Energy demand and exhaust gas emissions of marine engines

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Project no. 2014-122: Mitigating and reversing the side-effects of environmental legislation on Ro-Ro shipping in Northern Europe
Work Package 2.3, Report no. 03
September 2015

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ABBRIVIATIONS

DO	Diesel oil
ECA	Emission control area (an area with very strict demands for allowable SOx emissions according to IMO)
EGR	Exhaust Gas Recirculation
GHG	Green house gas
HFO	Heavy fuel oil
IMO	International Maritime Organization
LFO	Light fuel oil
LNG	Liquefied natural gas
LPG	Liquefied petrol gas
MDO	Marine diesel Oil
MGO	Marine gas oil
SCR	Selective Catalytic Reduction
SFOC	Specific fuel oil consumption

INTRODUCTION

In recent years more and more focus has been placed on the environmental aspects of ships, because of the great attention to exhaust gas emissions from ships including CO_2, a leading contributor to Green House Gasses (GHG) emissions, due to their negative effect on global warming. This report describes the different exhaust gas emissions products, their negative effect and how they can be reduced. Furthermore data and methods on how to calculate the amount of these emissions will be presented. This description will also include a description of the different mitigation measures for the reduction of some of the most critical exhaust gas emissions.

ENERGY DEMAND AND EMISSION FACTORS

Engine types

In order to calculate the energy demand and emissions for the different ship types it is necessary to know the specific energy demand requirements, i.e. the specific fuel oil consumption (SFOC) and the emissions from the engines which are installed for propulsion and the generation of electrical power. A very comprehensive description of the exhaust gas emissions and the combustion engines used on-board can be found in the book “*Exhaust Emissions from Combustion Machinery”* by Andy Wright. The author was the task leader of the very extensive investigation into exhaust emissions from ships carried out by Lloyds Register (LR) in 1995, where emissions of various marine engines were investigated for the first time. This LR study has since 1995 been a principal source on the issue of exhaust gas emissions.

For ship propulsion the following engine types are used:

- Low speed two stroke diesel engines (50 – 300 RPM)
- Medium speed four stroke diesel engines (300 – 1000 RPM)
- High speed four stroke diesel engines (1000 – 3000 RPM)
- Gas turbines (very high RPM > 5000)

Specific oil consumption

The efficiency of diesel engines has constantly increased since the first maritime diesel engine was introduced on an ocean-going merchant ship, the SELANDIA in 1912. The improvement in marine diesel engine efficiency is shown in Figure 1, which shows the SFOC for two stroke engines based on data for MAN Diesel and Turbo engines since 1912 to 2012.

As can be seen, the oil crisis in 1973 had a pronounced influence on the specific oil consumption, which improved low speed diesel engine fuel efficiency at a higher rate lowering specific fuel consumption to approximately 0.17 kg/kW/h until 2000, when the new NOx regulations MARPOL Annex VI legislation entered into force. These regulations stopped the steady decrease of the specific fuel oil consumption quite distinctly, as most of the NOx reducing measures have the general effect of counteracting possible fuel oil savings. The steadily improved engine efficiency is thus counteracted by the negative influence from the different NOx reducing initiatives, such that nearly constant specific fuel oil consumption has been observed since 2000.

However it is possible to decrease the specific fuel oil consumption even more than the general trend since 1973 by de-rating of a diesel-engine, where the engine is operated at its normal maximum cylinder pressure for the design continuous service rating, but at a lower mean effective pressure and shaft speed. Other fuel reducing measures have also been developed and will be introduced in the coming years. The specific fuel oil consumption for de-rated two-stroke engines is also shown in Figure 1.

Table 1 shows the approximate specific fuel oil consumption for different marine engine types, which apply for service conditions. These oil consumptions are conservative to account for the actual engine working conditions which influence the consumption compared with the consumption measured under ideal conditions by the engine manufacturer on the test bed (as shown in Figure 1).

The oil consumption corresponds to fuels with the specified calorific value of 42.7 MJ/kg corresponding to marine diesel oil or gas oil (MDO and MGO). If heavy fuel oil (HFO) with a calorific value of 40.5 MJ/kg is used, the SFOC values in Table 1 are 5.7 % higher (42.7/40.5). For a de-rated engine the SFOC is approximately 4 % lower than the values given in Table 1, according to information from different engine manufacturers.

Table 1: Approximate/typical SFOC values for different engine types (at 42.7 MJ/kg oil)

Low speed engines:	155 - 175 gram/kW/hour
Medium speed engines:	175 - 200 gram/kW/hour
High speed engines:	195 - 225 gram/kW/hour
Gas turbines:	240 - 300 gram/kW/hour

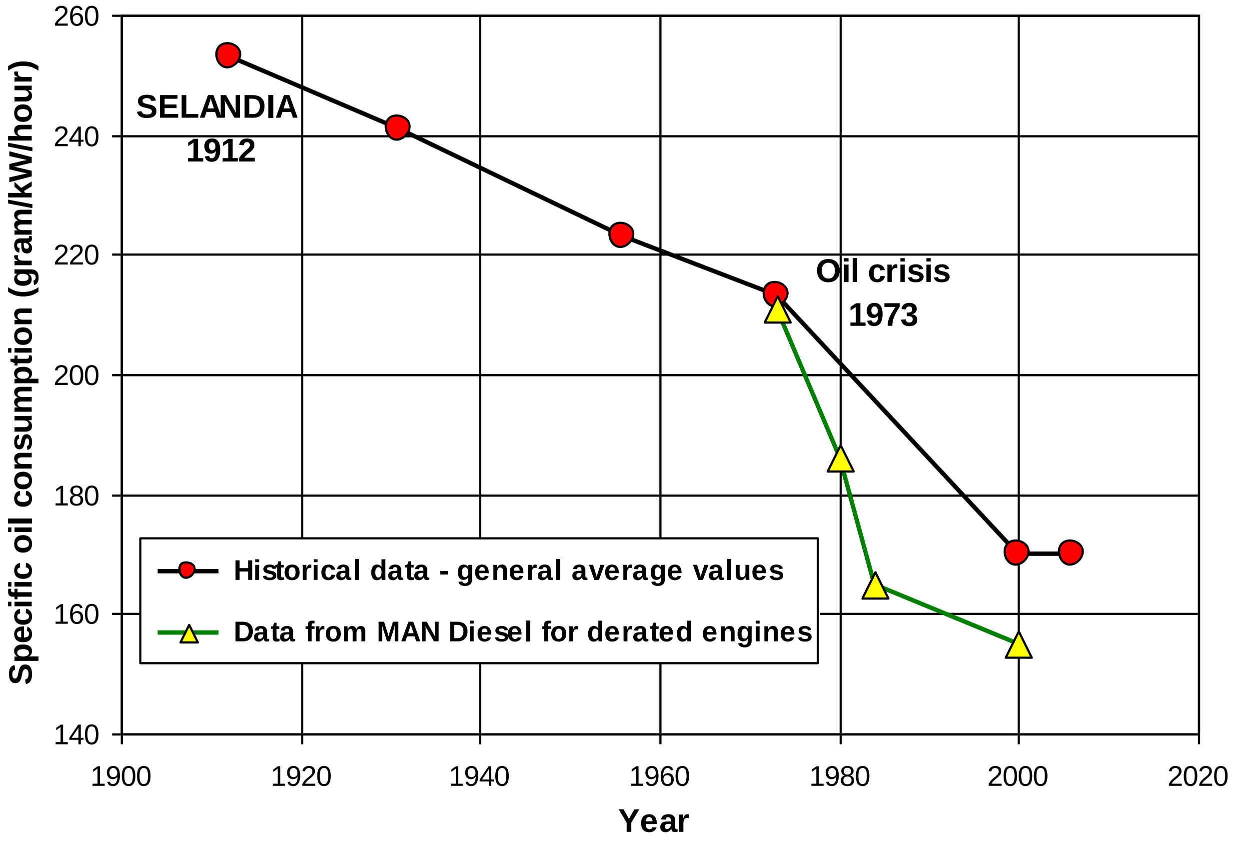

Figure 1 Development of specific oil consumption for two stroke low speed diesel engines (test bed conditions, 42.7 MJ/kg oil)

Change of specific fuel consumption due to change of engine loading

The SFOC is not constant over the whole operation range as it depends on the engine loading in percent of the maximum continuous service rating (% MCR). Two representative examples are shown in Fig. 2a and 2b for two 2-stroke MAN Diesel slow speed engines.

In table 28 are shown SFOC data for two 4-stroke medium speed engines, where the SFOC as function of MCR is shown.

