combustion chamber may therefore be accelerated compared to the case without EGR. In addition, since exhaust gases contain gaseous sulphur species, an added corrosion problem from sulphuric acid formation is introduced.

Attempts have been made using electrostatic precipitators and catalysts to ensure an improved particle removal and wet scrubber techniques have been applied to remove sulphur species. Despite this, the fundamental difficulties have meant that the probability of using EGR for marine diesel engines using heavy fuel oils on a fully commercial scale within the next 5 years is still considered fairly minimal.

At present, no specific installation calculation has been made for a full-scale marine test. One can speculate that even with future development and advances with EGR on marine engine durability, EGR will still be most suited to engines running on high-grade low sulphur marine distillate.

Selective Catalytic Reduction (SCR)
The SCR process relies on injecting a urea solution into an exhaust gas stream in combination with a catalyst housing in the exhaust channel. SCR is a classic "add-on" exhaust treatment

system, thus it does not interfere with the basic engine design and allows a free choice of engine manufacturer.

Usually the catalyst housing replaces the silencer in the exhaust uptakes, giving noise reductions, and rendering it suitable for both new vessels and retrofit installations. No limitations regarding ship type are thought to have been encountered up to now.

Sufficiently high temperatures in the exhaust are required, typically above around 270^{o}C, for the process to function as desired. Consequently, NO_x reductions are achieved at generally higher engine loads and in practice a warm-up time (around 20 – 30 minutes) is required after a cold start.

The main drawbacks commented on are the space and additional weight requirements (which may even affect ship handling). Some ship personnel regard the maintenance (e.g. cleaning urea injection nozzles), handling of urea and training to operate and understand the control panel as excessive. Others indicate that the investment/operational costs are appreciable. Despite this, SCR offers one of the very few established techniques to achieve significant NO_x reductions for the marine application.

Although catalyst lifetime is enhanced by using low-sulphur marine distillates, SCR systems can still operate on engines running on heavier residual oils with higher sulphur contents. The costs of catalyst replacement and fuel switching can therefore be compared and optimised, with more expensive low sulphur marine distillate resulting in less SCR maintenance.

Urea is normally purchased in a solution form (around 40% concentration). Since urea is a very common, well-established commodity, supply is not a problem and cost is relatively low. The non-poisonous, odourless solution is considered relatively safe to transport and store at ambient temperature and pressure.

'Ammonia slip' refers to the unwanted and unused reducing agent which exits with the exhaust. This occurs when the amount of urea or ammonia injected into the exhaust stream is more than will react with NO_x to nitrogen and water, and is therefore emitted as ammonia to atmosphere in the exhaust. Besides being a pollutant, ammonia is implicated in corrosion problems that can occur along the exhaust channel. Although the feedback loop mentioned above is rapid, an increased risk for ammonia slip exists for transient load changes i.e. manoeuvring. Making sure the urea injection probes do not become blocked is a vital part of the maintenance routines required.

Installation considerations focus largely on the space and weight of the major components: catalyst reactor and urea storage tank. Although installation time in the shipyard for a retrofit can vary between 1 – 3 weeks, for a new vessel there is probably little time penalty at the shipyard.

Emissions reductions

Table 1 presents the estimated mid range values of emission reduction efficiencies of the NOx abatement techniques on the main pollutants considered in this study. The associated uncertainty is considered in Section 1.2. In some cases manufacturers claim emission benefits for pollutants other than NOx; these are discussed in the report, but because of uncertainties and limitations of data are not presented in the following table for all pollutants and measures.

Table 1 Estimated emission reduction efficiencies

Measure	% Emissions reduction (-) / increase (+) per vessel			
	NOx	SO_2	PM	VOC
Basic IEM (2 stroke slow speed only)	-20%	0%	0%	0%
Advanced IEM	-30%	0%	0%	0%
Direct water injection	-50%	0%	0%	0%
Humid air motors	-70%	0%	0%	0%
Exhaust gas recirculation[1]	-35%	-93%	>-63%[2]	±[3]
Selective catalytic reduction (2.7% RO)	-90%	0%	0%	0%
Selective catalytic reduction (1.5% RO)	-90%	-44%	-18%	±
Selective catalytic reduction (0.1% MD)	-90%	-96%	>-63%[4]	±

Section 3.3 presents details of the impact of these measures on other emissions and noise.

Costs

Table 2 presents the estimated mid range values of cost-effectiveness of the NOx abatement techniques, expressed in terms of €/tonne NOx abated. The associated uncertainty is considered in Section 1.2. An indicative estimation of the NOx reduction potential in EU seas is also presented, based on reference emissions for existing vessels in 2000 in 200 mile zones of the 29 European countries considered in this study.

[1] Assumed switch from 2.7% sulphur RO to MD for technical reasons.

[2] US EPA 2003 outline that a switch from 2.7% sulphur RO to 0.3% MD reduces PM by 63%. The PM reduction to 0.1% MD will therefore be slightly higher than 63%.

[3] ± no or not conclusive information available

[4] PM reductions estimated in the same way as for EGR.

Table 2 Estimated cost effectiveness of NOx abatement technologies (mid-range values) (€/tonne NOx abated)

Measure	Ship type	Small Vessel (€/tonne NOx)	Medium Vessel (€/tonne NOx)	Large Vessel (€/tonne NOx)	NOx reduction potential in EU seas (existing ships, 2000)[5] (kT/year)	NOx reduction potential in EU seas (new ships, 2010-2020)[6] (kT/year)
Basic IEM (2 stroke slow speed only)	New	12	9	9	n.a.	n.a.
Basic IEM (2 stroke slow speed only), young engines[7]	Retrofit	12	9	9	110	n.a.
Basic IEM (2 stroke slow speed only), older engines	Retrofit	60	24	15	75	n.a.
Basic IEM (2 stroke slow speed only), young and older engines	Retrofit				185 (Total)	n.a.
Advanced IEM	New[8]	98	33	19	n.a.	480
Direct water injection	New[9]	411	360	345	n.a.	800
Humid air motors	New	268	230	198	n.a.	1120
Humid air motors	Retrofit	306	282	263	1900	n.a.
SCR outside SO_2 ECA[10]	New	740	563	526	n.a	900
SCR outside SO_2 ECA	Retrofit	809	612	571	1600	n.a.
SCR inside SO_2 ECA	New	543	424	398	n.a.	510
SCR inside SO_2 ECA	Retrofit	613	473	443	870	n.a.
SCR, Ships using MD	New	413	332	313	n.a.	14
SCR, Ships using MD	Retrofit	483	381	358	25	n.a.
SCR, all areas and ships	Retrofit				2495 (Total)	n.a.
SCR, all areas and ships	New				n.a.	1424 (Total)

More details of estimated costs, including estimated capital and operating costs for different size vessels, specific costs (€/kW capital, €/MWh operating) and total costs scaled up for all EU-flagged vessels are given in Sections 4, 5 and 6.

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[5] Estimated based on indicative NOx emissions (2800kt/year in 2000) within 200 mile zones of the 29 European countries in 2000 for existing vessels.

[6] Estimated based on indicative NOx emissions (4000kt/year in 2020) within 200 mile zones of the 29 European countries in 2020 for new and existing vessels. Assuming all new vessels from 2010 onwards have applied this abatement technique alone, 4% new vessels entering the fleet every year (i.e. 40% of fleet applying the new technique by 2020)

[7] 'Older' engines require development costs to enable retrofitting of basic IEM. A rough guide to which engines are 'older' are engines older than 15 years, around 40% of the EU-flagged fleet.

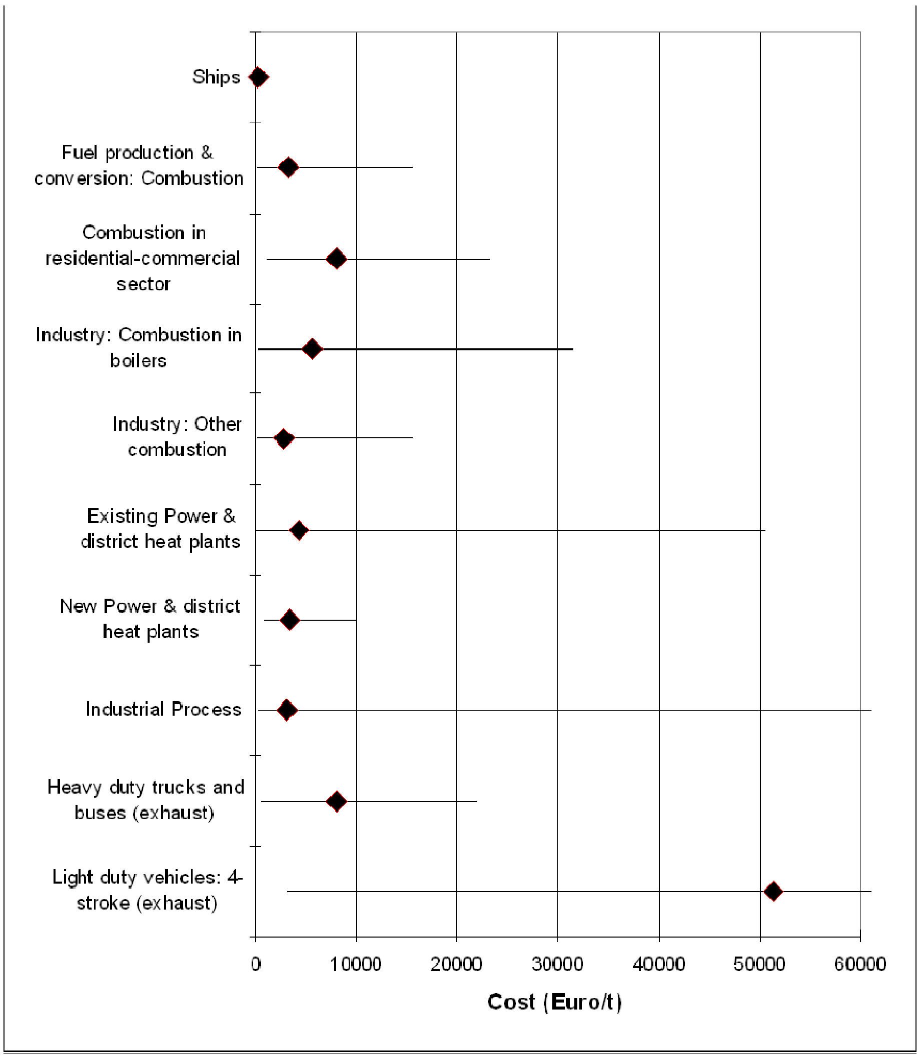
[8] Costs for retrofitting Advanced IEM were not included due to a very high uncertainty in cost estimation.

[9] Costs for retrofitting DWI were not included due to a very high uncertainty in cost estimation.

[10] SCR operating costs depend upon the fuel used. Fuels with higher levels of sulphur (i.e. used in general outside SO_2 ECA) cause more catalyst poisoning, requiring the catalyst to be replaced more often, with associated significant operating costs. These costs do not include the cost of switching between fuels.

