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The cost-efficiency of water-based marine emission abatement

Bachelor’s Thesis 2013

ABSTRACT

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Today about 90 per cent of the world's trade is concluded by using ships. This entails that the seafaring is one of the main attempters for the poisonous greenhouse gases. Through the globalization and the tendency to produce and sell goods all around the world, leads to wider use of ship transportation and hence increasing emissions.

According to this fact it is important to find ways to abate ship emissions. This is supported with stricter emission limits in the Baltic Sea. To meet these regulations, vessels need to have installed an emission abatement system. In the range of this thesis the two water-based NO_x abatement measures DWI and HAM are observed, especially regarding their cost-effectiveness.

To find a figure how many € per abated ton of NO_x these technologies cost, a case study with two ships was made. One ship was retrofitted with a HAM system and the other ship was new build with DWI technology. The calculations were based on figures found in literature and the ship owners.

In conclusion, the costs per abated ton of NO_x vary greatly with the specific ship. For DWI they are in the range from 243,25 €/t to 928,08 €/t. The HAM system is not so cost-intensive it varies from 282,58 €/t to 378,46 €/t.

SYMBOLS AND ABBREVIATIONS

a	Year
e.g.	Exempli gratia
g	Gram
GRT	Gross registered tonnage
GT	Gross tonnage
Js	Joule second
K	Kelvin
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
RPM	Revolutions Per Minute
m	Metre
m^3	Cubic metre
mil	Million
nm	Nanometre
NOK	Norwegian krone
ppm	Parts per million
s	Second
SEK	Swedish krona
t	Tons
μg	Microgram
μm	Micrometre
°C	Degree celsius
%	Per cent
λ	Lambda, excess air ratio
Ω	Ohm
€	Euro

ABDC	After Bottom Dead Centre
BBDC	Before Bottom Dead Centre
BDC	Bottom Dead Centre
BSR	Baltic Sea Region
BTDC	Before Top Dead Centre
CAC	Charge Air Cooler
CapEx	Capitel Expenditure
CASS	Combustion Air Saturation System
CFC	Chlorofluorocarbon
CH_4	Methane
CIMAC	International Council on Combustion Engines
CLD	Chemiluminescence Detector
CO	Carbon monoxide
CO_2	Carbon dioxide
DWI	Direct Water Injection
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
EU	European Union
FINAS	Finnish Accreditation Service
H_2O	Water
H_2SO_4	Sulphuric acid
HAM	Humid Air Motor
HCFC	Hydrochlorofluorocarbon
HCN	Hydrogen Cyanide
HELCOM	Helsinki Commission
HFO	Heavy Fuel Oil
i.e.	that is
IMO	International Maritime Organization
MARPOL	Marine Pollution
ME	Main Engine
MFO	Marine Fuel Oil
N	Nitrogen
N_2	Dinitrogen
NECA	Nitrogen Emission Control Area
NH_3	Ammonia
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NTG	Net registered tonnage
O	Oxygen
O_3	Ozone
PM	Particulate Matters
Ro-Ro	Roll on – Roll off
SAM	Scavenge Air Moistening

SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SEIS	Ship Environment Index System
SMA	Swedish Maritime Administration
SO_2	Sulphur dioxide
SOx	Sulphur oxides
STID	Steam Injected Diesel Engine
TBO	Time Between Overhaul
TDC	Top Dead Centre
UN	United Nations
VOC	Volatile Organic Compounds
WHO	World Health Organization

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1 INTRODUCTION

Today about 90 per cent of the world's trade is concluded by using ships. This entails that the seafaring is one of the main sources for the poisonous NO_x and SO_x emissions. The amount of SO_x from the 15 biggest ships for example is presumed to be with 78.000 tons even higher than the global car traffic. Through the globalization and the tendency to produce and sell goods all around the world, leads to wider use of ship transportation and hence increasing emissions.

There are many different approaches to reduce the production of these environmental and health damaging emissions. Engine manufactures are developing low-emission-engines and the worldwide research in abatement technologies is going forward. Also the governments of nations with coastal areas are anxious to find a way to an emission free seafaring in the future. Measures that are already implemented are the creation of ECAs, like the North, Baltic and North American Sea in case of SO_x. Further areas and new regulations that treat also other emissions, like NO_x, are made by the different countries themselvs or cross-border by the EU or IMO, the maritime agency of the UN.