The variation of SFOC in per cent for the two engine categories have been analysed and the results are shown in Fig. 3, from which it can be seen that the SFOC deviation from minimum SFOC (occurring at appr. 75 % MCR for 2 stroke engine and 80 % MCR for 4-stroke engines) can be approximated by following equations:

2-stroke engines: SFOC deviation (%) = $0.0028 \cdot MCR^2 - 0.41 \cdot MCR + 15$

4-stroke engines: SFOC deviation (%) = $0.0036 \cdot MCR^2 - 0.58 \cdot MCR + 23$

where MCR is given in per cent

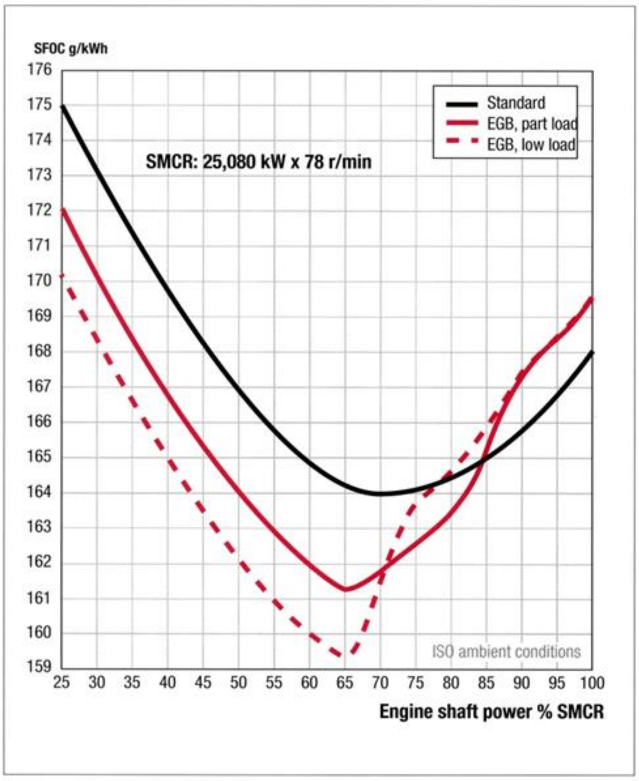

Fig. 2a: Example of SFOC reductions for 6S80ME-C8.2 with EGB

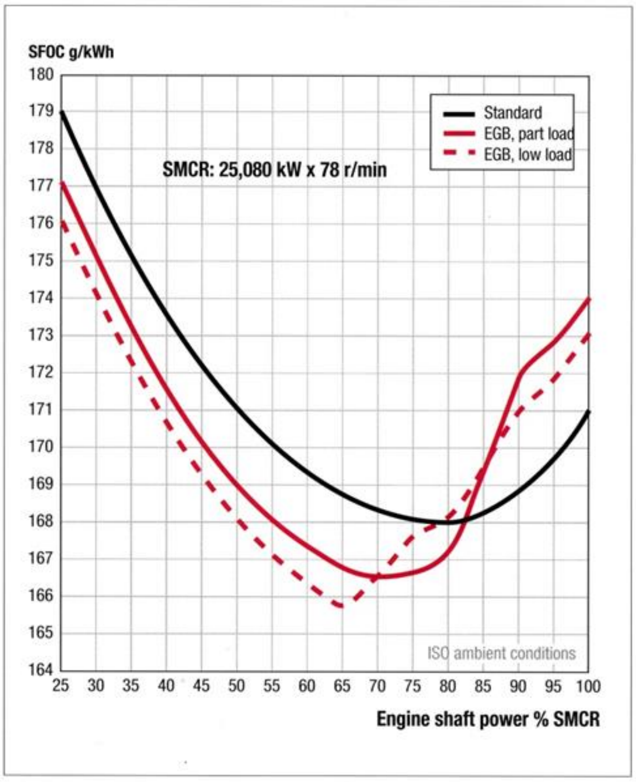

Fig. 2b: Example of SFOC reductions for 6S80MC-C8.2 with EGB

Engine 48/60CR – Mechanical propulsion with CPP

1,200 kW/cyl., 500 rpm or 514 rpm

	L48/60CR					V48/60CR				
% Load	**100**	**85 [1]**	**75**	**50**	**25**	**100**	**85 [1]**	**75**	**50**	**25**
Speed	**constant = 500 rpm or 514 rpm**									
Spec. fuel consumption (g/kWh) with HFO without attached pumps[2] [3] [4]	183	175	183	185	199.5	181	173	181	183	197.5
Spec. fuel consumption (g/kWh) with MGO (DMA, DMZ) or MDO (DMB) without attached pumps[2] [3] [4]	183	175	183	185	199.5	181	173	181	183	197.5

[1] Warranted fuel consumption at 85 % MCR.

[2] Tolerance +5 %.

Note! The additions to fuel consumption must be considered before the tolerance for warranty is taken into account.

[3] Based on reference conditions, see table Reference conditions, Page 83.

[4] Due to engine´s certification for compliance with the NO_x limits according E2 (Test cycle for "constant-speed main propulsion application" including diesel-electric drive and all controllable-pitch propeller installations) factory acceptance test will be done with constant speed only.

Table 28: Fuel oil consumption 48/60CR – Mechanical propulsion with controllable pitch propeller – Constant speed

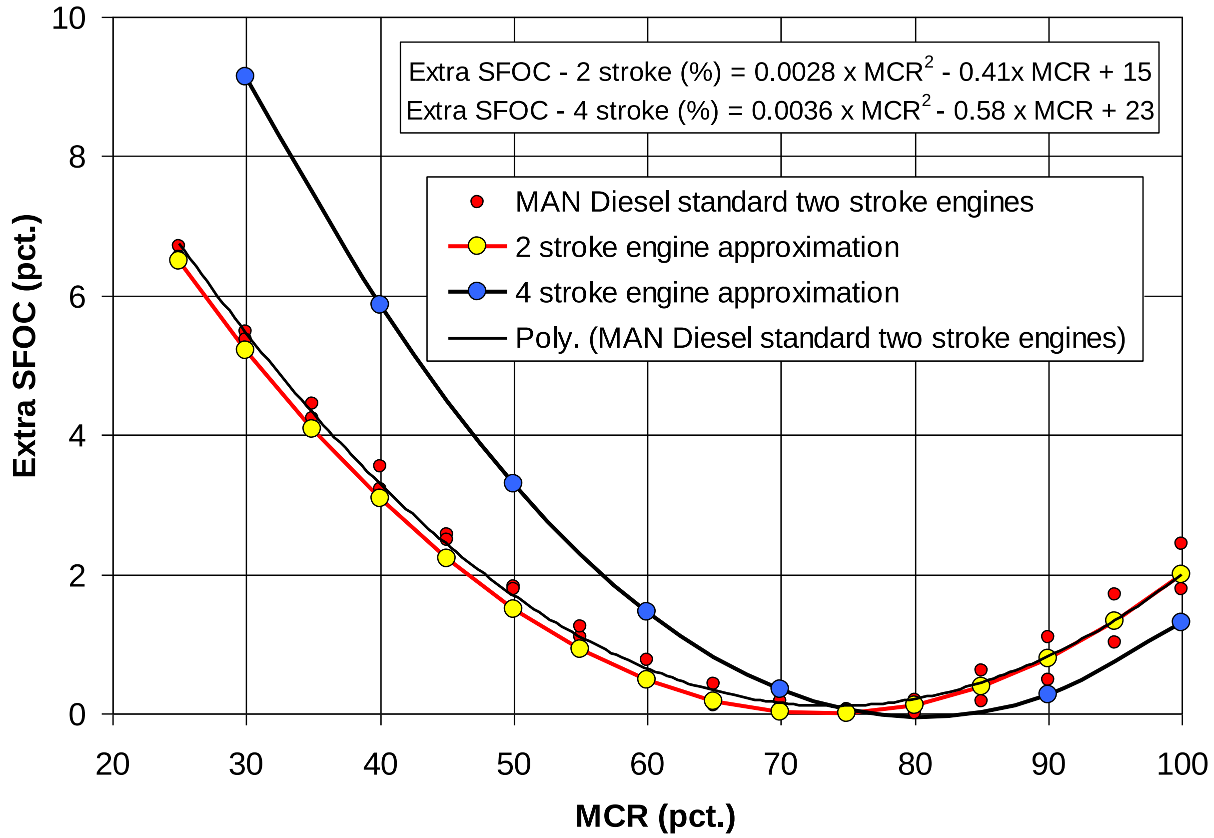

Fig. 3 Variation of SFOC for 2- and 4-stroke engines as function of MCR in per cent (data from MAN Diesel A/S)

Emission types

Exhaust emissions from marine diesel engines largely comprise of nitrogen, oxygen, carbon dioxide and water vapor with smaller quantities of carbon monoxide, oxides of sulphur and nitrogen, partially reacted and non-combusted hydrocarbons and particulate material, as shown in Figure 4. A similar composition will be apparent under both steady state and transient operating conditions, however, quantitative differences are likely between steady state and transient modes of operation.

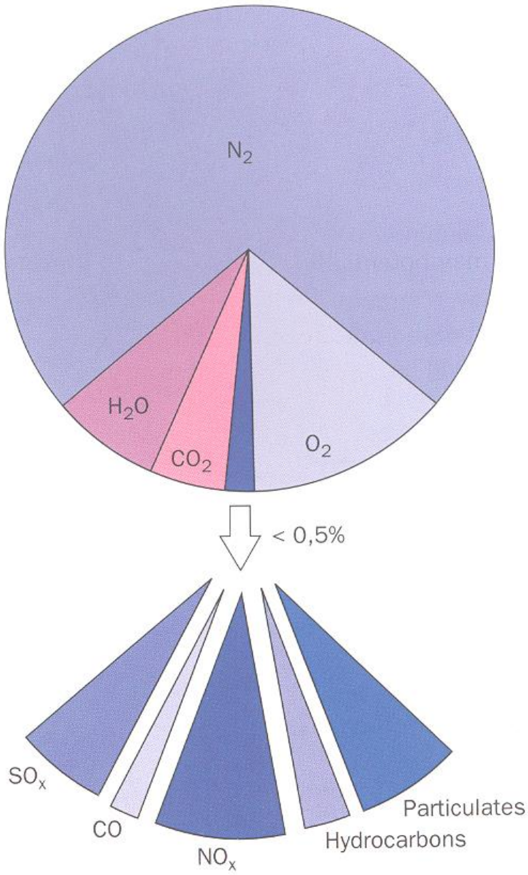

Figure 4 Marine diesel engine exhaust emission compositions (Lloyds Register 1995)

Nitrogen and Oxygen

Free nitrogen (N_2) and oxygen (O_2) comprise the major components of both the air intake and the exhaust emissions from an engine. N_2, forming 78% by volume of the intake air, remains largely unreacted in the combustion process, although a very small proportion will react chemically forming various oxides of nitrogen. Oxygen, originally forming 21 % of the intake air, will be only partially converted by the combustion process, consequently the free oxygen component of the exhaust will be a function of the excess air ratio with which the engine is operated.