Figure 1 compares the range of cost effectiveness of NOx abatement measures for ships against the range of cost effectiveness of NOx abatement for other sources. A comparison of the cost effectiveness of NOx abatement measures for ships against NOx abatement for other sources is shown in more detail in Section 5.2.

Figure 1 **Range of cost effectiveness of NOx abatement measures for ships against NOx abatement for other sources, supplied by IIASA (Symbol represents average cost effectiveness)** [11]



[11] Range for Industrial Process and Light duty vehicles is off the scale and therefore not fully shown in this figure

Contents

1. Introduction

1.1 General

This report forms part of the deliverables under Task 2 of the European Commission contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments.

Task 2 requires an investigation of the costs, emission reduction potential and practicalities of ship emissions abatement technologies. The technologies to be considered are:

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This report investigates the costs, emissions reductions and cost effectiveness of specific NO_x reduction measures on ships. The following measures are investigated:

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

Most of these measures are at an early stage of development for application to ships and therefore there is currently only a limited amount of consistent information available. Due to the limited information basis and lack of long term experience with most of the measures the uncertainty of the derived results is high. The presented results can be regarded as best estimates for average conditions based on the existing literature and information gathered, however for specific applications major variations have to be expected.

Chapter 2 presents the technical descriptions of the abatement technologies. Chapter 3 discusses the emission reduction efficiencies of the measures and Chapter 4 estimates associated costs. Chapter 5 depicts the expected cost effectiveness of these measures and Chapter 6 gives an indication of the scale up costs for the European fleet.

Some of these technologies also impact on emissions of other pollutants, both positively and negatively. These impacts are described in Chapter 3.3 but the main objective of the study is to quantify and cost the NOx reduction element.

The underlying method and assumptions are described in the General Report.

1.2 Uncertainty of Results

The two key results of this study are the costs of a measure and the achieved emission reduction by this measure i.e.

$$Cost - Effectiveness_{measure\ i}(\ \text{/tonne of pollutant}) = \frac{\text{Cost of measure i (/year)}}{\text{Emission reduction (tonne of pollutant/year)}}$$

Costs of measures: It is estimated that depending on the measure the costs derived in this study are subject to a 20 to 30% uncertainty range compared to the best estimate cost figure which are quoted. The key contributors to the uncertainty in the above estimates include:

- Advanced IEM, HAM, EGR, and DWI on ships have not been commercially exploited and the market prices have not been developed. The quoted costs are estimates based on the experience with the prototypes and discussions with experts; and
- Inherent variations in costs of retrofitting abatement equipment on different ships due to ship-specific factors.

Emission reductions: It is estimated that depending on the measure the emission reductions derived in this study are subject to a 20 to 30% uncertainty range compared to the best estimate emission reduction figures which are quoted. This is caused by a number of factors including:

- The variation in possible designs of technology;
- The level of maintenance of the equipment;
- The operating modes and load factors of the ship; and
- Uncertainty of emissions produced without measure ie NOX baseline emission factor.

Based on these uncertainty ranges it can be estimated that the cost-effectiveness of measures derived in this study are subject to a 30 to 40% uncertainty range compared to the best estimate cost effectiveness figures which are quoted.

2. Technical Description

The following sections contain the technical description of the different NO_x reduction measures investigated:

- Internal Engine Modifications (IEM) (section 2.1)
- Direct Water Injection (DWI) (section 2.2)
- Humid Air Motors (HAM) (section 2.3)
- Exhaust Gas Recirculation (EGR) (section 2.4)
- Selective Catalytic Reduction (SCR) (section 2.5)

2.1 Internal Engine Modifications (IEM)

There are a large range of methods by which engines can be modified to reduce NO_X emissions, as outlined in Table 2.1. These methods aim to either optimise combustion, improve air charge characteristics or alter the fuel injection system. Research and development is required to determine the correct combination of modifications appropriate for each engine type. The application of these modifications to existing engines will be limited by existing restrictions of engine design. For example, an engine can only have increased fuel pressure up to the point to where the construction material can handle the stress of increased pressures.

Table 2.1 Range of IEM available (US EPA 2003 3)

Modification grouping	Specific modification
Combustion optimisation	Fuel injection timing and electronic control; combustion chamber geometry; compression ratio; valve timing; swirl.
Improving charge air characteristics	Improvements in after-coolers.
Fuel injection	Fuel injection pressure; nozzle geometry (including slide valves); controlling the timing and rate of injection; common rail; electronic-hydraulic control of fuel injection and exhaust valve actuation.

This study has chosen to represent the large range of IEMs available with two categories discussed in the following sections:

- 'Basic IEM' – slide valves for slow-speed 2 stroke engines; and
- 'Advanced IEM' .

2.1.1 Basic IEM (Slide Valves)

The most widespread IEM is the exchange of conventional fuel valves with low-NO_x fuel valves of the sliding type. This measure is only applicable for slow-speed 2 stroke engines. Virtually all new slow speed 2 stroke engines delivered after 2000 have these valves fitted as standard, as a means of meeting the IMO NOx standard (Cronhamn, 2004).

Slide valves are designed to optimise spray distribution in the combustion chamber without compromising on component temperatures and thereby engine reliability.

The main purpose of these valves was initially to reduce fouling at the piston top, exhaust channels and exhaust boiler (Kubel, 2004). With a conventional fuel injector, the air swirl and the fuel vapour pressure during the scavenging interval will blow out a part of the fuel from the so-called sac volume. This fuel enters the combustion zone when the temperature is too low for a complete combustion to occur which results in engine fouling and increased soot and VOC emissions.

Heat release with slide valves is somewhat lower than conventional fuel injectors, which means they also result in a beneficial NO_x reduction. This can be enhanced further by special low-NO_x atomisers on the valve where the spray pattern is optimised for reducing NO_x by around 20% and even lower in special cases (Kubel, 2004). The actual NO_x emission performance level for individual engine types is normally tested in the laboratory in advance.

Slide valves may provide considerable reductions in VOC and PM emissions (Aabo, 2003, Kubel, 2004). Tests have shown that the main source of smoke and soot deposits is the fuel trapped into the fuel injector sac hole, which enters the combustion chamber in an uncontrolled way during the expansion stroke (US EPA 2003 3).

The assumed NO_X reduction efficiency of slide valves is shown in Table 2.2.

Table 2.2 NO_X reduction efficiency of slide valves and impact on other emissions quoted by manufactures

In-engine changes	NO_X	SFC	PM	VOC	CO
Slide valves	-20%	0%	Unconfirmed up to -50%, dependant upon fuel type	Unconfirmed up to -50%, dependant upon fuel type	Some increases possible
Reduction efficiency assumed in this study	**-20%**	**0%**	**0%**	**0%**	**0%**

Retrofit installations are easy to undertake. The retrofit only entails removing the old valves, and enlarging the fuel injector holes in the cylinder covers. It is usually possible to enlarge the hole with the cover still in position i.e. by removing just the exhaust valve. In addition, some engines may require stronger spring housings for securing the fuel valves to the cylinder cover. Changes are normally made on all cylinders simultaneously, and consequently installation can take a few hours work by the ship's crew per cylinder, totalling around a day per engine, and not requiring the ship to be in dry dock (Cronhamn, 2004).

Retrofitting of slide valves has been developed for some 2 stroke engines. Such engines include, for example, the motor series C type ('MC type') engine family produced by the 2 stroke engine manufacturer, MAN B&W. MAN B&W have proprietary technology for slide values and claim a market share of over 50 percent on slow speed diesels during the last years.

Retrofitting of slide valves is likely to be technically possible for all 2 stroke engines, but development work is required to fully test the application of slide valves to these engines (Cronhamn 2005). Since the MC type represents engines younger than 15 years produced by MAN B&W, it is assumed that young engines (less than 15 years old) can be immediately retrofitted with slide valves without development costs (Cronhamn 2005).

The Wallenius Lines' ship the *MS Manon* was consulted as a case study for the use of low NOx slide valves. The low NOx slide valves were supplied by MAN B&W. Costs and practical issues experienced onboard the *MS Manon* with slide valves are included in this study.

Figure 2.1 Wallenius Line, *MS Manon*, Case study for Low NO_X slide Valves

2.1.2 Advanced IEM

Specific combinations of IEM which are being developed by manufacturers can be seen in Table 2.3 (US EPA 2003, 3). This table shows the NO_X reduction efficiency. It is important to note that the NO_X reductions quoted are targets which the manufacturer has set, and that advanced IEMs are still in the development phase (Kullas-Nyman, 2004). The costs for IEM represented in this study include research and development costs still required by manufacturers. The research and development costs included are enough to allow for exploration beyond fuel injection modifications.

Since the available cost data is for IEM combinations which reduce NO_X emissions by 30% below the IMO NO_X standard (US EPA 2003, 3), the NO_X reduction efficiency is assumed at 30% below the IMO NO_X standard. That can be seen as a readily achievable figure.

Table 2.3 Combinations of advanced internal engine modifications, NO_X reduction efficiency and impact on other emissions

Manufacturer	In-engine changes	NO_X	sfc	PM	VOC	CO
Wärtsilä	Retard injection, Miller cycle valve timing, Higher compression ratio, Increased turbo efficiency, Higher max cylinder pressure, Common rail injection	-40% below IMO NO_X standard	unknown	unknown	unknown	Unknown
Caterpillar (MaK)	Higher compression ratio, Higher cylinder pressure, Higher charge pressure, Flexible injection system	-33% below IMO NO_X standard	0%	unknown	unknown	Unknown
FMC	Two stage injection, Miller cycle valve timing, Greater stroke/bore ratio, Adjustable compression, Two stage turbocharger, Low intake temperature	-34% below IMO NO_X standard	-2%	Unknown	unknown	Unknown
Reduction efficiency assumed in this study		**-30%**	**0%**	**0%**	**0%**	**0%**

Since advanced IEM is still in development, no case study was available.

2.2 Direct Water Injection (DWI)

2.2.1 Technical Description

One of the suppliers of DWI is Wärtsilä, who utilise a twin injector system where freshwater is injected through a single valve with two needles. An electric pump drives the freshwater at pressures of 200 - 400 bar up to the computer-controlled injection nozzles. Water is delivered just before fuel is injected into the combustion chamber. Built-in safety features enable immediate water shut-off in the event of excessive water flow or water leakage. The water system is completely separate from the fuel system, which means if water shut-off should prove necessary, engine operation is not affected. Wärtsilä state that the system imposes no significant additional strain on the camshaft (i.e. no power loss) and space requirements for the equipment are minimal. One should bear in mind however that storage and bunkering of freshwater is necessary. Installation can be carried out while the ship is in normal operation.