The basis for such new regulations establishes results from projects like the BSR Innoship project. This project shall yield findings how the upcoming IMO limitations III 2016 for the Baltic countries can be fulfilled.

In the context of this project the available thesis was written to figure out the costs and the cost-efficiency of the two water-based NO_x abatement technologies DWI and HAM. The main aim was to find the costs per abated ton of NO_x. For this purpose a case study with two ships was made. One ship was retrofitted with a HAM system and the other ship was new build with DWI technology. The calculations were based on figures found in literature and from the shipowners.

2 THE BSR INNOSHIP PROJECT

The Innoship project for the Baltic Sea Region was initiated by the EU and HELCOM in 2007 to develop national and international plans to keep the IMO limitations III 2016 for the Baltic countries.

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Figure 1: The Innoship project to find solution approaches for the Baltic Sea Region has duration from 2007 to 2013.

Through increasing shipping in the Baltic Sea and the associated rising emissions the need for a project that coordinates and encourages the cooperation between international, national and regional governments, was noticed. The aim of the project is to develop and establish a model area for clean and sustainable shipping in Europe. For this reason the Baltic Sea is already since 2006 declared as SECA and will be prospectively designated as NECA. These progresses create the need for technical approaches for an efficient abatement of NO_x and SO_x emissions, which should be figured out during the project. Therefore institutes, universities, governments and companies of the littoral states of the Baltic Sea are working as partners. All together about 45 partners from Finland, Germany, Sweden, Norway, Denmark, Lithuania, Latvia, Estonia, Poland and Russia are involved.[1] Firstly is the Baltic Institute of Finland the lead partner, but a further one is for example the Kymenlaakso University of Applied Sciences in Finland which is entrusted with the task of marine emission measurements. The Kymenlaakson University of Applied Sciences distinguishes itself in the ability to perform measurements in its emission laboratory that is accredited by FINAS according to the SFS-EN ISO/IEC 17025:2500 standard. The further equipment for measurements on ships is proved by the standard ISO 8178-2 and Annex VI to MARPOL 73/78.[2]

3 MARINE DIESEL ENGINES

Ships can be classified into different types. In a broad overview there are passenger or cargo ships, whereas not only the freight is the main difference. Compared to their tonnage passenger ships have larger engines than cargo carrying vessels.[3] These two types are further divided as there are cargo ships which carry also passengers and the other way around. M/S Mariella is a passenger ferry, its main purpose is to carry passengers but there is also space for cargo.

As it can be seen in the appendix 1 there are quite a lot of subcategories for cargo ships depending on how or what kind of freight they are transporting. As the M/S MISIDA is a Ro-Ro ship this kind should be explained further.

The term Ro-Ro refers to Roll on/Roll off ship what means it loads and transports wheeled goods that are driven by its own over the ships' ramp. Generally this may be cars, railway waggons, lorries or their trailers. The M/S MISIDA mainly carries forest products, like paper and pulp. For this reason the ship is also loaded with containers and other cargo units.

Marine diesel engines are often divided in three different groups. This classification was done by the EPA and rates the engine power. The engines of the category 1 have more the 1.000 kW and their displacement per cylinder is less than 5 litres. With a displacement between 5 and 30 litres and a rated power between 1.000 and 3.000 kW an engine belongs to the category 2. Diesel engines of this size are often used as auxiliary engines on ships. There they have the purpose to produce the electricity to run all equipment and provide energy for pumps or hydraulic machines as well as for cooling or heating aims. The ones belonging to the last category are mainly used as main engines, which are in charge of producing the power for the propulsion. Likewise all main engines of the M/S Mariella and M/S MISIDA are category 3 diesel engines. In figures this group contains engines with a size of more than 3.000 kW and a gas displacement of at least 30 litres per cylinder.[4]

Another categorization of vessels is their speed – Slow-, Medium- or High-Speed engines – defined by the rotation speed. With a rotation speed less than 130 RPM an engine is called slow-speed. Furthermore, because of the lower RPM it is determined that it is a two-stroke type. Engines with low rotation speed have the biggest construction. Starting with 130 RPM up to 1.400 RPM the medium-speed engines are operating with four-stroke technique. Beyond 1.400 RPM engines are called high-speed. This type is used for instance in smaller vessels like fishing boats or yachts. Either medium- or slow-speed engines can be used as main engines, whereas an auxiliary engine is always a medium-speed type.[4]