Oxides of Nitrogen

The formation of oxides of nitrogen (NOx) occurs as a result of the oxidation of molecular nitrogen in the combustion air or the oxidation of organic nitrogen in the fuel. In the latter case it would be expected that the bulk of the organic nitrogen will be oxidized during the combustion process. Dependent upon the fuel, this organic nitrogen may account for a significant proportion of the total NOx emissions, particularly for engines operating on heavy fuel oil. When considering oxidation of atmospheric nitrogen, the reaction will be influenced by local conditions in the combustion chamber with increased production of nitric oxide (NO), the primary reaction product, favored at high temperatures and at optimal air-to-fuel ratios within the engine. Later in the combustion cycle and during flow through the exhaust system, 5-10% of the NO formed will convert largely to nitrogen dioxide (NO_2), while at the same time a limited proportion of nitrous oxide (N_2O) will also be formed. Oxidation of NO to the more toxic NO_2 will subsequently continue at ambient temperatures after expulsion from the exhaust system. Due to more strict rules for the allowable NOx emissions and the increasing number of ECA in certain regions of the world, under MARPOL Annex VI, different technologies and ways to control the combustion process are used and will be used extensively in the coming years when the stricter rules enter into force. The rules and the NOx reducing measures are described later in this report.

Adverse effects due to NOx are diverse. NO_2 is of particular concern as it has detrimental effects on respiration and vegetation, as well as contributing significantly to acid deposition. In addition, NOx emissions, together with volatile organic compounds (VOC), are also involved in a series of photochemical reactions leading to an increase in tropospheric ozone, which in turn, may adversely affect human health, crop yield and natural vegetation. At a global level, N_2O may also play a small part in both stratospheric ozone depletion and global climate change.

Carbon Dioxide and Water Vapour

Carbon dioxide (CO_2) and water vapor will be formed in all combustion processes in which complete, or nearly complete, combustion of a hydrocarbon fuel takes place with relative proportions being determined primarily by the hydrocarbon composition of the fuel. Thus the production of both CO_2 and water vapor is a function of the quantity of fuel burnt, which to a large extent is determined by the engine power required, the plant efficiency and the elemental composition of the fuel being burnt.

Although, traditionally not regarded in the light of a pollutant, CO_2 has become of increasing concern in recent years on account of its importance as a GHG and the consequences for global climate of the trend of rising CO_2 concentration. Therefore, the IMO is focusing very much on the increasing CO_2 emissions from shipping, because of the increasing international traffic. New legislation on a new so-called Energy Efficiency Design Index (EEDI) will enter into force from 1st January 2013. After this date the attained EEDI for all new ships shall be lower than the required EEDI which is the upper limit value for EEDI. Shipping is totally contributing approximately 3% of the total CO_2 emissions worldwide according to IMO´s Green House Gas study, 2009.

Oxides of Sulphur

The oxides of sulphur (SOx) are derived directly from the sulphur content of the fuels used. In the combustion chamber the sulphur is oxidized principally forming sulphur dioxide (SO_2) and, to a much lesser extent, sulphur trioxide (SO_3). The use of alkaline lubricants to protect the engine surfaces from acidic corrosion converts a small proportion of the SOx produced by the combustion process to calcium sulphate. However, this is a relatively insignificant proportion and the sulphur emissions from the engine will essentially be proportional to the percentage sulphur mass content of the fuel. Concern over SO_2 emissions lies in their detrimental effects to human respiration, vegetation and building materials.

As for NOx emissions new more strict regulations for reduction of SOx emission are now coming into force and will be even more stringent in the coming years by imposing strict sulphur limitations to the fuel used for marine applications, as stated in the regulation 14 of the MARPOL Annex VI legislation. These rules and alternative ways to reduce SOx emissions will be described later in this report.

Carbon Monoxide

Carbon monoxide (CO) is a product of incomplete combustion of carbonaceous material. Its formation in the diesel engine is thus principally a function of the excess air ratio, the temperature of combustion and the uniformity of the air/fuel mixture in the combustion chamber. In general, CO emissions are low due to high excess oxygen concentrations and an efficient combustion process.

However, in poorly maintained engines or at low power ranges, the proportion of CO may be expected to increase considerably in relative concentration.

Concern over CO emissions is largely based on adverse health effects resulting from reduced oxygen carrying capacity of the blood in persons exposed to CO. Increasingly serious effects are apparent with prolonged exposure and range from impaired performance to respiratory failure and death. Broader environmental effects are not generally of major concern, although, carbon monoxide may have some small influence on global climate change.

Hydrocarbons

The hydrocarbon (HC) fraction of the exhaust gas will predominantly consist of un-burnt or partially combusted fuel and lubricating oils. In reality, this fraction comprises a myriad of individual organic compounds with almost every chemically variation of C, H, O, N and S represented, albeit, at extremely low concentrations.

Individual components may be present in either vapor or particulate phases or may distribute between the two phases with evaporation, condensation and polymerization reactions leading to a constantly changing distribution. Consequently, the diverse nature of the hydrocarbon fraction components makes for difficulties in both quantifying the emissions and in identifying the specific health and environmental problems. In general, health effects range from drowsiness and eye irritation at one end of the spectrum to high toxicity, mutagenicity and carcinogenicity at the other. These latter effects are discussed under 'micro pollutants'.

As regards wider environmental effects, the more volatile organic compounds (VOC) are of concern on the account of their involvement in photochemical reactions leading to the formation of tropospheric ozone depletion and global climate change.

In general, hydrocarbon emissions will result from incomplete combustion. The nature and levels of hydrocarbons in the exhaust will, thus, be largely dependent upon the combustion characteristics and thermal efficiency of the engine, which in turn are significantly influenced by engine load and condition.

Particulates

The particulate fraction of the exhaust emission represents a complex mixture of inorganic and organic substances largely comprising elemental carbon, ash minerals and heavy metals and a variety of non- or partially-combusted hydrocarbon components of the fuel and lubricating oils. An intermittent discharge of accumulated deposits from the exhaust system may also be encountered. With the exception of the latter, the majority of diesel particulates are likely to be less than μm in diameter, readily transportable by air currents and of low settling velocity. Potentially detrimental effects may thus be encountered away from the immediate vicinity of the exhaust gas plume.

Although, studies of the marine diesel particulate exhaust composition are limited, extrapolation of results from other diesel engine applications would suggest that general respiratory problems, as well as more serious toxic, mutagenic and carcinogenic effects, may potentially occur.

To a large extent, the magnitude of particulate emissions is dependent upon the completeness of combustion, with 'smoke' traditionally acting as a measure of combustion quality. However, quantification of this fraction is difficult due to the complex nature of the particulate emissions and multiple terms employed to describe both the nature and quantity of particulate matter. Many terms are derived from, and defined by, sampling and quantification methods and include the suspended particulate matter and the total suspended particulates. Terms, such as 'inhalable' or 'respirable' relate to the site of deposition in the respiratory tract, whilst PM_{10} (particulate matter with an aerodynamic diameter of less than 10 µm) has both a physiological and sampling component. An inability, in general, to translate the results of measurements using one method into those using another, further complicates this issue.

Micro pollutants

The term micro pollutants generally refers to those pollutants present in trace quantities, typically of the parts per billion level, which demonstrate severe adverse effects even at these low concentrations. In the context of diesel engine exhaust emissions, micro pollutants will encompass both organic micro pollutants and heavy metals.

Organic micro pollutants typically include such trace organic contaminants as polyaromatic hydrocarbons (PAH), dioxins and furans. With respect to the combustion processes, the presence, and in many cases carcinogenicity, of PAH in the exhaust gas stream are well documented. More recently highly mutagenic nitrated PAH have also been identified and are believed to originate from chemical reaction between PAH and NOx in the exhaust system. In addition, highly toxic emissions of polychlorinated biphenyls (PCB), polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) have also been reported. These latter compounds being amongst the most toxic substances presently identified. However, any significant concentrations of polychlorinated compounds are only likely to be associated with isolated incidences of chemical contamination of oil fuels.

The group referred to as heavy metals includes many transition elements such as cadmium, chromium, copper, mercury, nickel and zinc; some non-transition metals, such as lead and the metalloids arsenic and selenium. The presence of these elements in marine exhaust emissions generally reflects concentrations in the oil fuels combusted. Oil fuel heavy metal composition in turn reflects the component oil blends and any elements incorporated during storage and transfer, less those removed in the course of on-board treatment.

Heavy metals are well known inhibitors of biological processes with toxic effects mediated through the poisoning of enzymes involved in biochemical reactions. As such, effects are widespread ranging from reduced diversity of aquatic ecosystems, through fish kills to cancer in man.