The injected water cools the combustion chamber before combustion commences thereby reducing NO_x formation. Typical ratios of water to fuel used are 40% – 70% to achieve NO_x emission reductions of 50 - 60%. Table 2.4 outlines the assumptions used in this study, including a 50% NO_X reduction efficiency with a 40% water to fuel injection rate.

Different sources quote a range of different changes in specific fuel consumption. However all sources quote very small changes, around one or two percent (USEPA 2003 3). Since there is not a consensus on the absolute change in fuel consumption, it is assumed that fuel efficiency is not affected (Cooper, 2004). Even if the fuel consumption was increased by two percent, the impact on emissions and costs are insignificant for the purposes of this study.

Table 2.4 NOx reduction efficiency, DWI and impact on other emissions

DWI	NO_X	sfc	SO_2	VOC	PM
Reduction efficiency assumed in this study	-50%	0%	0%	0%	0%

Silja Line's *MS Silja Symphony* was consulted as a case study for the use of DWI. Wärtsilä Corporation OY supplied DWI to the *MS Silja Symphony*. Costs and practical issues experienced onboard the *MS Silja Symphony* with DWI are included in this study.

Figure 2.2 Silja Line, *MS Silja Symphony*, Case study for DWI

2.2.2 Background and Further Technical Details

Application of DWI to individual engine families requires research and development. At the time of writing it is believed that only Wärtsilä has undertaken this research and development, and therefore presently DWI is limited to Wärtsilä engines. Since Wärtsilä holds the largest market share in the sale of medium speed ship diesel engines (27%) (US EPA 2003 3), this technology may not be significantly constrained at the present time by being linked to only one engine manufacturer.

Wärtsilä has only tested engines running on fuels with sulphur contents less than 3%, but since the average sulphur content of RO in European waters is assumed to be 2.7%, this is unlikely to be a major restriction. Some initial problems were encountered when the system was newly delivered onboard one ship (1999) but most of these problems have now been resolved (Göras, 2004).

2.3 Humid Air Motors (HAM)

2.3.1 Technical Description

The Humid Air Motor (HAM) concept uses heated charge air enriched with evaporated seawater to reduce NO_x formation during the combustion process. As a rough guide, about three times as much water vapour as fuel is introduced into the engine to achieve 70-80% NO_x reduction. We have assumed a 70% NO_x reduction for this technology in this study, in view of the limited available data.

The HAM system can be considered an integrated part of the engine since it replaces the conventional engine air inter-cooler. The technique utilises sea water (around 60 tons for a voyage between Stockholm and Helsinki) and spill heat from the engine as consumables. As engine waste heat is also used for generation of hot water for other onboard uses, installation of HAM could lead to capacity problems calling for additional boiler capacity. Further details on the reduction principle (covered by a Munters Europe AB patent) and test trials are presented in the literature (Riom et al., 2001). Although only four retrofit installations exist on one ship, *MS Mariella* [12], one can summarise the experiences thus far as very positive. The technology has been awarded two prestigious prizes; the Euromot Award 1999 for best branch invention and the Seatrade Environmental Award 2000.

The main drawbacks of HAM are the high initial costs, which are significantly higher than alternative NO_X abatement measures, and the need for integration with the engine. Despite positive results on the *MS Mariella*, it has been difficult to justify such significant up front costs for installation on other vessels (Hagström, 2004).

One of the causes of this high initial cost is the need for significant pre-installation work. The research and development costs invested by S.E.M.T. Pielstick are reflected in the costs shown in this study. S.E.M.T. Pielstick only hold about 1% of the market share for sales of medium speed ship diesel engines (US EPA 2003 3). However since the research and development costs are reflected in the costs in this study, the cost effectiveness of this measure can be applicable to any engine manufacturer.

Table 2.5 outlines the assumptions made in this study about the efficiency of HAM in reducing NOx emissions.

[12] A land based diesel engine located in Corsica also uses the technique.

Table 2.5 NO_X reduction efficiency, HAM, and impact on other emissions (Cooper 2004)

HAM	NO_X	sfc	SO_2	VOC	PM
Reduction efficiency assumed in this study[13]	**-70%**	**0%**	**0%**	**0%**	**0%**

Viking Line's *MS Mariella* was consulted as a case study for the use of HAM. Munters Europe AB supplied HAM to the *MS Mariella.* Costs and practical issues experienced onboard the *MS Mariella* with HAM are included.

Figure 2.3 Viking Line, *MS Mariella*, Case study for HAM

2.3.2 Installation Considerations

The central part of the HAM system is a humidification tower. At the *MS Mariella* this comprises of a cylindrical vessel weighing around 3 tons and dimensions of around 1,3 m in diameter and around 4 m long which requires space close to the engine. Although this can be a drawback in planning the installation, the towers are located neatly above the engines on *MS Mariella*. Other accessory equipment for the system includes a circulation pump and filter, heat exchanger (to heat the incoming water), a "bleed-off" system (to control the contents of salt and minerals in the water) and a water tank (0,5 m x 1,5 m x 1m size located in the engine room).

[13] IVL reported 70-80% reduction of NOx while Viking Line recently reported 75-85% reduction. A conservative figure of 70% was used in this study.

Figure 2.4 HAM installed on the MS Mariella

Initially, a requirement was that the system could be switched between conventional air cooler and HAM modes. This was achieved using a butterfly valve arrangement. However, this condition is now deemed superfluous by the ship-owner. In an emergency case with HAM failure and even without the air cooler, the available power is still at 50- 60% of maximum load. An additional aspect in the installation was how to compensate for the mass flow increase on the turbine side. Rather than matching the turbocharger, a by-pass and waste gate (to avoid over-speed of the turbocharger) was installed.

2.3.3 Background and Further Technical Details

Prior to installation on the *MS Mariella*, several comprehensive research and development efforts were conducted at the University of Lund in Sweden[14] and at the engine manufacturer in St Denis, France (S.E.M.T. Pielstick) in order to be able to present a viable concept suitable for a field trial. The large capital investment costs quoted for installing HAM are thus a reflection of this pre-installation work.

The first installation (main engine 1 in July 1999) was largely carried out during the daytime stops scheduled at Stockholm for the ferry. The other three installations (main engines 2, 3, and 4) were made during the ship's routine dry-dock week in May 2001. This demonstrates that HAM may require significantly less installation work than SCR.

[14] The inventors were Lars-Ola Olsson and Per Rosén (PhD student).

Due to high calcium contents present in the Baltic Sea water, some calcium deposits were noted in the evaporation tower during the early stages of the test period, but this was solved using a low-cost additive. The maintenance costs specified by the ship-owner are largely due to breaking of the bellows at the inlet of the humidification tower and automation problems with the equipment. A less significant cost relates to opening of the humidification tower for cleaning the water injectors inside the tower, which as pointed out by the crew could be made significantly easier in future designs (Hagström, 2004).

In contrast to SCR, no warm-up time is necessary with HAM and NO_x reduction commences more or less once the motor is engaged. As a precaution to minimise possible corrosion in the humidification tower however, the water flow is turned off around 15 minutes before engine shut down to dry out the tower. Although *MS Mariella* operates using a low sulphur heavy fuel oil (IF 220), an additional claimed advantage over SCR is that HAM is suitable for residual oils with higher sulphur contents.

Finally, it should be noted that other humidification techniques similar to HAM (i.e. water vapour being added to the air intake) are under development elsewhere. Wärtsilä Corporation OY are working with CASS (Combustion Air Saturation System) which uses a pressurised water flow in to the air intake after the turbocharger compressor. An auxiliary engine equipped with the first prototype of the system is currently undergoing field trials onboard *MV Manon* (Gorton, 2004; Kullas-Nyman, 2004). A similar designed system marketed by M.A. Turbo/Engine Design Ltd of Vancouver is also being tested with a Caterpillar 3508 auxiliary engine onboard the *ferry Queen of Westminster* in British Columbia. However emission reductions and costs associated with CASS are not covered in this study.

2.4 Exhaust Gas Recirculation (EGR)

2.4.1 Technical Description

The central principle behind exhaust gas re-circulation relies on a fraction of the exhaust gases after the engine outlet being filtered, cooled and re-routed back to the engine charge air. Since the specific heat capacities of the principal exhaust components are higher than air, the process results in a reduced combustion temperature and thereby less NO_x formation. Also as a secondary effect, a shortage of oxygen in the chamber means that there is less available to combine with nitrogen to form NO_x.

The major obstacle and limitation in EGR however, is that it is very difficult to remove all particulate matter before the exhaust re-mixes with the combustion air. Consequently, particulates will deposit on cylinder walls in the engine and thereby contaminate the lubrication oil increasing its viscosity. This therefore puts extra requirements on the properties of the lubrication oil used.

The deterioration and wear of the combustion chamber may be accelerated compared to the case without EGR. Soot deposits may also be formed throughout the EGR system piping, coolers and valves that in time will reduce the efficiency of the system. In addition, since exhaust gases contain gaseous sulphur species, an added corrosion problem from sulphuric acid formation is introduced.

Attempts have however been made using electrostatic precipitators and catalysts to ensure an improved particle removal and wet scrubber techniques to remove sulphur species. Some promising, short-term EGR trails have been performed in the MAN B&W laboratory on a 4T50ME-X research engine (Aabo and Kjemtrup, 2004). Despite this, the fundamental difficulties have meant that the probability of using EGR for marine diesel engines using heavy fuel oils on a fully commercial scale within the next 5 years is still considered fairly minimal (Cooper, 2004).

At present, no specific installation calculation has been made for a full-scale marine test. Therefore it was not able to refer to a case study for EGR. One can speculate that even with future development and advances with EGR on marine engine durability, EGR will still be most suited to engines running on high-grade low sulphur marine distillate.

Therefore it is assumed that at present EGR are only available for practical application to ships using 0.2% (and lower) sulphur marine distillate. Table 2.6 outlines the assumptions used in this study regarding the impact of EGR on emissions.[15]

Table 2.6 NO_X reduction efficiency, EGR and impact on other emissions

Reduction efficiency of EGR assumed in this study	NO_X	Sfc	SO_2	VOC	PM
Exhaust Gas Recirculation, including switch to MD (ships originally using RO)	-35%	0%	-93%	±?	>-63%[16]
Exhaust Gas Recirculation (ships originally using MD)	-35%	0%	0%	0%	0%

2.4.2 Installation Considerations

Installation time is thought to be long and space requirements and other limitations are difficult to specify at present (Aabo, 2004), however space requirements and weight are likely to be lower than for SCR.

2.5 Selective Catalytic Reduction

2.5.1 Technical Description

The SCR process relies on injecting a urea solution into an exhaust gas stream in combination with a catalyst housing in the exhaust channel. 90% reductions of NO_x emissions have been achieved with a urea injection rate of 15 g/kWh (Cooper 2004). Table 2.7 outlines the assumptions used in this report regarding NO_X reduction efficiency and the impact on other emissions.

[15] Cooper (2004) outlines NOx reduction as 20-50%. This study assumes the average value of 35% NOx reduction.