3.1 Working principle

The diesel engine is originally based on the diesel process, but it is technically not possible to bring heat into a process at constant pressure. Therefore the Seiliger cycle, also called dual or mixed cycle, is a more suitable pattern to represent the operation of a diesel engine. The theoretical sequence is shown in figure 2 with the volume on the abscissa and the pressure on the ordinate. From point one to two the compression takes place, and theoretically there is no heat exchange but in a real engine there are losses over the walls. Starting at point two the fuel injection initiate the combustion and brings the heat in the process, first isochoric (until point 3), then with a constant pressure (point three to point four). Realised in an engine the events between points two and four are curved lines and not a complete isochoric and isobaric heat supply. From point four starts the expansion until point five. Closing the cycle from point five to one there is the scavenging. This change of the gases also cannot be realised completely isochoric.

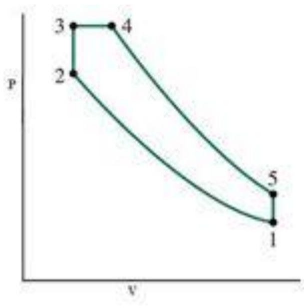

Figure 2: Seiliger Cycle

Distinguishing how much time the scavenging takes, engines are divided into two stroke or four stroke types. The four stroke engine needs two revolutions of the piston to fulfil one power cycle of the engine where one revolution is for the scavenging. A two stroke engine on the other hand needs only one revolution for a power cycle because the air change has a duration of 1/3 of a revolution.[5] The M/S Mariella and M/S MISIDA have four stroke marine engines. The four strokes are called introduction, compression, expansion and exhaust stroke.

1. Induction stroke:

The first part of figure 3 refers to the introduction stroke, when the piston goes down from the TDC. After the TDC, for a short time, the inlet and outlet valve are both open so that the suction of the fresh air starts. The exhaust valve is open in order to let the exhaust gases, which have a slight overpressure, escape more thoroughly. The inlet air needs a higher pressure than the exhaust gases to prevent the contamination of the fresh air while both valves are open. When the inlet valve is open to let in the combustion air and the exhaust valve is already closed, the income of the fresh air is facilitated because the pressure in the cylinder decreases due to the descending of the piston. As a consequence of the pressure difference, the air is forced to flow in.

A change in the valve opening and closing time is part of the engine manufacturers' developments for low NO_x engines. By closing the inlet valve before the piston reaches the BDC, the fresh air is forced to enlarge due to the down going piston. Therefore the pressure and the temperature in the cylinder is lower, which leads to less NO_x emissions in the exhaust gases. This procedure is called Miller cycle or Miller timing.

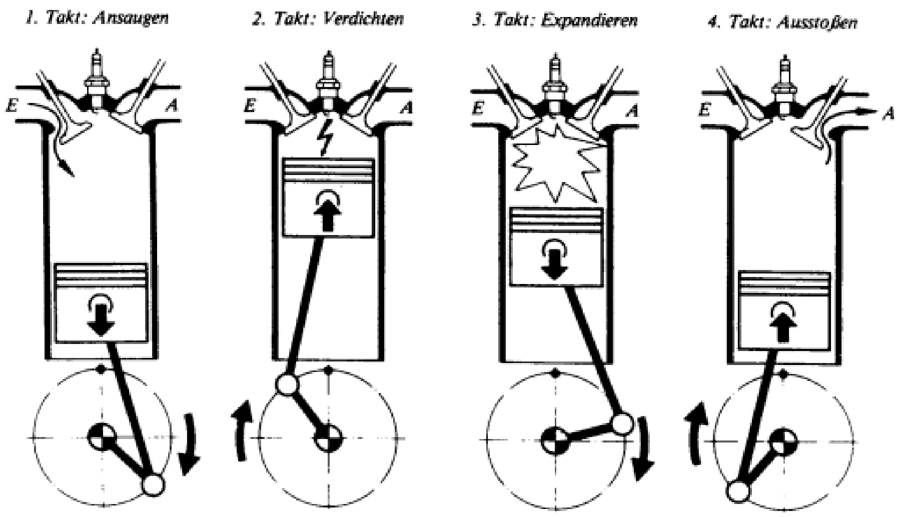

Figure 3: Four strokes (1.Stroke: Introduction, 2.Stroke: Compression, 3.Stroke: Expansion, 4.Stroke: Exhaustion)

2. Compression stroke:

The piston has now reached the BDC and the cylinder is filled with fresh air. At this point the inlet stroke is over, although the inlet valve may be still open. It will close at about 25-35° after the BDC (shortly called ABDC).[6] Because of the slight under pressure some more air comes into the cylinder even when the piston reached the BDC.