In the remaining part of this report focus will only be paid to following products emitted as a result of the combustion process:

- CO_2, Carbon dioxide
- NOx, Oxides of Nitrogen
- SO_2, Sulphur dioxide
- HC, Hydro Carbons
- CO, Carbon Monoxide
- Particulates

Fuel specific emission rates

CO_2

The emission of CO_2 is proportional with the fuel oil consumption by following fuel specific emission rates (IMO, 2009):

Heavy Fuel Oil (HFO):	3.114 t per t oil
Light Fuel Oil (LFO):	3.151 t per t oil
Diesel Oil/Gas Oil (DO/GO):	3.206 t per t oil
Liquefied Natural Gas (LNG):	2.750 t/t gas
Liquefied Petroleum Gas (LPG):	3.000 t/t Propane and 3.003 t/t Butane
LNG/DO:	2.78 t/t fuel (In some gas engines DO is used to ignite the gas in the combustion process by using 4 – 6 % diesel oil. The emission rate becomes: $(0.94 \cdot 2.75 + 0.06 \cdot 3.206) =$ 2.78 t/t fuel

SO_2 (SOx)

SO_2 is proportional with the fuel oil consumption and the content of sulphur in the oil by the following theoretical fuel specific emission rate equation:

21 x %S kg SO_2 per ton fuel oil;

Where S is the percentage mass sulphur content in the fuel, as shown in Figure 5 (Lloyds Register 1995).

It is seen that the lower the sulphur content is the lower fuel specific emission rate of SO_2, which is the reason why more and more strict demands towards lower sulphur content are imposed on oil for marine diesel engines in the coming years. Concern over pollution is likely to mean that heavy fuel oils with a sulphur content below the current average of more than 2% will become more common in the years ahead, as forthcoming legislation restricts emission limits of both SOx and NOx.

The Baltic Sea and the North Sea are now ECA areas (Emission Control Areas) with a sulphur limit of 1 % in 2010 and set to reduce to 0.1 % in 2015, as shown in Figure 6. From 2010 only marine and gas oil with a sulphur content less than 0.1 % must be used in EU ports for ships at berth exceeding 2 hours. Passenger vessels sailing between EU ports will also have to comply with this level from the same date (originally July, 2007).

1st August, 2012 sees the North American Emission Control Area for SOx enters into effect. From this date, the same requirements will apply as for the existing Baltic and North Sea ECA-SOx, including the requirements for recording data on entry and exit.
The North American ECA-SOx covers three distinct areas:

1. off the North American Atlantic/Gulf coasts;
2. off the North American Pacific coast; and
3. around certain parts of Hawaii.

The North American ECA-SOx also includes the St Lawrence Seaway, the Great Lakes and rivers (such as the Mississippi), which are accessed by shipping. Ships operating in or entering the North American ECA-SOx on or after 1st August, 2012, will need to have on-board sufficient compliant fuel oil (1.00% m/m maximum sulphur content) and bring it into use as required.

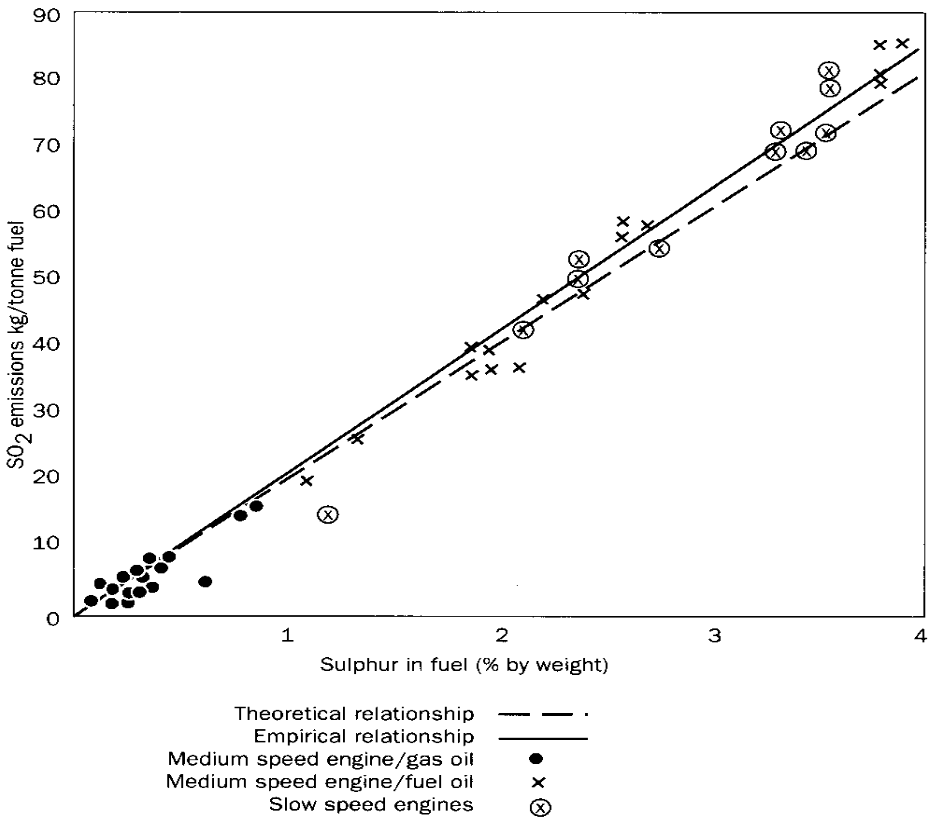

Figure 5 Relationship between fuel sulphur content and SO_2 missions for marine diesel engines (Lloyds Register 1995)

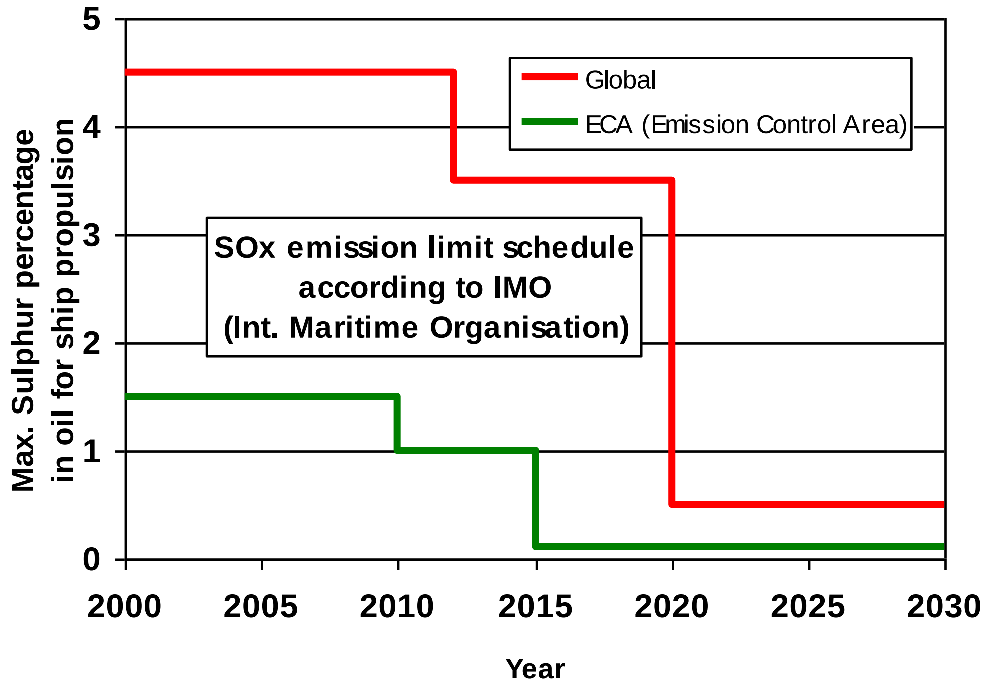

Figure 6 Maximum allowable sulphur content according to IMO legislation

Reduction of SO2 emissions
SO_2 emissions can be reduced either by using fuels with low sulphur content, which makes the fuel more expensive. An alternative solution is to use so-called scrubbers, which can be used for washing the exhaust gas from the main engine, and in principle it can be compared to a large shower cabinet placed in the funnel of a ship. It is possible to reduce the sulphur emissions by 98 %, i.e. to a level as low as if low sulphur fuel oil was used. Scrubbers can use both fresh water mixed with caustic soda (NaOH) and salt water in the washing process. Scrubbers can reduce SO_X and particulate matter with little increase in fuel consumption for electrical power generation, mainly to feed pumps to circulate water (approximately 3 % according to Alfa Laval).

In practice, the scrubbing process may contain several steps. During the first step, the heat in the exhaust gas is reduced and used by cooling it to 160-180°C in an exhaust gas economizer. In the second step, the exhaust gas is treated in a special ejector where it is further cooled by injection of water and where the majority of the soot particles in the exhaust gas are removed. During the third stage, the exhaust gas is led through an absorption duct where it is sprayed with water and thus, cleaned of the remaining sulphur dioxide. Water and sulphur react to form sulphuric acid, which is neutralized with alkaline components in the seawater.

Filters separate particles and oil from the mixture, before the cleaned water is led back into the sea. The solid particles removed from the gases are trapped in a settling or sludge tank and collected for disposal on land.

It is estimated that a scrubber can reduce SO_X emissions by up to 98% and at the same time reduce particulate emissions by 40-75% (personal communication with Alfa Laval 2011).

The scrubber technology can be used to reduce SO_X emissions for vessels sailing in the co-called Emission Control Areas ECA areas instead of using distilled fuel with less that 0.1% sulphur. Scrubbers may be also used to reduce particulate emissions.