[16] The SO_2 and PM reduction figures here are as a result of the required switch to marine distillates, not the EGR itself. US EPA 2003 outline that a switch from 2.7% sulphur RO to 0.3% MD reduces PM by 63%. The PM reduction to 0.1% MD will therefore be slightly higher than 63%.

Table 2.7 NO_X reduction efficiency, SCR and impact on other emissions

SCR	NO_X	sfc	SO_2	VOC	PM
Reduction efficiency assumed in this study	-90%	0%	0%	0%	0%

The *MS Sigyn* was consulted as a case study for the use of SCR, though it is worth noting that there are many more ships using SCR in the EU – certainly more that those using other secondary abatement techniques. Argillon GmbH supplied SCR to the *MS Sigyn.* Costs and practical issues experienced onboard the *MS Sigyn* with SCR are included in this study.

Figure 2.5 *MS Sigyn*, Case study for SCR

2.5.2 Installation Considerations

Installation considerations focus largely on the space and weight of the following major components:

- Catalyst reactor mounted in the exhaust channel - For a main engine example, this can be 2 x 2 x 4 meters and have a weight of around 3,500 kg (but considerably smaller for auxiliary engines). If the volume of an exhaust silencer is replaced this usually means a weight gain of around 30 – 60%.
- Urea storage tank, piping and urea – Urea tank (and urea) is normally located in the ship hull and contributes a weight gain of 2 – 10 tons and 50 – 200 m^3 volume. In some cases the urea tank can replace a ballast tank on board.

In addition, other components include urea dosage panel and pump station, control panel, air compressors, and in most cases a NO analyser and sampling system. Although installation time in the shipyard for a retrofit can vary between 1 – 3 weeks, for a new vessel there is probably little time penalty at the shipyard. The SCRs are delivered in relatively few sections as pre-built modules. As an example, weight gain for a high speed passenger ferry (dead weight 450 ton, gross register 5,600 tons, with installed engine capacity of around 29 MW) is calculated as about 17 tons.

Most SCR experience has been gained with four-stroke medium and high-speed diesel engines. Usually the catalyst housing replaces the silencer in the exhaust uptakes, giving noise reductions and rendering it suitable for both new vessels and retrofit installations. In the latter case, it may also be necessary to move exhaust boilers if space requirements are a problem.

Some SCR systems have also been fitted on slow-speed, two-stroke engines where the SCR is placed before the turbocharger down in the engine room (for exhaust temperature reasons). Since space in the engine room is usually very limited, the slow-speed SCRs are best suited for new vessels where installation can be planned early in the design stages.

Regarding ship type, no limitations have been encountered up to now. SCR systems exist on large passenger ferries, small short-route ferries, RO-RO vessels, container ships, cargo ships, tankers etc. High-speed fast ferries, where space and vibration difficulties can be significant, have not yet prevented SCRs from being fitted.

SCR is a classic “add-on” exhaust treatment system, thus it does not interfere with the basic engine design and allows a free choice of engine manufacturer. Since the residence time of the exhaust in the catalyst is a key factor for NO_x reduction, however, the catalyst is dimensioned for the exhaust flow rather than the baseline level of NO_x (although this is also considered). This means that for ships powered by gas turbine engines which have a high flow relative to the amount of NO_x in the exhaust, SCR might not be a suitable option for further NO_x reduction.

The main drawbacks commented on with the technique are the space and additional weight requirements (which may even affect ship handling). Some ship personnel regard the maintenance (e.g. cleaning urea injection nozzles), handling of urea and training to operate and understand the control panel as excessive (Cooper 2004). Others indicate that the investment/operational costs are appreciable (Cooper 2004). Despite this, SCR offers one of the very few established techniques to achieve significant NO_x reductions for the marine application.

2.5.3 Background and Further Technical Details

Catalyst

The focus of SCR catalyst design is on optimising large active surface areas, high activity, resistance to poisons, and compact dimensions but minimising exhaust back pressure. Sufficiently high temperatures in the exhaust are required, typically above around 270^{o}C, for the process to function as desired. Consequently, NO_x reductions are achieved at generally higher engine loads and in practice a warm-up time (around 20 – 30 minutes) is required after a cold start.

In contrast to the three-way catalysts used on cars, the marine SCR systems have the ability to reduce NO_x in the presence of relatively high levels of oxygen. Additional SCR options include use of an oxidation catalyst (VOC and CO emission reductions and conversion of ammonia slip) and integrated silencers. For further reading, several comprehensive reviews are available in the literature (Götmalm, 1993; Jensen, 2000; Zimmerlein, 2003).

Although catalyst lifetime is enhanced by using low-sulphur marine distillates, SCR systems can still operate on engines running on heavier residual oils with higher sulphur contents. One of the longest operating SCR systems (12 years) for a marine distillate powered ferry still shows no notable signs of catalyst ageing, while newer systems on engines using residual oils (1.5% sulphur) have needed catalyst block replacements every 4-5 years (Cooper 2004). The costs of catalyst replacement and fuel switching can therefore be compared and optimised, with more expensive low sulphur marine distillate resulting in less SCR maintenance. In theory, fuels with sulphur contents exceeding 2.0% can be used in conjunction with SCR (Cooper 2004), but to our knowledge this has not yet been done in practice.

One of the main poisons for the catalyst is potassium oxide (K_2O) that is present in soot particles in the exhaust. Other alkaline metal oxides (sodium, calcium, and arsenic) and phosphorus oxide can also deactivate the catalyst. Generally these species are more abundant in residual oils and some may even be present in the lubrication oil. One identified problem is calcium sulphate deposits (originating from calcium in the alkaline lubrication oil and sulphur in the fuel) that can often physically block the catalyst pores (leading to an increased back pressure). To prevent this, a soot blower or similar device is usually required to keep the pores clean.

Urea usage and ammonia slip

Urea ($CO(NH_2)_2$) is normally purchased in a solution form (around 40% concentration). Since urea is a very common, well-established commodity and is used in fertilisers, skin care products etc, supply is not a problem and cost is relatively low. The non-poisonous, odourless solution is considered relatively safe to transport and store at ambient temperature and pressure.

As a 40% solution, crystallisation will not occur above 0 ^{o}C, and weaker solutions e.g. 35% solutions, are stable down to around –15 ^{o}C, if storage temperature proves a problem. Storage of weaker solutions however has the drawback of higher consumption costs.

From the storage tank the urea solution is transferred at a raised pressure by a metering pump to a high-pressure injection nozzle system. Following injection into the exhaust, the urea decomposes to ammonia (NH_3) which is the active agent achieving the reduction of NO_x to nitrogen (N_2) and water (H_2O).

The exact urea dosage at a given load is automatically calculated using a well-tested algorithm based on engine load and measured exhaust NO as input signals. An even and homogeneous mixing of the injected urea across the exhaust channel cross-section is critical for the system to function correctly. This permits not only an efficient NO_x reduction but also minimal ammonia slip – see below.

'Ammonia slip' refers to the unwanted and unused reducing agent which exits with the exhaust. This occurs when the amount of urea or ammonia injected into the exhaust stream is more than will react with NO_x to nitrogen and water, and is therefore emitted as ammonia to atmosphere in the exhaust. Besides being a pollutant, ammonia is implicated in corrosion problems that can occur along the exhaust channel.

Although the feedback loop mentioned above is rapid, an increased risk for ammonia slip exists for transient load changes i.e. manoeuvring. Making sure the urea injection probes do not become blocked is a vital part of the maintenance routines required. In particular for ships operating within the Swedish system for differentiated fairway dues (Swedish Maritime Administration, 1999), daily checks of urea flow-meters, urea tank level and NO exhaust concentration are required in order to verify operation.[17]

[17] Ammonia is a regulated pollutant in the Swedish NO_x certificate scheme.

3. Emissions Reductions

3.1 Introduction

In assigning performance criteria for NO_x abatement technologies, the following sources have been used:

- Experiences from NOx certification measurements onboard ships within the Swedish system for environmentally differentiated fairways dues (Cooper and Gustafsson, 2004).
- Contacts with chief engineers and ship-owners using the equipment.
- Contacts with suppliers of NOx emission reduction equipment; Argillon GmbH, (Zimmerlein, 2004); Munters Europe AB (Holmström, 2004), Haldor Topsoe A/S (Nielsen, 2004), MAN B&W Diesel A/S (Cronhamn, 2004), Wärtsilä Corporation OY (Kullas-Nyman, 2004).
- Other literature sources and reviews (Fleischer, 1996; Klokk, 1997; Buhaug, 1999; Kågeson, 1999; European Commission, 1999; DeMers and Walters, 2000; Corbett and Fischbeck, 2002, US EPA, 2002, US EPA 2003).

When summarising the data below, priority has been given to onboard measurements (where they exist) and contacts with chief engineers on the general operation and experience of the systems. Since for some techniques only a few installations are in operation, the statistical basis for the assignments and thereby uncertainty can clearly differ. Thus one should bear in mind that individual installations may differ from the performances given in Table 3.1, which are intended to reflect the equipment supplied by the main suppliers on the market.

3.2 Emissions Reduced

Table 3.1 depicts the assumed abatement efficiency of the different measures and Table 3.2 estimates the average achieved emission reduction per year for different sizes of vessels.

Table 3.1 Summary of NO_X abatement efficiency as % of baseline emissions

	NO_X	sfc	SO_2	VOC	PM
Basic IEM (Slide Valves)	-20%	0%	0%	0%	0%
Advanced IEM	-30%	0%	0%	0%	0%
Direct water injection	-50%	0%	0%	0%	0%
Humid Air Motor	-70%	0%	0%	0%	0%
Exhaust Gas Recirculation (ships originally using RO but switching to MD (accounting for SO_2 & PM reductions))	-35%	0%	-93%	±?	>-63%
Exhaust Gas Recirculation (ships originally using MD)	-35%	0%	0%	0%	0%
Selective Catalytic Reduction	-90%	0%	0%	0%	0%

Table 3.2 Estimated NO_X emissions abated per vessel and year

	Vessel		
	Small	**Medium**	**Large**
	(t NOx/year)	**(t NOx/year)**	**(t NOx/year)**
Basic IEM (Slide Valves)	43	144	361
Advanced IEM	70	230	577
DWI	117	384	962
HAM	164	538	1346
EGR	82	269	673
SCR	211	691	1731

3.3 Other Emissions (CO, CO_2, CH_4, N_2O and Noise)

Impacts of **Basic IEM (slide valves)** on other emissions are not well documented, but they may reduce PM and VOC emissions, dependant upon fuel type. Slide valves may increase CO emissions. Basic IEM is not known to affect noise produced by the engine.

Impacts of **Advanced IEM** on other emissions are also not well known. The range of different techniques used to reduce NO_X can impact other emissions in a variety of ways. For example, delayed injection timing may increase fuel consumption, leading to increased PM, CO, CO_2 and VOC emissions (Cooper 2004). However, since these impacts are not well documented, this study assumes there are no significant impacts on other emissions. Advanced IEM is not known to affect noise produced by the engine.