During the actual compression stroke work is carried out in the air, while both valves are closed. In this phase the piston compresses the charge of air up to about 40 bar, hence it is possible to reach a temperature of about 550 °C [6] in the cylinder.

Near the TDC the injection of the fuel starts. Regardless that there are different fuel injection systems, all have in common that the fuel is injected with high pressure through a nozzle with small holes to reach droplets with a size of about 10 μm.[7] It is significant for the combustion that the fuel is atomized, because compared to a petrol engine (Otto engine) there is only a short period for the fuel to mix with the combustion air. That is the reason why it is injected with up to 1.200 - 1.800 bar [6]. Due to the high pressure there is a fuel spray which mixes well with the hot air to ensure the ignition.

3. Expansion stroke:

Generally the actual ignition starts very close to the TDC (at about 2-7°BTDC [6]), based on the further compression of the air, mixed with the atomized fuel, the self-ignition takes place. Starting with the premixed combustion, which proceeds fast, follows the slower main combustion. During the main combustion more heat is released and the peak temperature will be reached. The energy from the fuel is releases through heat, so there are temperatures in the range of 1.500 – 2.500 °C. The pressure in the cylinder performs work because it pushed the piston down and the gases are expanding.

4. Exhaust stroke:

Before the end of the expansion stroke, before the piston reaches the BDC, the exhaust valve opens already. The reason for the opening at 60 – 30° BBDC [6] is that the pressure in the cylinder forces the exhaust gases to issue. In this way less pumping work is necessary. Another reason is that the energy in the exhaust gas can be used in the turbocharger. After the BDC the exhaust valve is completely open and the ascending piston pushes the remaining flue gases out of the cylinder. To use the pressure difference the inlet valve starts to open at about 70 - 80° BTDC [6] and sucks fresh air into the combustion chamber. In the meantime the exhaust valve starts to close and when the piston is at the TDC both valves are at the same level and the power cycle is completed.

3.2 Further components

To increase the efficiency of a diesel engine a turbocharger is installed. Like mentioned before, it uses the heat in the exhaust gases. For the two relevant ships considered in this report the average exhaust gas temperature after the turbocharger is between 320 and 330 °C.[8,9] Using the exhaust gases to power the turbocharger is particularly effective because about 35 per cent [6] of the energy provided by the fuel is still in these gases. With this energy a turbine is driven, which is mounted on the same shaft as a compressor. The hot exhaust gases are led into the turbine (left part of figure 4), where they are expanding and the heat energy is converted to kinetic energy. After that the exhaust gases are leaving through the exhaust pipes. The purpose of the compressor is to increase the density of the charge air so that it is possible to introduce more air in the cylinder. With more air it is possible to burn more fuel, which leads to a greater power output of the engine. According to this the compressor has a supply of fresh air which hits the compressor wheel and gets a high velocity (right part of figure 4). After this the air is led through a diffuser to convert a part of the kinetic energy into higher pressure, leading to higher density of the charge air.

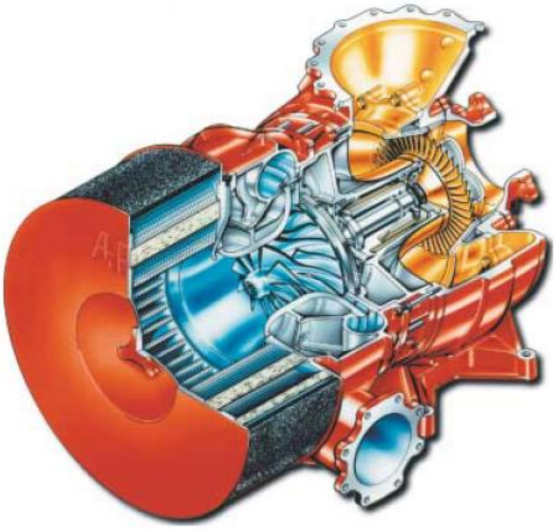

Figure 4: Turbocharger

Besides the advantages of a higher power output from the engine and an improved specific fuel consumption at all loads, the drawback of compressed air is a higher temperature. Due to the adiabatic compression the temperature rises and so the air density decreases. Therefor it is necessary to cool the charge air before entering the cylinder. Otherwise would the mass of the air be less than without the turbocharger, hence less fuel could be combusted.