NOx

The fuel specific NOx emission rate for diesel engines depends on different factors of which one is the engine type. Another factor is the fuel type, as example shift from oil to gas (see later). Slow speed engines have generally higher NOx emissions compared with medium speed engines, which is also reflected in the demands already imposed by IMO in the MARPOL Annex VI: *"Regulations for the Prevention of Air Pollution from Ships"*. New NOx demands came into force in May 2005, however, with the clause that all diesel engines manufactured after January 2000 has to fulfil the NOx demands, as shown in Figure 7.

As can be seen the highest allowable specific NOx emission rate (IMO Tier I level for engines manufactured before 2011) is 17 g NOx per kW per hour for low speed engines, while the rate for medium speed engines (750 RPM) is approximately 12 g NOx/kW/hour. For high speed engines at about 1100 RPM the allowable NOx emission rate according to Tier 1 is approximately 11 g/kW/hour. In the coming years, so-called Tier II and III levels have to be fulfilled corresponding to 20 % and 80 % NOx reduction respectively, compared with Tier I level, as shown in Figure 7. In 2016 Tier III level will only be introduced in ECA areas, but the extent of these areas will most probably be larger in the coming years. Gas turbines have a clear advantage with a NOx emission factor of only 4 g/kW/hour - for some gas turbines NOx emissions can be even lower!

It is seen that there is more and more focus on NOx emissions (as for SOx emissions) and the engine manufacturers are still improving engine performance to reduce NOx emissions. Several methods have been and are being developed. The two most promising methods are described briefly in this report, and some general comments will be given.

The NOx reducing methods need to be refined and done even cheaper before they can be regarded as fully developed and commercially viable options. The interesting thing is of course the effectiveness and reliability of the different NOx reducing measures with the price being considered as an important factor for the take-up of any technology.

The following two NOx reducing technologies are believed to be the most promising in the coming years:

1. Exhaust Gas Recirculation (EGR)
2. Selective Catalytic Reduction (SCR)

In addition, methods where water is used in the combustion process, such as Water in Fuel Injection (WIF) and Humid Air Motor (HAM)) have also been considered in recent years, but are not seen as the best future solutions as they cannot reduce the NOx level to Tier III level.

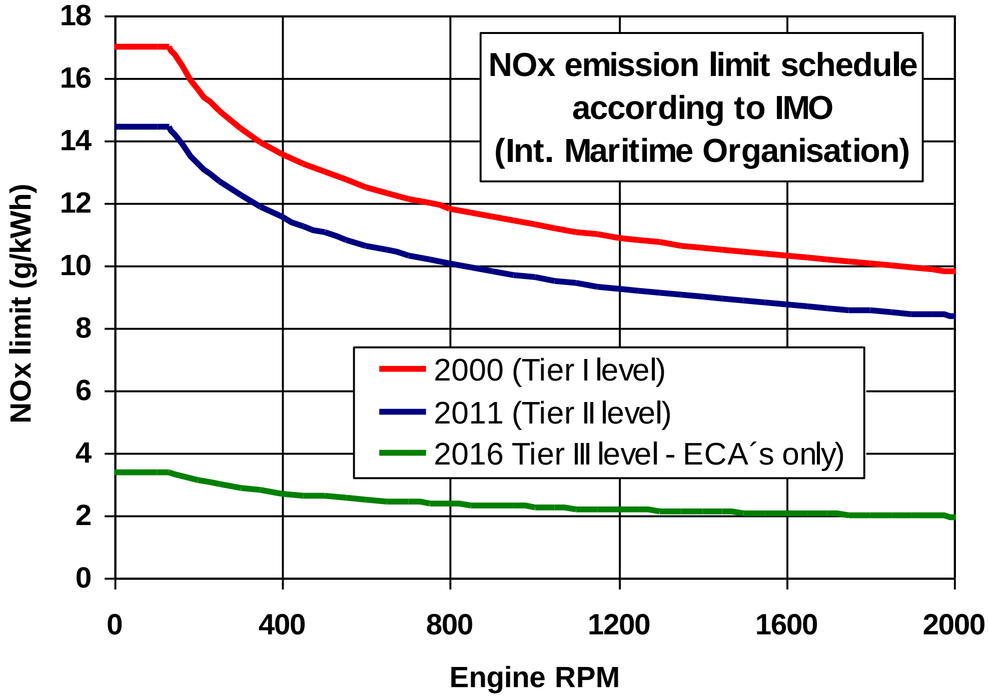

Figure 7 Maximum allowable fuel specific NOx emission rate according to IMO, MARPOL Annex VI

EGR - Exhaust Gas Recirculation

Exhaust Gas Recirculation is a method to significantly reduce NOx emissions from marine engines. It is proven to be able to meet the Tier III NOx requirements, which will apply to all new ships entering a NOx Emission Control Area (ECA) from 2016.

The illustration in Figure 8 shows an EGR system from MAN Diesel. Part of the exhaust gas is diverted from the exhaust gas receiver through a wet scrubber which cleans the gas and reduces the temperature of the exhaust gas. The gas flows through a cooler and water mist catcher and finally through the EGR blower which lifts the pressure to the scavenge air pressure. A water handling system supplies the scrubber with recirculating fresh water with the addition of NaOH to neutralize the effect of sulphur in the fuel.

The effect of this system will be that a minor part of the oxygen in the scavenge air is replaced by CO_2 from the combustion. The heat capacity of the scavenge air will be slightly increased and the temperature peaks of the combustion will be reduced. Accordingly the amount of NOx generated in the combustion chamber is reduced but it is also followed by a minor fuel penalty. The NOx reduction value is dependent of the ratio of recirculating gas.

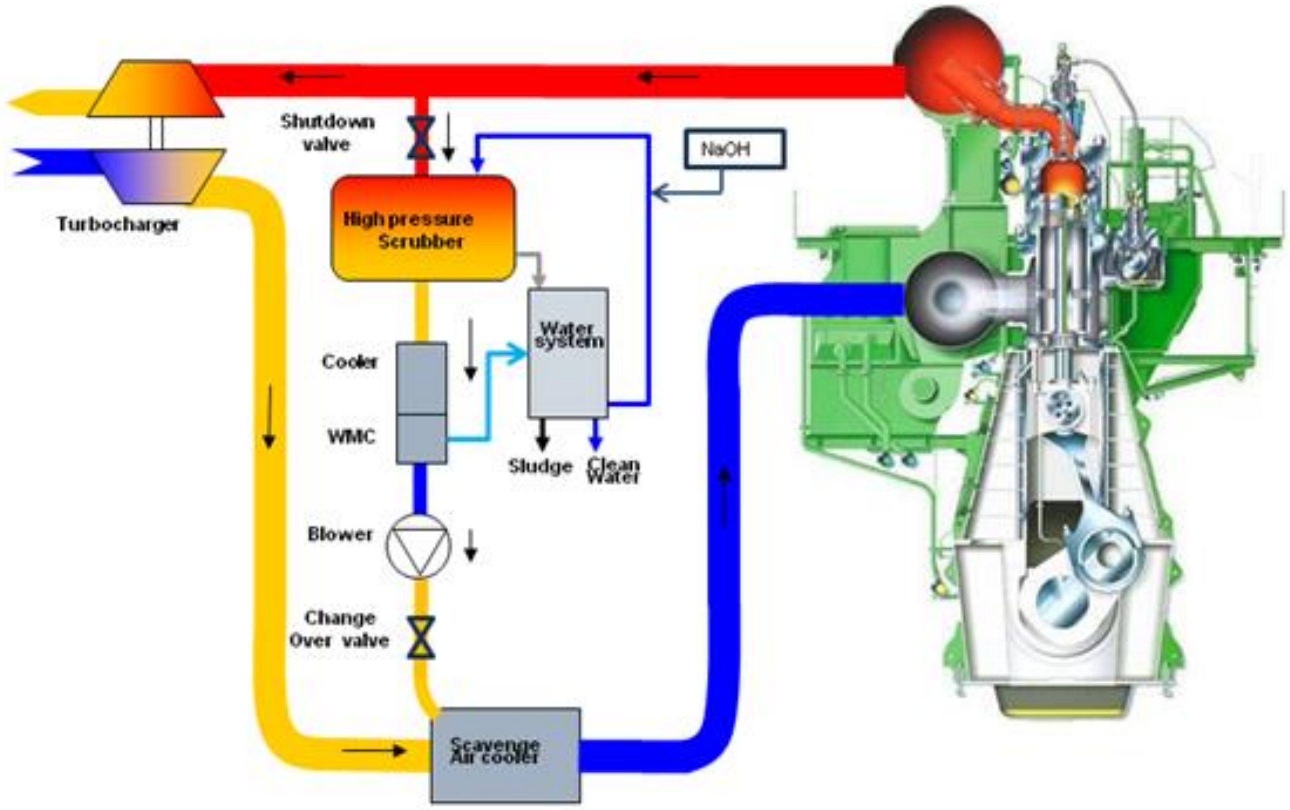

Figure 8 Principles of an EGR system (MAN Diesel)

SFOC penalty due to use of EGR
It is well known that EGR, besides of significantly reducing the NOx emissions, results in an increased SFOC, known as the SFOC penalty. It is experienced that a 10% increase of EGR results in a 20% NOx reduction followed by a SFOC penalty of 0.5 g/kWh.

SFOC gain due to use of EGR
A method of reducing the negative impact on SFOC from EGR systems, is to use a fuel optimized engine. Although this will increase the NOx emission value and, thereby require a higher EGR percentage, the gain is found higher than the penalty from an increased EGR. A SFOC gain of 0.5 g/kWh can be obtained by a NOx increase of 1.0 g/kWh.