Impacts of **DWI** on PM, VOC, CO_2 and CO emissions are reported as negligible (Cooper 2004). Impacts on other emissions have not been documented (Cooper 2004). DWI is not known to affect noise produced by the engine.

HAM may slightly increase VOC, CO_2 and CO emissions at lower loads, and slight increases in PM emissions are reported but not quantified (Cooper 2004). HAM is not known to affect noise produced by the engine.

The use of **EGR** is expected to increase PM, VOC and CO emissions (Cooper 2004). Since EGR is not expected to impact fuel consumption, it is likely that there will be no change in CO_2 emissions (Cooper 2004). EGR is not known to affect noise produced by the engine.

The use of **SCR** has been claimed to reduce PM emissions by 30-45%, but this has not been widely documented (Cooper 2004). There is some evidence that SCR reduces N_2O (Kuwabara et al., 2000). If SCR is poorly trimmed, a risk exists for excessive NH_3 emissions. In general however, NH_3 emissions are low, around 0.10 g/kWh. If SCR is used in conjunction with an oxidisation catalyst, VOC emissions can be reduced by 75-90% and CO emissions by 50-90% (Cooper 2004). Since there is no expected change in fuel consumption, there is not expected change in CO_2. SCR may have the potential to reduce noise produced by the engine by 20-35 dB (A) (Cooper 2004).[18]

[18] For comparison, noise level limits on ships are 60-75 dB(A) for navigation and accommodation spaces, and 85-110 dB(A) for work spaces.

4. Costs

4.1 Basic IEM (Slide Valves)

4.1.1 Maturity and Certainty of Cost Estimations

The most common and widespread modification to date is the use of installing new fuel valves of the sliding type. The number of installations in use however, is difficult to specify. MAN B&W (a leading manufacturer) report that the valves were fitted as standard engine equipment from year 2000 and other ships have retrofits. Therefore cost estimations are reasonably certain. However, slide valves have not been applied to older engines, and therefore cost estimates for older engines are less certain (Cronhamn 2005). Table 4.1 summarises the number of existing installations and the age of the technology.

Table 4.1 Existing installations of Slide Valves

Abatement technique	Approximate no. of commercial installations	Approximate year of first commercial system
Basic IEM	> 500	1998

4.1.2 Capital Costs

Basic IEM includes changing the air injection nozzle to slide valves which allow improved combustion conditions. This change is low cost and simple. Installation costs for a retrofit are not significant, and therefore costs will not vary considerably from installation on new ships to existing ships. Retrofitting of slide valves would require the removal of exhaust valves and widening of the fuel injector holes. It is estimated to take around one day for the crew to fit the new valves into the engine (Cronhamn, 2004).

Fuel valves are routinely replaced during regular engine maintenance, as they have a lifespan of around 2.5 years. Therefore, the capital cost for using slide valves is the increased valve cost of using a slide valve instead of a conventional valve. A slide valve costs €2,100-3,000, which is about €200 more than conventional valves. Engines have in general two valves per cylinder and total capital costs therefore depend upon the number of cylinders.[19] An installation cost of one day labour is assumed per engine (Cronhamn, 2004).

[19] MAN B&W, 2004. Personal Communication, December 2004. Slide valves were estimated to cost 1000 DKK_{2004} (€130_{2000}) more than conventional valves. It was assumed the capital costs of a fuel atomiser, which may be required alongside the slide valves, were €70/valve, bringing the total Basic IEM capital costs to €200/valve.

Costs for slide valves depend upon the number of cylinders per engine. This is shown in Table 4.2.

Table 4.2 Costs of basic IEM for young and new engines

Engine Size	SSD 2-stroke	ME Engine Capacity	Number of Cylinders per engine[20]	Number of slide valves required	Additional cost per slide valve	Costs for slide valves	Additional Labour costs[21]	Total costs
		(kW)	(-)	(-)	(€/valve)	(€/engine)	(€/engine)	(€/engine)
ME Small	48%	3,000	2.1	4.2	200	840	320	1,160
ME Medium	58%	10,000	7	14	200	2,800	320	3,120
ME Large	55%	25,000	17.5	35	200	7,000	320	7,320

Development of internal engine modifications requires research and development costs. This development includes time for engineers to determine the engine modifications required for each engine family. As a rough rule, it is assumed that 2 stroke engines younger than 15 years do not require further development to install slide valves, however older engines will need development time (Cronhamn, 2005).

To reflect development costs for older 2 stroke engines, it is assumed such costs may be of the order of 10% of the development costs outlined for advanced IEM main engines (see Table 4.7). Table 4.3 outlines cost estimations for older engines.

Table 4.3 Costs of basic IEM for older engines

Engine Size	R+D costs for older engines	Cost basic IEM young engines (see Table 4.2)	Total costs
	(€/engine)	(€/engine)	(€/engine)
ME Small	4,900	1,160	6,060
ME Medium	4,900	3,120	8,020
ME Large	4,900	7,320	12,220

[20] The ratio of cylinders to engine capacity was 0.7 cylinders per MW of power (based on ratios shown in Cooper, 2004).

[21] An installation cost of one day labour is assumed per engine independent of the number of slide valves to be change (Cronhamn, 2004). This is considered a reasonable assumption and is not a sensitive parameter in the overall cost estimation.

4.1.3 Lifespan

The lifespan of a fuel valve is assumed to be 2.5 years (Cronhamn 2004).

4.1.4 Operating and Total Costs

There are no operating costs associated with the use of slide valves. There may be some engine service benefits such as reduced fuel oil consumption for lubrication, but these benefits have not been quantified so total costs are assumed to be equal to the capital costs.

Table 4.4 Costs of Basic IEM (Slide Valves) for Young Engines

	Vessels		
	Small (SSD ME only)	Medium (SSD ME only)	Large (SSD ME only)
New build and retrofit capex (€)	1,160	3,120	7,320
Equipment lifespan (year)	2.5	2.5	2.5
Annualised costs (€/year)	497	1,336	3,135
Capex per kW installed (€/kW)	0.39	0.31	0.29
O&M costs (€/year)	0	0	0
Total annual costs - new build and retrofit (€/year)	**497**	**1,336**	**3,135**

Table 4.5 Costs of Basic IEM (Slide Valves) for Older Engines

	Vessels		
	Small (SSD ME only)	Medium (SSD ME only)	Large (SSD ME only)
New build and retrofit capex (€)	6,060	8,020	12,220
Equipment lifespan (year)	2.5	2.5	2.5
Annualised costs (€/year)	2,595	3,435	5,234
Capex per kW installed (€/kW)	2.02	0.70	0.42
O&M costs (€/year)	0	0	0
Total annual costs - new build and retrofit (€/year)	**2,595**	**3,435**	**5,234**

4.2 Advanced Internal Engine Modifications

4.2.1 Maturity and Certainty of Cost Estimations

Advanced combinations of IEM are presently being developed by engine manufacturers. A reduction efficiency of 30% NO_X against IMO NO_X standards is a target which major engine manufacturers are currently developing engines to achieve (Kullas-Nyman 2005). Therefore cost estimations have a low degree of certainty. Retrofitting of advanced IEM varies significantly from engine to engine and is not commonly considered, and therefore retrofitting cost estimations have a very low degree of certainty (Kullas-Nyman 2005, Cronhamn 2005, Michalson 2005).

4.2.2 Capital Costs

Advanced IEM includes a range of engine alterations to optimise combustion, fuel injection and charge air characteristics. IEM costs can be split into two components, firstly fuel injection costs and secondly engine modifications. Cost estimations for fuel injection upgrade in new build engines are shown in Table 4.6 (US EPA 2003[22] 3, CITEPA 2003, 2).

The premium for retrofitting engine modifications is difficult to estimate. This is because the alterations required to achieve 30% NO_X reductions will vary from engine to engine. For example costs will depend upon the engine's de-rating (Corbett 2002, Cronhamn 2005). To retrofit the modifications listed in Table 2.3, it is likely that an engine's cylinder head may need replacement (Spencer 2005).

A rough estimate of the cost of replacing an engine's cylinder head is 25% of the cost of a new engine (Spencer 2005). The cost of a new engine can be roughly approximated as €210/kW (Michalson 2005). Therefore the additional cost of retrofitting 4 stroke engines is estimated as €52.5/kW. Approximations for the additional costs of retrofitting made by Wärtsilä were €50-70/kW (Kullas-Nyman 2005). It should be noted that this is likely to be an overestimate for 2 stroke engines, which do not have valve equipment in cylinder heads and therefore may not need cylinder heads replaced. These cost estimations are not further used in this study due to the high uncertainty.

[22] Costs for US sales were used. It was assumed that sales volumes in the US would be equivalent to sales volumes in the EU. Projected future cost reductions for manufacturers increasing sales to a global scale were not used.

Table 4.6 Estimated fuel injection upgrade costs[23]

	Fuel Injection Costs incl Installation
Engine Size	**(€/engine)**
New build AE Small	361
New build AE Medium	466
New build AE Large	6,500
New build ME Small	7,840
New build ME Medium	15,920
New build ME Large	48,580

Development of internal engine modifications require research and development costs. This development includes time for engineers to determine the engine modifications required for each engine family. Table 4.7 outlines cost estimations for development costs (US EPA 2003 3). It is assumed that development costs for individual AEs are 25% of that for MEs, based on the assumption that there are four times as many AEs than MEs installed in the EU fleet.

Table 4.7 Development and installation costs for engines[24]

	Engine modification costs (€) per engine incl. installation
Engine type	**(€/engine)**
Main Engines new (ME)	49,000
Auxiliary Engines new (AE)	12,250

4.2.3 Lifespan

The lifespan of IEM Combinations will be up to the life of the engine, assumed to be 25 years for new build engines. In practice, the lifespan will depend on the specific details of the particular IEM combination.

[23] Costs for engines are based on USEPA 2003, except for AEs. The costs shown in US EPA (2002) are reduced by 10% according to comments received on the original costs (US EPA 2003, 2). AEs are based on costs from CITEPA (2003).

[24] These costs were quoted for engines of 4MW and above. It is assumed that the engineering time required for engine modification developments are not dependent upon engine size, and therefore these development costs apply for AEs.

4.2.4 Operating and Total Costs

There are no operating costs associated with the use of advanced IEM. There may be some engine service benefits such as reduced fuel oil consumption for lubrication. However this benefit is not quantified. Therefore total costs are equal to the capital costs.

Table 4.8 Costs of Advanced IEM

	Vessels		
	Small	**Medium**	**Large**
New build capex (€)	107,284	119,764	172,580
Equipment lifespan (year)	25	25	25
Annualised costs (€/year)	6,867	7,666	11,047
Capex per kW installed (€/kW)	30	10	6
O&M costs (€/year)	0	0	0
Total annual costs - new build (€/year)	**6,867**	**7,666**	**11,047**

4.3 Direct Water Injection (DWI)

4.3.1 Maturity and Certainty of Cost Estimations

Experiences with DWI appear positive up to now, but at present the system is limited to only a small number of engine manufacturers eg Wärtsilä[25]. DWI is the water injection technique with perhaps most operational hours to date (Cooper, 2004). The number of commercial installations are shown Table 4.9. Therefore the cost estimations are relatively certain for new build vessels.

Table 4.9 Existing Installations of DWI

Abatement technique	Approximate no. of commercial installations	Approximate year of first commercial system
DWI – Direct Water Injection	50 (23 ships)	1998

Although development with DWI continues, Wärtsilä have also chosen to pursue CASS (Combustion Air Saturation System) as an alternative means of using water to reduce NO_x emissions. Although CASS is still under development, the preliminary tests results and general operating experience for the first prototype are positive and trials will continue (Gorton, 2004).

[25] MaK Global also have a program investigating water injection as a means for NO_x control.

4.3.2 Capital Costs

Costs are based on US EPA (2003, 3) for main engines. Costs for AEs are based on costs from CITEPA (2003, 1). The cost of water injectors was approximately 22% of total capex of the system (US EPA, 2003, 3).

The cost premium of retrofitting DWI is likely to be high, since it may require installation of additional cylinder heads (Spencer 2005). To reflect this, a rough estimate of the cost of replacing an engine's cylinder head can be made as 25% of the cost of a new engine (Spencer 2005). The cost of a new engine can be roughly approximated as €210/kW (Michalson 2005). Therefore the additional cost of retrofitting is estimated as €52.5/kW. Approximations for the additional costs of retrofitting made by Wärtsilä were €50-75/kW (Kullas-Nyman 2005). It should be noted that this is likely to be an overestimate for 2 stroke engines, which do not have valve equipment in cylinder heads and therefore may not need cylinder heads replaced. These cost estimations are not further used in this study due to the high uncertainty.

4.3.3 Lifespan

Water injectors are likely to have a lifespan of around 4 years, and are routinely changed every four years. The rest of the equipment, including pressure modules, water tank, piping and control unit, is likely to last around 25 years.

4.3.4 Operating Costs

Based on a 45% water injection rate, the quantity of water required is about 90 g/kWh. A high water quality is required to avoid engine damage, and it is assumed that distilled water is used at a cost of €15/m^3 (US EPA, 2003, 3, Hume 2005). This equates to specific additional costs for distilled water of €1.36/MWh.

4.3.5 Total Costs

Table 4.10 depicts the estimated total costs of the DWI technology.

Table 4.10 Costs of DWI

	Vessels		
	Small	**Medium**	**Large**
New build			
Cost of injectors (€)	29,581	58,969	119,633
Equipment lifespan (year)	4	4	4
Annualised costs (€/year)	8,149	16,245	32,958
Cost of rest of equipment (€)	106,151	211,609	429,300
Equipment lifespan (year)	25	25	25
Annualised costs (€/year)	6,795	13,545	27,480
Total Capex (€)	135,732	270,578	548,933
Capex per kW installed (€/kW)	38	24	19
Total Annualised costs	14,944	29,791	60,438
O&M costs (€/year)	33,190	108,560	271,000
Opex per MWh (€/MWh)	2.11	2.11	2.11
Total annual costs - new build (€/year)	**48,134**	**138,351**	**331,438**

4.4 Humid Air Motors

4.4.1 Maturity and Certainty of Cost Estimations

Only four installations of HAM are thought to be in commercial use at the time of writing onboard a passenger ferry. Therefore cost estimation certainty is not high.

The performance and experience obtained with the systems so far are, however, very positive. On face value, one would expect an increasing number of ship-owners to invest in the technique. The problem at present however, is that HAM is limited to certain engine types (eg Pielstick engines) and a considerable amount of research and development work is required on the part of the engine manufacturer before installation is possible.

At the moment HAM has only been designed and tested for one type of Pielstick engine (Pielstick 12 PC2.6, 12 cylinder Vee engine with 5,750 kW rated power at 500 rpm). In theory, other ships using this engine ought to be able to gain an advantage with the development costs already laid down. Space limitations exist but appear to be no more demanding than SCR and thus several ship types could apply the technique.

Table 4.11 summarises the number of existing installations and the age of the technology.

Table 4.11 Existing Installations of HAM

Abatement technique	Approximate no. of commercial installations	Approximate year of first commercial system
HAM – Humid Air Motor	4 installations, of which only one is installed on a ship	1999

4.4.2 Capital Costs

Based on information from ships' engineers on the MS Mariella, which uses HAM, costs per kW installed were reported to be 90-130 €/kW for new build engines and 110-130 €/kW for retrofitting (Cooper 2004).

4.4.3 Lifespan

The humidifier is the main cost involved with HAM. If the humidifier is made out of durable material, such as non-corrosive or galvanised materials, then it is likely the humidifier will last for approximately 25 years. However, if the humidifier is made out of mild steel, the lifespan will be significantly shorter. An approximate lifespan of 15 years is assumed based on information from the *MS Mariella*. For retrofitting the lifespan will be the remaining ship's average lifespan of 12.5 years.

4.4.4 Operating and Maintenance Costs

Operation of the humidification system will require some maintenance. Based on data from installed HAM systems, maintenance costs are approximated at 4,000 € per year for a 5.7 MW engine (Cooper 2004). This cost is assumed to be directly proportional to engine use, and is therefore around €0.15/MWh.[26]

4.4.5 Total Costs

Table 4.12 depicts the estimated costs for HAM.

[26] Maintenance cost of €4,000 per year were assumed to relate to an 80% load for 6,000 hours per year.

Table 4.12 Costs of HAM

	Vessels		
	Small	**Medium**	**Large**
New build capex (€)	462,800	1,292,400	2,744,000
Equipment lifespan (year)	15	15	15
Annualised costs (€/year)	41,625	116,240	246,798
Capex per kW installed (€/kW)	131	113	95
Retrofit capex (€)	462,800	1,392,400	3,244,000
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	47,769	143,720	334,837
Capex per kW installed (€/kW)	131	121	113
O&M costs (€/year)	2,360	7,660	19,120
Opex per MWh (€/MWh)	0.15	0.15	0.15
Total annual costs - new build (€/year)	**43,985**	**123,900**	**265,918**
Total annual costs - retrofit (€/year)	**50,129**	**151,380**	**353,957**

4.5 Exhaust Gas Recirculation

4.5.1 Maturity and Certainty of Cost Estimations

To our knowledge, no experience with commercial EGR systems onboard ships has been gained at the time of writing. Based on literature reviews, the technique suffers from the problem that the exhaust gas must be filtered from particles before entering back into the engine to prevent excessive engine wear.

This means that the available cost data is based on a small number of studies and operating experiences, none of which are on ships. Therefore there is high uncertainty associated with these cost estimates. However since the capital costs of EGR are low, the total cost effectiveness of EGR will not be significantly affected by a variation in capital costs.

Further work on the EGR technology is scheduled and this may enable an improvement in the accuracy of cost estimations. EGR is targeted in a future development project partly funded by the European Commission. The project, named *Hercules*, involves 57 partners including universities, major engine manufacturers and shipowners and aims to develop new and existing abatement techniques (Hercules, 2004). In addition, the advances in EGR for road vehicles (trucks, buses etc.) may prove transferable to this part of the marine sector in the near future for similar sized engines in small passenger ferries (Rideout, 2004; Ecotraffic, 2004).

Table 4.13 summarises the number of existing installations and the age of the technology.

Table 4.13 Existing Installations of EGR

Abatement technique	Approximate no. of commercial installations	Approximate year of first commercial system
EGR – Exhaust Gas Re-circulation	0	-

4.5.2 Capital Costs

EGR is commonly used in highway diesel trucks, however the residual oil fuel used in marine engines contains significantly higher fractions of sulphur and particulates than fuel used in highway diesel trucks. The higher sulphur and particulate levels lead to higher loading in exhausts which, when recycled, leads to contamination of lubricating oil and causes engine wear. For this reason, EGR is not at a commercial stage for application to marine diesel engines using RO.

Cooled EGR systems have been considered for reducing emissions from non-road equipment. The US EPA (2003, 1) estimate costs for small engines, up to 735kW, in non-road equipment, tractors etc., according to the following formulae[27]:

Near term: $517+$17*engine displacement (L) = €394 + €13* engine displacement (L)

Long term: $499+$13*engine displacement (L) = €380 + €10* engine displacement (L)

Using these formulae, capital costs can be estimated from engine displacement. Medium size main engines can be either medium or slow speed engines, having either 12 cylinders with 55L displacement per cylinder (medium speed), or 4 cylinders with 900L displacement per cylinder (slow speed) (USEPA 2003,3). According to the above formulae, displacement per cylinder makes a very significant difference to EGR costs, indicating EGR is very expensive for slow speed engines. In the case of medium size engines, EGR will cost around 10 times more for slow speed engines than medium speed engines.

This significant jump may be due to the fact that the formulae are based on smaller engine sizes. Therefore extrapolation into main engine sizes, especially slow speed engines, seems not to result in reliable cost estimates. Since the uncertainty of cost estimations for slow speed engines and marine application is so high, these cost estimations are not used further in this study.

4.5.3 Lifespan

The lifespan of EGR on marine vessels is difficult to determine since there are no commercial applications of this technology.

4.5.4 Operating Costs

Since engine manufacturers do not recommend the use of RO with EGR technology, operating costs for EGR use include additional costs for using MD fuels (Corbett 2002). Based on a RO

[27] Assuming an exchange rate of $/€0.8 that the costs are based in $\$_{2002}$ and that the inflation rate between 2000 and 2002 was 2.5%.

price of €113/tonne, a MD price of €227/tonne, and an average specific fuel consumption of 200g/kWh, the cost of fuel switching is about €23/MWh.

4.5.5 Total Costs

Total costs are not presented due to the high uncertainty associated with estimating capital costs.

4.6 Selective Catalytic Reduction

4.6.1 Maturity and Certainty of Cost Estimations

Of the advanced NO_X abatement techniques, SCR can be considered relatively well standardised in view of the number of installations, operating hours gained and the number of established manufacturers offering the technique as can be assumed from Table 4.14. Therefore cost estimations have a relatively high degree of certainty.

It is probable that as the market demand increases further cost savings are possible. However, feedback from chief engineers indicate that the systems require some maintenance in operation. In addition, the crew need to be educated with a satisfactory training course.

Table 4.14 Existing Installations of SCR

Abatement technique	Approximate no. of commercial installations	Approximate year of first commercial system
SCR – Selective Catalytic Reduction	350 (80 ships)	1989

4.6.2 Capital Costs

Costs for SCR for main engines were based on estimations made by the US EPA (2003, 3). SCR costs for auxiliary engines are based on estimations from CITEPA (2003, 1). The retrofitting premium is estimated at 50% of new build capital costs (Cooper 2004).