SFOC change due to use of EGR
The final SFOC change of a Tier II engine and a fuel optimized engine is shown in Table 2. In ECA areas, as well as non ECA areas, the fuel optimised engine shows a better performance than a Tier II engine. However, other EGR costs needs to be taken into consideration when evaluating the engine layouts.

In some cases, EGR will lead to increased fuel consumption. In the case of the setup being based on a Tier II engine, adding an EGR NO_X reduction system is estimated to result in an increased fuel consumption of approximately 1 %. However, it will also be possible to combine the EGR technology with a Tier I fuel optimized engine, and in this case the fuel consumption is estimated to be approximately 1% lower compared with a Tier II engine without EGR.

Tier II engine – NOx 14.4 g/kWh				
Area	NOx request g/kWh	NOx reduction g/kWh	%	SFOC change g/kWh
ECA – Tier III	3.30	11.00	76%	1.91 (1.1 %)
Non ECA - Tier II	14.40	0.00	0%	0.00

Fuel optimised engine – NOx 21.0 g/kWh				
Area	NOx request g/kWh	NOx reduction g/kWh	%	SFOC change g/kWh
ECA – Tier III	3.30	17.60	84%	-1.20 (-0.7 %)
Non ECA - Tier II	14.40	6.60	31%	-2.51 (-1.5 %)

Table 2
SFOC change at different engine layout and sailing area (MAN Diesel)

In addition to the above mentioned corrections in SFOC, the electric power consumption of an EGR system has to be taken into account. The main consumers are the EGR blower, scrubber water pump and the water cleaning plant. The total electrical power consumption is approximately 2 % of the total main engine power, such that the SFOC is indirectly increased by 2 % plus corrections due to change in NOx emissions. The resulting SFOC changes are shown in table 3.

Tier II engine – NOx 14.4 g/kWh				
Area	NOx request g/kWh	NOx reduction g/kWh	%	SFOC change g/kWh
ECA – Tier III	3.30	11.00	76%	**3.1 %**
Non ECA - Tier II	14.40	0.00	0%	**2.0 %**

Fuel optimised engine – NOx 21.0 g/kWh				
Area	NOx request g/kWh	NOx reduction g/kWh	%	SFOC change g/kWh
ECA – Tier III	3.30	17.60	84%	**1.3 %**
Non ECA - Tier II	14.40	6.60	31%	**0.5 %**

Table 3
Total SFOC change corrected for added electric power consumption at different engine layout and sailing area (MAN Diesel)

SCR - Selective Catalytic Reduction
Selective Catalytic Reduction (SCR) is a well-known and widely used technology for removing NO_X from exhaust gases. The SCR uses a catalyst to convert NO_X into nitrogen and water by using reaction reducing agents, such as ammonia (NH_3) or urea. There are no limitations to ship types, and application of the technology may lead to a reduction in NO_X emissions of up to 90 - 95%. To reach a 90% NO_X reduction, approximately 15 g of urea is needed per kWh energy from the engine. In addition to the catalyst that ensures reduction of NO_X, the cleaning technology may also include an oxidation step, resulting in significant reduction of HC, CO and particles. In addition to the SCR catalyst, an SCR system consists of a reactor tank, a pump and control system for dosage of ammonia/urea.

One of the most critical problems is the relatively large space required for the SCR system and storage of ammonia or urea, especially in connection with a retrofit solution. On the other hand, in a recent case, from the Danish Navy, it was shown to be possible to install a retrofit SCR system on vessels with limited free space, such as for instance the so-called Diana Class patrol vessels.

SCR systems have mostly been used on four-stroke engines, but SCR systems can also be installed on two-stroke engines, and it is expected that the SCR technology will be used increasingly on two-stroke slow-speed engines in the future. It is technically possible to achieve NO_X reductions of more than 95% using SCR systems. However, most common applications are set up to reduce the NO_X emissions slightly below the maximum capacity, most often 85 - 90% in order to reduce the risk of ammonia emissions.

Particulates, PM

The emission of particulates have been found to be particularly affected by the sulphur content as shown in Figure 9 with results from different investigations. Based on these curves the following equation has been derived for the particulate emission factor for diesel engines:

Particulate emission factor in g/kWh = $0.26 + 0.081 \cdot S + 0.103 \cdot S^2$

Where S is the sulphur content in %.

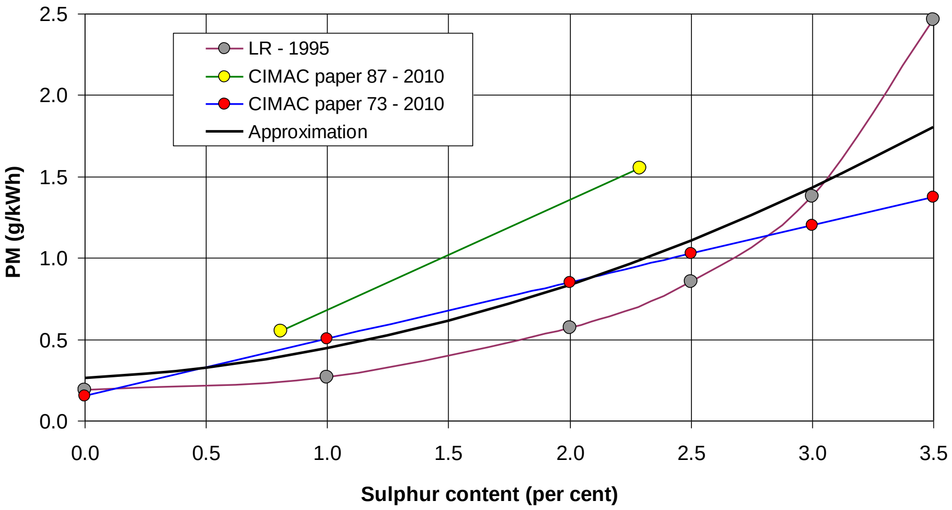

Fig. 9 Relationship between fuel sulphur content and emissions of particulates, PM (Lloyds Register 1995 and CIMAC 2010)

HC and CO:

HC and CO emission factors are partly based on the measurements done by Lloyds Register (Lloyds Register 1995) and the results from MAN Diesel (Pedersen et al. 2010) with tests with different fuel valves (conventional and sliding valves) have shown that slide fuel valves reduce emissions of HC, CO and particulate maters. Slide fuel valves are introduced to meet the stricter Tier II NOx requirements.

There can be quite large variations in the emission factors depending on the engine loading (steady state/transient). For marine diesel engines the variation in steady-state mode is as follows, according to Lloyds Register 1995:

NOx:	8 - 20 g/kW/hour
HC:	0.2 – 1.0 g/kW/hour
CO:	0.4 – 4.0 g/kW/hour
Particulates:	0.2 – 2.0 g/kW/hour

Table 4 shows the averaged steady-state HC and CO emissions from Wärtsilä two- and four-stroke engines, while Figures 10 and 11 show comparable data from MAN Diesel & Turbine.

Table 4 Specific HC and CO emissions for diesel engines

	HC (g/kWh)	CO (g/kWh)
2 stroke diesel engine	0.5	0.35
4 stroke diesel engine	0.5	0.5

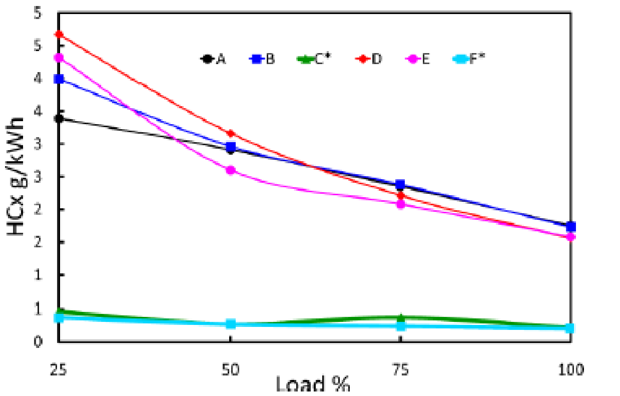

Figure 10 HC emissions for 2 stroke engines (C* and F* fulfil Tier II NOx levels, CIMAC 2010)

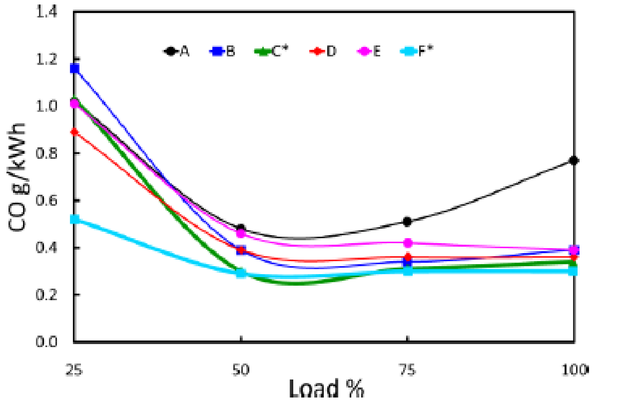

Figure 11 CO emissions for 2 stroke engines (C* and F* fulfil Tier II NOx levels, CIMAC 2010)

Emission factors for gas driven engines

There is increasing focus on gas as an alternative to ordinary fuel oils for ship propulsion. LNG is natural gas that has been converted temporarily, at low temperatures, to liquid form to ease storage and transportation. The main reason for using natural gas as an alternative fuel is that, in the near future, the production worldwide of LNG from gas wells is expected to increase rapidly. Furthermore, natural gas is currently much cheaper compared to conventional fuels.

LNG is advancing as an important fuel of the future. However, establishing LNG bunkering facilities, comprising small-sized LNG terminals and a network of LNG supply ships, is costly and time-consuming and, furthermore, subject to safety concerns and broad public debate. Currently, only a few countries (e.g. Norway) have a LNG network in place to support the general use of gas as a marine fuel.

Gas gives a much cleaner exhaust regarding NO_X and particulates. Having very low or no sulphur (< 0.01%), and therefore, sulphur oxide emissions are negligible in the exhaust gas and particulates are reduced considerably (Bengtson, Anderson and Fridell). For two-stroke engines, the NO_X reduction is 10-20% according to MAN Diesel & Turbo [personal communication with Niels Kjemtrup at MAN Diesel & Turbo] because the two-stroke engines from a combustion point of view are working as dual fuel engines using small amount of pilot diesel fuel injected to ignite the natural gas fuel.

Table 5 lists an arbitrary comparison of emissions (CO_2, NOx, SOx and HC) from HFO and natural gas injected into a 50-bore MAN Diesel & Turbo ME-GI engine, which can burn LPG and LNG when adapted properly to the differences in the physical properties of the two gas types.

The emissions of particulates from a MAN Diesel long stroke engine running on gas oil and pilot fuel and LNG respectively are shown in Table 6 and based on this table a specific PM emission value of 0.01 g/kWh seems reasonable.

Rolls-Royce diesel manufactures engines which only burn LNG, i.e. directly injected LNG as fuel. The fuel consumption and emissions of this engine type are shown in Table 7.

Table 5 Energy demand and exhaust gas emissions from a MAN Diesel Dual Fuel engine

Emission comparison for an S50ME-GI Mark 8 operating on 48% propane and 48% butane and 5% pilot oil compared with HFO operation (3.5% sulphur)

Load	SFOC	Pilot oil	Gas	CO_2		SO_x		HC		NO_x - Tier II	
				ME/MC	ME-GI	ME/MC	ME-GI	ME/MC	ME-GI	ME/MC	ME-GI
%	g/kWh	%	%	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
100%	170.6	5.00%	95,00%	559	472	11.94	0.60	0.34	0.68	13.5	11.9
95%	169.4	5.26%	94,74%	555	469	11.86	0.62	0.34	0.68	13.9	12.3
90%	168.4	5.56%	94,44%	552	466	11.79	0.65	0.34	0.67	14.2	12.5
85%	167.6	5.88%	94,12%	549	464	11.73	0.69	0.34	0.67	14.5	12.7
80%	167.0	6.25%	93,75%	547	462	11.69	0.73	0.33	0.67	14.6	12.9
75%	166.7	6.67%	93,33%	546	461	11.67	0.78	033	0.67	14.7	129
70%	166.6	7.14%	92,86%	546	461	11.66	0.83	0.33	0.67	14.7	12.9
65%	167.0	7.69%	92,31%	547	462	11.69	0.90	0.34	0.67	14.7	12.9
60%	167.8	8.33%	91,67%	550	464	11.75	0.98	0.34	0.68	14.6	12.9
55%	168.8	9.09%	90,91%	553	467	11.82	1.07	0.34	0.68	14.5	12.8
50%	170.0	10.00%	90,00%	557	470	11.90	1.19	0.35	0.69	14.5	12.7
45%	171.4	11.11%	88,89%	562	474	12.00	1.33	0.36	0.71	14.4	12.7
40%	172.9	12.50%	87,50%	567	478	12.10	1.51	0.37	0.74	14.4	12.7
35%	174.6	14.29%	85,71%	572	483	12.22	1.75	0.41	0.81	14.4	12.7
				IMO NO_x Cycle:						14.4	12.9

NO_x from fuelbound nitrogen not included in estimated NO_x values

Actual emissions may deviate due to actual optimisation of engine

Table 6 Results of particulate measurements (PM) from MAN Diesel Test Centre in Copenhagen, March 2012

Load	ISO 8178	ISO 8178	Fuel
%	mg/Nm³	g/kWh	-
75	5.15	0.04	GO (<0.05 % S)
25	13.35	0.12	GO (<0.05 % S)
75	4.93	0.03	LNG
25	15.71	0.14	LNG

Table 7 Energy demand and exhaust gas emission for Rolls-Royce engines

gas heat value = 49,4 MJ/kWh, Methane number = 81,2 Values are acc. to E2 cycle.		
Engine type (output)	C26:33L (270 kW/cyl)	B35:40V G2 (480 kW/cyl)
Specific Fuel consumption	161 (g/kWh)	155 (g/kWh)
Specific Nox	1,3 (g/kWh)	1,3 (g/kWh)
Specific Particles	0,03 g/kWh	0,03 g/kWh
Specific CO	1,3 (g/kWh)	1,3 (g/kWh)
Specific Hydrocarbons (CH4)	4 (g/kWh)	4 (g/kWh)

Summary of emission factors

All the described emission factors have been summarized and are shown in Tables 8 - 14, where they are related to kW/hour and to kg fuel combusted respectively for different propulsion cases, with different emission reduction technologies and fuel types being employed as described in this report. Finally they have also been related to the calorific value of the fuel by relating them to MJ.

It shall be pointed out that the exhaust gas emissions and fuel consumption values may vary from engine to engine manufacturer but may also vary due to many different, often rather complex, factors which influence the combustion process individually. The values listed in Tables 8 – 14 are therefore to be regarded as typical steady state average values obtained from the available literature and engine manufacturer’s technical information.

Table 8: 2 stroke main engine – running on different fuels – Tier 2 NOx level – Not fuel optimized engine

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	1	2	1	2	1	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	1	2	2	2	4	4
Fuel optimised main engine? (0 = NO, 1 = YES)	0	-	0	-	0	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	2	2	2	2	2	2
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	3	3	3	3	3	3
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.179	0.190	0.170	0.190	0.150	0.160
CO2 emission (g/kW/hour)	564	609	545	609	417	445
NOx emission (g/kW/hour)	13.6	9.6	13.6	9.6	12.0	2.4
CO emission (g/kW(hour)	0.35	0.50	0.35	0.50	0.30	1.30
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.44	0.44	0.44	0.44	0.10	0.10
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	3.76	3.99	3.57	3.99	0.00	0.00
CO2 emission (g/kg fuel)	3144	3206	3206	3206	2780	2780
NOx emission (g/kg fuel)	75.9	50.5	80.0	50.5	80.0	15.0
CO emission (g/kg fuel)	1.95	2.63	2.06	2.63	2.00	8.13
HC emission (g/kg fuel)	2.79	2.63	2.94	2.63	3.33	3.13
Particulates (g/kg fuel)	2.5	2.3	2.6	2.3	0.7	0.6
SO2 emission (g/kg fuel)	21.0	21.0	21.0	21.0	0.0	0.0
Calorific value (MJ/kg fuel)	40.5	42.7	42.7	42.7	49.6	49.6
Calorific value (MJ/kg oil)	40.5	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.0	0	0.0	0
Total change of SFOC (pct.)	0.0	0	0.0	0	0.0	0
NOx reduction compared to Tier 1 (pct.)	20	20	20	20	20	20
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	0	0	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 9: 4 stroke main engine – running on different fuels – Tier 2 NOx level – Not fuel optimized engine

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	2	2	2	2	2	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	2	2	3	3	4	4
Fuel optimised main engine? (0 = NO, 1 = YES)	0	-	0	-	0	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	2	2	2	2	2	2
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	3	3	3	3	3	3
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.190	0.190	0.155	0.155	0.160	0.160
CO2 emission (g/kW/hour)	609	609	426	426	445	445
NOx emission (g/kW/hour)	9.6	9.6	1.3	1.3	9.6	2.4
CO emission (g/kW(hour)	0.50	0.50	1.30	1.30	1.30	1.30
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.44	0.44	0.03	0.03	0.10	0.10
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	3.99	3.99	0.00	0.00	0.00	0.00
CO2 emission (g/kg fuel)	3206	3206	2750	2750	2780	2780
NOx emission (g/kg fuel)	50.5	50.5	8.4	8.4	60.0	15.0
CO emission (g/kg fuel)	2.63	2.63	8.39	8.39	8.13	8.13
HC emission (g/kg fuel)	2.63	2.63	3.23	3.23	3.13	3.13
Particulates (g/kg fuel)	2.3	2.3	0.2	0.2	0.6	0.6
SO2 emission (g/kg fuel)	21.0	21.0	0.0	0.0	0.0	0.0
Calorific value (MJ/kg fuel)	42.7	42.7	50.0	50.0	49.6	49.6
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.0	0	0.0	0
Total change of SFOC (pct.)	0.0	0	0.0	0	0.0	0
NOx reduction compared to Tier 1 (pct.)	20	20	20	20	20	20
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	100	100	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 10: 2 stroke main engine – running on DO – Tier 2 NOx level (EGR) – Derated and Fuel optimized engines