4.6.3 Lifespan

The reactor is likely to need rebuilding after a number of years, as discussed further below, and therefore the rebuilding is treated as an operating cost. The remainder of the equipment, including tanks, piping, wiring etc. has an estimated lifespan of 15 years (Cooper 2004).

4.6.4 Operating and Maintenance Costs

Urea

The rate of urea use relates to the efficiency of NO_X reduction. To achieve around 90% NO_X reduction, a urea rate of approximately 15 g/kWh is required (Cooper, 2005). Aqueous urea at

40% concentration costs approximately €170/(tonne urea) (Hume, 2005). This equates to a cost of €2.55/MWh.

Maintenance

Maintenance costs of the SCR reactor will include:

- routine cleaning for optimum operation; and
- re-building of the reactor.

Routine cleaning is performed though the use of either ultrasound or compressed air, requiring 4-6 person hours per cleaning event (US EPA 2003 3). It is assumed that about 6 SCR cleaning events will be required for 1,000 hours of operation (US EPA 2003 3). At about €150 per cleaning event, this equates to around €8,000 per year per vessel (US EPA 2003 3).

SCR reactors

SCR reactors used on the exhausts of engines burning RO generally need to be rebuilt due to sulphur poisoning and other contamination from fuels. The rebuild requirement is estimated as every 20,000 hours of operation (around 3 years) when using 1 to 1.5% sulphur residual oil (US EPA 2003 3). This assumption may be too low, as Holmstrom (2004) suggests that SCRs on engines using residual oil are likely to have a reactor rebuild requirement of between 4 and 20 years depending on the type of fuel (RO or MD) and the fuel quality. A reactor rebuild requirement of every 5 years for engines using 1 to 1.5% sulphur fuel is assumed in this study.

Ships inside SO_2 Emission Control Areas (ECA) will need to use $\leq$1.5% sulphur fuel to meet legislative requirements. These ships may therefore be assumed to have a reactor rebuild requirement every 5 years. Ships outside SO_2 ECAs are likely to be using 2.7% sulphur fuel on average. Assuming that the rebuild requirement of the reactor relates directly to the sulphur content of the fuel, it can be roughly approximated that ships outside SO_2 ECAs will need to rebuild reactors every 2.5 years.[28]

Ships using MD are likely to have longer reactor lifespans. One of the oldest commercial SCR units started in 1991 (MS Aurora), and is still operating today and is expected to rebuild the reactor after 20 years (Holmstrom, 2004). However this suggested lifespan can not yet be proven. Therefore this study assumes that ships using MD require reactor rebuilds every 15 years.

Based on US EPA, 2003 3 the reactor rebuilding costs are estimated at 60% of the total retrofitting capex. It should be noted that the US EPA (2003 3) assumes that rebuilding of SCR reactors may cost three times the hardware costs to account for the higher cost of aftermarket parts, but this assumption is not used in this study.

4.6.5 Total Costs

Table 4.15 depicts the estimated costs for SCR.

[28] Assuming that an approximate doubling of fuel sulphur content relates to a halving of time between reactor rebuilds.

Table 4.15 Costs of SCR, Ships using RO, Outside SO_2 ECA

	Vessels		
	Small	**Medium**	**Large**
New build capex (€)	225,950	525,410	1,207,403
Equipment lifespan (year)	15	15	15
Annualised costs (€/year)	20,322	47,256	108,595
Capex per kW installed (€/kW)	64	46	42
Retrofit capex (€)	338,925	788,115	1,811,104
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	34,983	81,347	186,937
Capex per kW installed (€/kW)	96	69	63
O&M costs (€/year)	135,520	342,061	801,200
Opex per MWh (€/MWh)	8.6	6.7	6.2
Total annual costs - new build (€/year)	**155,842**	**389,316**	**909,795**
Total annual costs - retrofit (€/year)	**170,503**	**423,408**	**988,137**

Table 4.16 Costs of SCR, Ships using RO, Inside SO_2 ECA

	Vessels		
	Small	**Medium**	**Large**
New build capex (€)	225,950	525,410	1,207,403
Equipment lifespan (year)	15	15	15
Annualised costs (€/year)	20,322	47,256	108,595
Retrofit capex (€)	338,925	788,115	1,811,104
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	34,983	81,347	186,937
O&M costs (€/year)	94,107	245,762	579,904
Opex per MWh (€/MWh)	6.0	4.8	4.5
Total annual costs - new build (€/year)	**114,429**	**293,018**	**688,499**
Total annual costs - retrofit (€/year)	**129,090**	**327,109**	**766,841**

Table 4.17 Costs of SCR, Ships using MD

	Vessels		
	Small	**Medium**	**Large**
New build capex (€)	225,950	525,410	1,207,403
Equipment lifespan (year)	15	15	15
Annualised costs (€/year)	20,322	47,256	108,595
Retrofit capex (€)	338,925	788,115	1,811,104
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	34,983	81,347	186,937
O&M costs (€/year)	66,718	182,073	433,546
Opex per MWh (€/MWh)	4.2	3.5	3.4
Total annual costs - new build (€/year)	**87,040**	**229,329**	**542,141**
Total annual costs - retrofit (€/year)	**101,701**	**263,420**	**620,483**

5. Cost Effectiveness

5.1 Cost effectiveness of NOX abatement techniques for ships

Table 5.1 presents the derived cost effectiveness of the investigated measures.

Table 5.1 Cost effectiveness per tonne NOx pollutant abated

Measure	Ship type	Emission	Small Vessel	Medium Vessel	Large Vessel
			(€/tonne)	(€/tonne)	(€/tonne)
Basic IEM (2 stroke slow speed only)	New	NOx	12	9	9
Basic IEM (2 stroke slow speed only), young engines[29]	Retrofit	NOx	12	9	9
Basic IEM (2 stroke slow speed only), older engines	Retrofit	NOx	60	24	15
Advanced IEM	New	NOx	98	33	19
Direct water injection	New	NOx	411	360	345
Humid air motors	New	NOx	268	230	198
Humid air motors	Retrofit	NOx	306	282	263
SCR outside SO_2 ECA	New	NOx	740	563	526
SCR outside SO_2 ECA	Retrofit	NOx	809	612	571
SCR inside SO_2 ECA	New	NOx	543	424	398
SCR inside SO_2 ECA	Retrofit	NOx	613	473	443
SCR, Ships using MD	New	NOx	413	332	313
SCR, Ships using MD	Retrofit	NOx	483	381	358

Table 5.2 shows the cost effectiveness expressed in cost per tonne of fuel for the different measures and vessel sizes.

[29] 'Older' engines require development costs to enable retrofitting of basic IEM. A rough guide to which engines are 'older' are engines older than 15 years, based on an assumed lifespan of 25 years around 10/25=40% of the EU-flagged fleet are assumed to be old.

Table 5.2 Cost of measure per tonne fuel used

Measure	Ship type	Unit	Small Vessel	Medium Vessel	Large Vessel
			(€/tonne of fuel)	(€/tonne of fuel)	(€/tonne of fuel)
Basic IEM (2 stroke slow speed only)	New	Fuel	0.17	0.13	0.12
Basic IEM (2 stroke slow speed only), young engines	Retrofit	Fuel	0.17	0.13	0.12
Basic IEM (2 stroke slow speed only), older engines	Retrofit	Fuel	0.90	0.34	0.20
Advanced IEM	New	Fuel	2	0.7	0.4
Direct water injection	New	Fuel	15	14	13
Humid air motors	New	Fuel	14	12	10
Humid air motors	Retrofit	Fuel	16	15	14
SCR outside SO_2 ECA	New	Fuel	50	38	35
SCR outside SO_2 ECA	Retrofit	Fuel	55	41	39
SCR inside SO_2 ECA	New	Fuel	37	29	27
SCR inside SO_2 ECA	Retrofit	Fuel	41	32	30
SCR, Ships using MD	New	Fuel	29	23	22
SCR, Ships using MD	Retrofit	Fuel	34	27	25

5.2 Comparison of cost effectiveness of NOX abatement measures for ships compared with NOX abatement for other sources

In the context of EU policy development, emissions reductions should be sought where they are most cost-effective in achieving environmental objectives, taking into consideration all emission source groups. This section compares the marginal abatement costs of additional abatement measures for ships with the corresponding costs of additional abatement measures for other sectors.

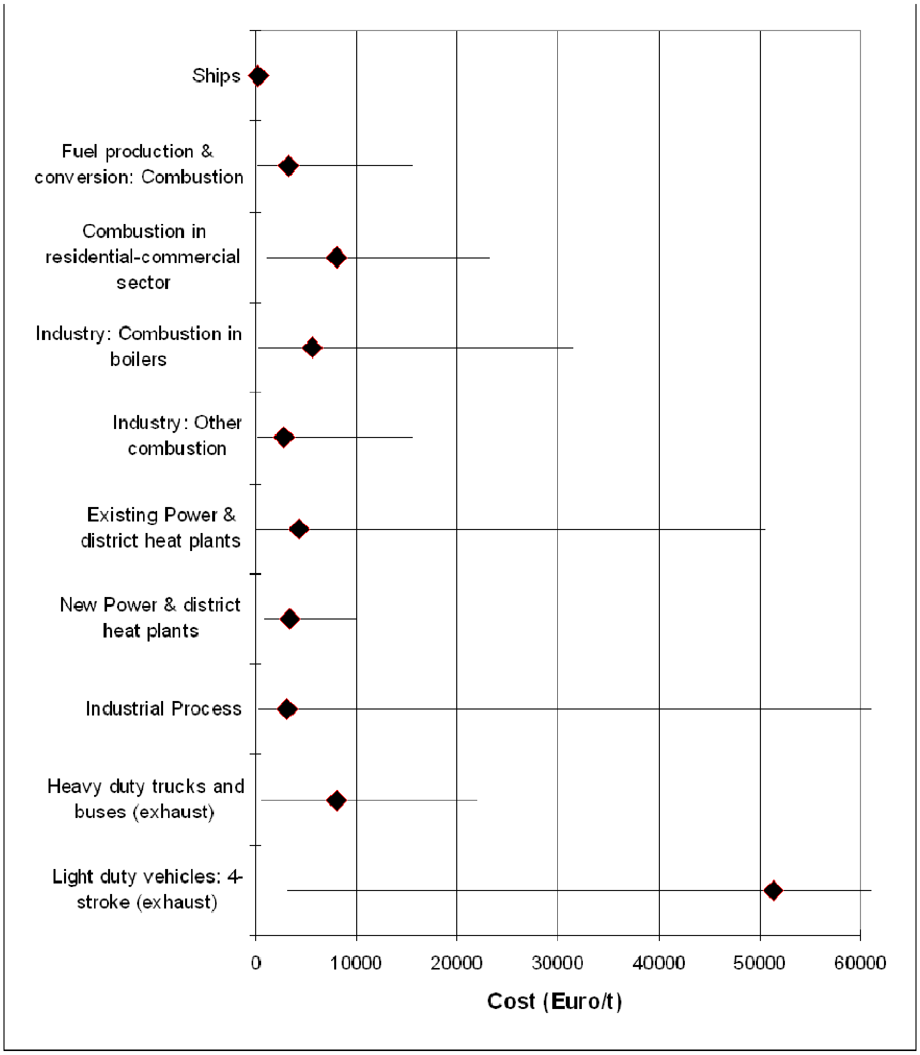
The marginal abatement costs of additional abatement measures for all sectors considered in the CAFÉ modelling work were supplied by IIASA, at the time of undertaking the research for this study, and represent measures beyond those that are estimated to be implemented under the CP_CLE scenario, i.e. the measures represent 'beyond BAU' measures and are under the maximum technically feasible reduction scenario – MTFR.