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	1	2	1	2	1	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	1	-	0	-	1	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	2	2	2	2	2	2
Fuel optimised main engine? (0 = NO, 1 = YES)	0	-	1	-	1	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	2	2	2	2	2	2
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	1	1	1	1	1	1
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.167	0.194	0.171	0.191	0.164	0.191
CO2 emission (g/kW/hour)	534	621	548	612	526	612
NOx emission (g/kW/hour)	13.6	9.6	13.6	9.6	13.6	9.6
CO emission (g/kW(hour)	0.35	0.50	0.35	0.50	0.35	0.50
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.44	0.44	0.44	0.44	0.44	0.44
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	3.50	4.07	3.59	4.01	3.45	4.01
CO2 emission (g/kg fuel)	3206	3206	3206	3206	3206	3206
NOx emission (g/kg fuel)	81.6	49.5	79.6	50.3	82.9	50.3
CO emission (g/kg fuel)	2.10	2.58	2.05	2.62	2.13	2.62
HC emission (g/kg fuel)	3.00	2.58	2.93	2.62	3.05	2.62
Particulates (g/kg fuel)	2.7	2.3	2.6	2.3	2.7	2.3
SO2 emission (g/kg fuel)	21.0	21.0	21.0	21.0	21.0	21.0
Calorific value (MJ/kg fuel)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	-4.0	0	0.0	0	-4.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	2.0	2	0.5	0.5	0.5	0.5
Total change of SFOC (pct.)	-2.0	2	0.5	0.5	-3.5	0.5
NOx reduction compared to Tier 1 (pct.)	20	20	20	20	20	20
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	0	0	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 11: 2 stroke main engine – running on DO – Tier 1, 2 and 3 NOx level (EGR) – Fuel optimized engines

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	1	2	1	2	1	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	2	2	2	2	2	2
Fuel optimised main engine? (0 = NO, 1 = YES)	1	-	1	-	1	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	1	1	2	2	3	3
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	1	1	1	1	1	1
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.170	0.190	0.171	0.191	0.172	0.192
CO2 emission (g/kW/hour)	545	609	548	612	552	617
NOx emission (g/kW/hour)	17.0	12.0	13.6	9.6	3.4	2.4
CO emission (g/kW(hour)	0.35	0.50	0.35	0.50	0.35	0.50
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.44	0.44	0.44	0.44	0.44	0.44
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	3.57	3.99	3.59	4.01	3.62	4.04
CO2 emission (g/kg fuel)	3206	3206	3206	3206	3206	3206
NOx emission (g/kg fuel)	100.0	63.2	79.6	50.3	19.7	12.5
CO emission (g/kg fuel)	2.06	2.63	2.05	2.62	2.03	2.60
HC emission (g/kg fuel)	2.94	2.63	2.93	2.62	2.90	2.60
Particulates (g/kg fuel)	2.6	2.3	2.6	2.3	2.6	2.3
SO2 emission (g/kg fuel)	21.0	21.0	21.0	21.0	21.0	21.0
Calorific value (MJ/kg fuel)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.5	0.5	1.3	1.3
Total change of SFOC (pct.)	0.0	0	0.5	0.5	1.3	1.3
NOx reduction compared to Tier 1 (pct.)	0	0	20	20	80	80
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	0	0	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 12: 4 stroke main engine – running on DO – Tier 1, 2 and 3 NOx level

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	2	2	2	2	2	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	2	2	2	2	2	2
Fuel optimised main engine? (0 = NO, 1 = YES)	1	-	1	-	1	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	1	1	2	2	3	3
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	1	1	1	1	1	1
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.190	0.190	0.191	0.191	0.192	0.192
CO2 emission (g/kW/hour)	609	609	612	612	617	617
NOx emission (g/kW/hour)	12.0	12.0	9.6	9.6	2.4	2.4
CO emission (g/kW(hour)	0.50	0.50	0.50	0.50	0.50	0.50
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.44	0.44	0.44	0.44	0.44	0.44
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	3.99	3.99	4.01	4.01	4.04	4.04
CO2 emission (g/kg fuel)	3206	3206	3206	3206	3206	3206
NOx emission (g/kg fuel)	63.2	63.2	50.3	50.3	12.5	12.5
CO emission (g/kg fuel)	2.63	2.63	2.62	2.62	2.60	2.60
HC emission (g/kg fuel)	2.63	2.63	2.62	2.62	2.60	2.60
Particulates (g/kg fuel)	2.3	2.3	2.3	2.3	2.3	2.3
SO2 emission (g/kg fuel)	21.0	21.0	21.0	21.0	21.0	21.0
Calorific value (MJ/kg fuel)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.5	0.5	1.3	1.3
Total change of SFOC (pct.)	0.0	0	0.5	0.5	1.3	1.3
NOx reduction compared to Tier 1 (pct.)	0	0	20	20	80	80
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	0	0	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 13: 2 stroke main engine – running on dual fuel (DO and gas) – Tier 1, 2 and 3 NOx level

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	1	2	1	2	1	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3 (only for 4 stroke), Dual fuel = 4)	4	4	4	4	4	4
Fuel optimised main engine? (0 = NO, 1 = YES)	0	-	0	-	0	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	1	1	2	2	3	3
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	3	3	3	3	3	3
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.150	0.160	0.150	0.160	0.150	0.160
CO2 emission (g/kW/hour)	417	445	417	445	417	445
NOx emission (g/kW/hour)	12.0	9.6	12.0	9.6	3.4	2.4
CO emission (g/kW(hour)	0.30	1.30	0.30	1.30	0.30	1.30
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.10	0.10	0.10	0.10	0.10	0.10
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	0.24	0.24	0.24	0.24	0.24	0.24
CO2 emission (g/kg fuel)	2780	2780	2780	2780	2780	2780
NOx emission (g/kg fuel)	80.0	60.0	80.0	60.0	22.7	15.0
CO emission (g/kg fuel)	2.00	8.13	2.00	8.13	2.00	8.13
HC emission (g/kg fuel)	3.33	3.13	3.33	3.13	3.33	3.13
Particulates (g/kg fuel)	0.7	0.6	0.7	0.6	0.7	0.6
SO2 emission (g/kg fuel)	1.6	1.5	1.6	1.5	1.6	1.5
Calorific value (MJ/kg fuel)	49.6	49.6	49.6	49.6	49.6	49.6
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.0	0	0.0	0
Total change of SFOC (pct.)	0.0	0	0.0	0	0.0	0
NOx reduction compared to Tier 1 (pct.)	0	0	20	20	80	80
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	0	0	0	0	0	0

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

Table 14: 4 stroke engine – running on pure gas – Tier 1, 2 and 3 NOx level

Engine and emission reduction technologies	Main engine	Auxiliary engines	Main engine	Auxiliary engines	Main engine	Auxiliary engines
Main engine type (2-stroke = 1, 4-stroke = 2)	2	2	2	2	2	2
Derated main engine - only for 2 stroke engines (NO = 0, YES = 1)	0	-	0	-	0	-
Fuel for main engine (HFO = 1, MDO/GO = 2, LNG = 3, Dual fuel = 4)	3	3	3	3	3	3
Fuel optimised main engine? (0 = NO, 1 = YES)	0	-	0	-	0	-
TIER 1, 2 or 3 engine (If individual NOx reduction technology is selected then press 0)	1	1	2	2	3	3
Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	3	3	3	3	3	3
Sulphur content in % in heavy fuel oil (HFO)	1	-	1	-	1	-
Sulphur content in % in diesel/gas oil (DO/GO)	1	1	1	1	1	1
Use of scrubbers (NO = 0, YES=1)	0	0	0	0	0	0
Emission factors						
Fuel consumption (kg/kW/hour)	0.155	0.155	0.155	0.155	0.155	0.155
CO2 emission (g/kW/hour)	426	426	426	426	426	426
NOx emission (g/kW/hour)	1.3	1.3	1.3	1.3	1.3	1.3
CO emission (g/kW(hour)	1.30	1.30	1.30	1.30	1.30	1.30
HC emission (g/kW/hour)	0.50	0.50	0.50	0.50	0.50	0.50
Particulates (g/kW/hour)	0.03	0.03	0.03	0.03	0.03	0.03
S content in oil (pct.)	1.0	1.0	1.0	1.0	1.0	1.0
SO2 emission (g/kW/hour)	0.00	0.00	0.00	0.00	0.00	0.00
CO2 emission (g/kg fuel)	2750	2750	2750	2750	2750	2750
NOx emission (g/kg fuel)	8.4	8.4	8.4	8.4	8.4	8.4
CO emission (g/kg fuel)	8.39	8.39	8.39	8.39	8.39	8.39
HC emission (g/kg fuel)	3.23	3.23	3.23	3.23	3.23	3.23
Particulates (g/kg fuel)	0.2	0.2	0.2	0.2	0.2	0.2
SO2 emission (g/kg fuel)	0.0	0.0	0.0	0.0	0.0	0.0
Calorific value (MJ/kg fuel)	50.0	50.0	50.0	50.0	50.0	50.0
Calorific value (MJ/kg oil)	42.7	42.7	42.7	42.7	42.7	42.7
Calorific value (MJ/kg LNG)	50.0	50.0	50.0	50.0	50.0	50.0
SFOC change due to engine type (pct.) derated versus normal engine	0.0	0	0.0	0	0.0	0
Extra energy demand due to scrubber (pct.)	0.0	0	0.0	0	0.0	0
Extra energy demand due to NOx reducing EGR technology (pct.)	0.0	0	0.0	0	0.0	0
Total change of SFOC (pct.)	0.0	0	0.0	0	0.0	0
NOx reduction compared to Tier 1 (pct.)	0	0	20	20	80	80
Particulate reduction (pct.)	0	0	0	0	0	0
SO2 reduction (pct.)	100	100	100	100	100	100

Dual fuel	
Diesel oil (pilot fuel) in pct.	6
Gas in pct.	94

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