The indicative average marginal abatement costs for sectors with 'beyond BAU' NOx measures are shown in Table 5.3. This includes all RAINS sectors except the shipping sector, due to the more specific ship emissions abatement estimates derived in this study. Within each sector in the table, the quoted marginal abatement cost represents an average across all fuel types, abatement techniques and countries. Hence, individual measures may differ significantly from the quoted figures. Figure 5.1 compares the cost range of NOx abatement measures for ships against the cost range of NOx abatement for other sources

Table 5.3 Indicative average marginal abatement costs for sectors with 'beyond BAU' NOx measures supplied by IIASA for 2010 and 2020

Sector	2010 Cost Curve - marginal cost (Euro/t)	2020 Cost Curve - marginal cost (Euro/t)
Fuel production & conversion: Combustion	3306	3362
Combustion in residential-commercial sector	8085	8034
Industry: Combustion in boilers	5588	5731
Industry: Other combustion	2792	3052
Power & district heat plants: Exist. other	4343	5270
Power & district heat plants: New	3378	3275
Industrial. Process: Cement production	839	848
Industrial. Process: Coke oven	1900	1900
Industrial. Process: Lime production	872	881
Industrial. Process: Nitric acid	3711	3825
Industrial. Process: Other non-ferrous metals prod. - primary and secondary	2651	2651
Industrial. Process: Pig iron, blast furnace	3844	3844
Industrial. Process: Petroleum refineries	8374	8690
Industrial. Process: Agglomeration plant - sinter	3049	3210
Other transport: other off-road, 4-stroke (military, households, etc.)	44398	44398
Other transport: rail (exhaust)	17266	18033
Heavy duty trucks and buses (exhaust)	8012	8562
Light duty vehicles: 4-stroke (exhaust, for PM module excludes GDI)	51322	56435
Motorcycles: 4-stroke (exhaust)	142964	134335
Waste: Agricultural waste burning	444	444
Waste: Flaring in gas and oil Industry	3520	3520
Waste: Open burning of residential waste	879	879

Figure 5.1 Range of cost effectiveness of NOx abatement measures for ships against NOx abatement for other sources with 'beyond BAU' NOx measures supplied by IIASA for 2010 (Symbol represents average cost effectiveness) [30]



It can be seen that the shipping sector is one of the most cost effective sectors (per tonne NOx abated) for achieving additional 'beyond BAU' NOx emissions reductions.

The marginal abatement costs of additional abatement measures for all sectors, supplied by IIASA, are presented in the following cost curve for NO_X for 2010, which is comprised of large numbers of individual 'beyond BAU' measures ranked in order of cost effectiveness. The curve starts at the left of each figure, at zero emissions reduction. As more and more 'beyond BAU' measures are taken into account, emissions are reduced with compliance costs increasing (ie as the cost curve moves to the top right of the figure).

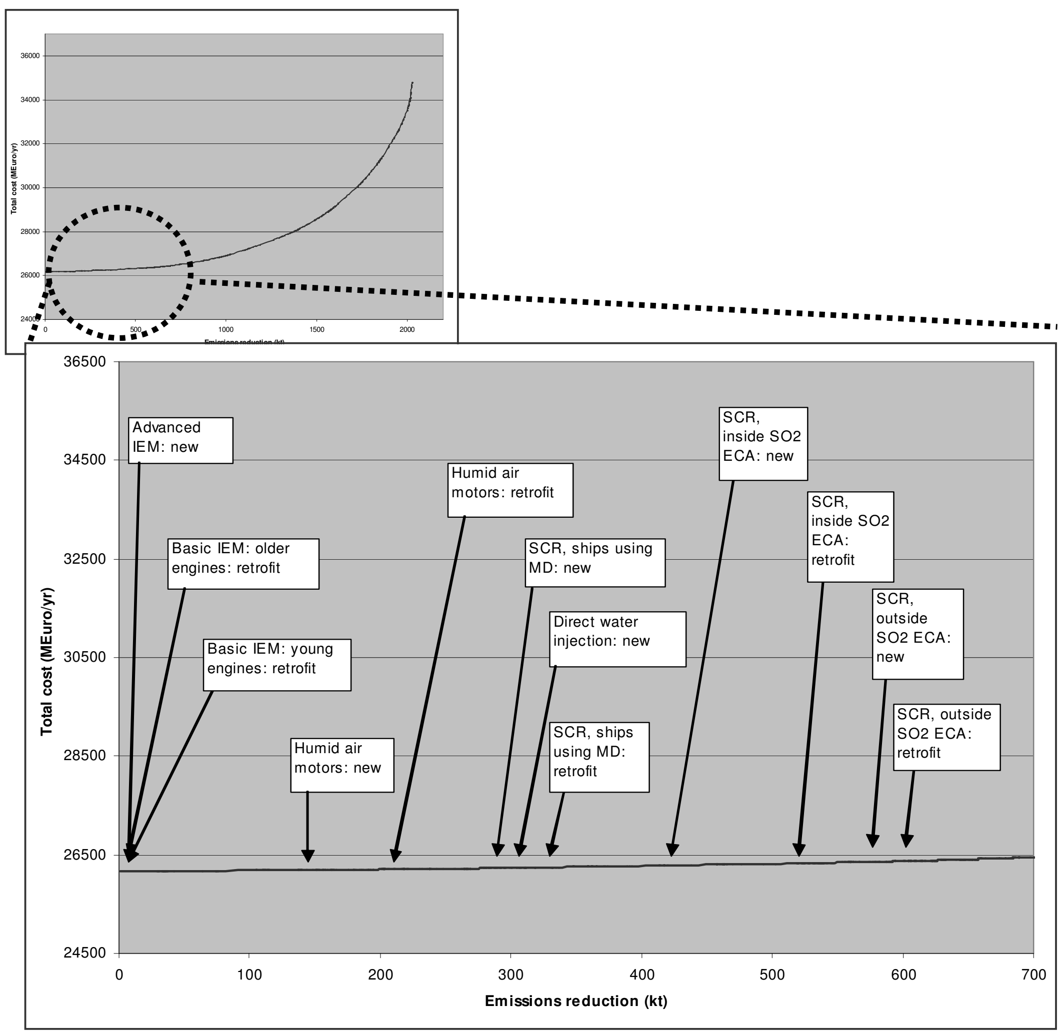
[30] Range for Industrial Process and Light duty vehicles is off the scale and therefore not fully shown in this figure

Each measure represents an individual point on the curve. The slope of the curve indicates the cost effectiveness at any given point.

Overlaid onto each figure are text boxes and arrows indicating the approximate relative position in the cost curve where the additional measures for ships considered in this report would fit, if they were included in the cost curves. It should be noted that the specific measures themselves are not currently integrated into the RAINS cost curves and therefore their impact on remaining emissions and incremental costs is not explicitly taken into account in the cost curves that are presented here.

These figures simply enable the relative cost effectiveness of additional measures for ships to be considered in comparison to the cost effectiveness of 'beyond BAU' measures already included in the RAINS model.

Figure 5.2 Cost curve for NO_X for 2010 showing position in cost curve where additional measures for ships would fit (all measures for ships are for medium size vessels) (Source: IIASA, 2004)



The potential additional measures for NO_X for ships are all positioned to the left of the cost curve, with the three IEM measures being more cost effective than any other measures currently included within the cost curve.

It is emphasised that whilst the potential position of a measure in a single-pollutant cost curve is a useful gauge of its relative cost-effectiveness, it is not necessarily indicative of its relative cost-benefit performance, due to the generally greater distance of ship emission sources to nearest receptor populations and environments. However, dispersion modelling conducted for the Clean Air for Europe programme suggests that by spending €28 million on ship emissions abatement, up to €300 million could be saved on land-based abatement measures.[31]

The scope of this particular study does not extend to a cost-benefit analysis, however this would be important in any further policy development related to potentially tighter standards in the shipping sector. If such work was to be done, it would clearly be necessary to consider the costs in more detail (including relevant wider economic impacts) and to quantify the health and environmental benefits of any potential emissions reductions (including impacts on other pollutants). In such an analysis, the location of ship emissions relative to receptor populations and environments would need to be taken into account.

[31] http://www.europa.eu.int/comm/environment/air/cafe/activities/pdf/cafe_scena rio_report_6.pdf

6. Total Costs for all EU-Flagged Ships

As mentioned in the General Report only commercial ships > 500 GT are included in this study. Assumptions on the number of ships in the EU-flagged fleet and the global fleet are shown in Table 6.1.

Table 6.1 Number of ships in the EU-flagged and Global fleets

Number of EU-flagged vessels > 500 GT	7,150
Number of world wide vessels > 500 GT	31,000

The costs for applying the technologies to the EU-flagged fleet are shown in Table 6.2. This table illustrates costs per year for retrofitting each measure to all applicable existing ships. The additional costs per year for each new build ship are presented in Section 4 for each abatement measure.

Table 6.2 Costs for applying measures to existing vessels in the EU-flagged fleet

	Vessels			
	Small	**Medium**	**Large**	**Total**
Fraction of total EU-flagged ships	55%	35%	10%	100%
Fraction of ships using SSD 2-stroke engines qualifying for basic IEM of this vessel size	48%	58%	55%	-
Fraction of total EU-flagged ships that qualify for basic IEM[32]	16.8%	13.2%	3.55%	-
Basic IEM, annualised costs for retrofitting all potential Slow Speed 2-stroke Diesel ships (€millions/year)	1.6	2.1	1.0	4.7
HAM, annualised costs for retrofitting all existing ships (€millions/year)	197	379	253	829
SCR, annualised costs for retrofitting all existing ships (€millions/year) [33]	607	965	644	2216

Note: Cost for vessel class (€millions/year) = Fraction of EC-flagged ships that qualify (-) * Total number of EU-flagged ships (-) * Cost per ship of class (€millions/year)

[32] = Fraction of total EU-flagged ships [-]*maximum uptake of basic IEM i.e. 70% of 2 stroke slow speed engines [-]*Fraction of ships using SSD 2-stroke engines of this vessel size [%] - Fraction of total EU-flagged ships [-]*estimated existing uptake in ships [%]

[33] Based on costs for ships outside SOx-ECAs using RO