With a so-called intercooler or aftercooler the temperature of the combustion air is lowered by adding a heat exchanger. The air transfers energy to either cold water, which after that works in the engine cooling system, or to the cooler atmospheric air. For example the Wärtsilä engine 6L46F from the M/S MISIDA has a maximum temperature of the intake air of the cylinder of 50 °C.[9] When the charge air is cooled the density increased again, leading to a greater amount of air flowing into the cylinder. To ensure that the temperature of the inlet air does not raise again, the pipe, connecting the charge air cooler and the cylinder, has to be insulated and this part should be as short as possible. Further benefits of an intercooler can be seen in a lower maximum temperature in the cylinder due to the lower temperature of the intake air and equally less emissions in the exhaust gases.

Another very important part of the engine, which has also a great influence on the emissions, is the fuel injection system. There are many different ways to bring the fuel into the combustion chamber. Anyway it is important that the certain amount of combustion air mixes well with the fuel to achieve complete combustion. In case of direct injection of the fuel, this mixing takes place in the combustion chamber due to the force of the atomized fuel. On the other hand, with indirect injection there is a coarse spray at low pressure into a pre-chamber where it mixes with the air.

Glow plugs are sometimes necessary to support the ignition when the engine should be started. For example there might be failed ignition during low ambient pressures because there are greater heat losses over the cylinder walls which may cause problems in starting an engine with indirect injection.

State-of-the-art for low emission marine diesel engines is the fuel injection with a common rail system. The main engines of the M/S MISIDA are also equipped with common rail technology and therefore the vessel emits even without the DWI technology below 10 g/kWh of NO_x emissions.

The difference and likewise advantage compared to a mechanical fuel injection system is that the injection pressure is provided regardless the engine rotation speed. In this way the fuel is supplied with a constant and high pressure for each cylinder. In conventional fuel systems the pressure varies with the load. This leads to a rather low pressure and bigger droplets at lower loads. To provide a constant high pressure a common rail system has a separate fuel pumping and injection system, hence more atomized fuel forms a greater homogeneous mixture of combustion air and fuel. Simultaneously it is possible to change the parameters for each cylinder easily due to the engine control system or also called electronic diesel control of each injector. For instance parameters like the rail pressure, timing and duration of injection are regulated very accurate with the computer-controlled system. In figure 5 the components of a modern common rail fuel injection system are shown.

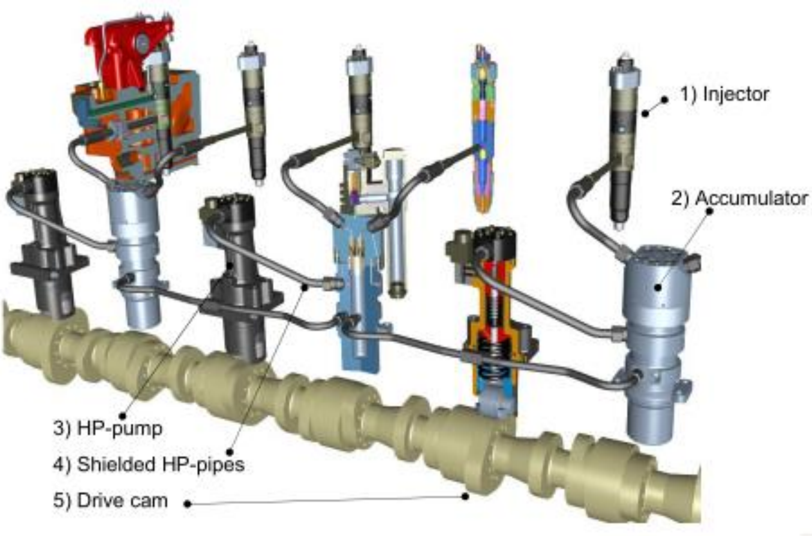

Figure 5: Wärtsilä Common Rail System

The high pressure pumps are installed on the camshaft which is also driving the valves. One accumulator and one high pressure pump serve two cylinders. The accumulator is used to store fuel under high pressure, which is coming from the pressurising pump. Each one is connected to two injectors. A safety function is that there is only during the actual injection the high pressure of up to 2.000 bar. [6] The solenoid valve in the injector cuts the pressure, hence there is no pressure on the nozzle while there is no injection.

A further convenient fact of the common rail system is the flexible switch between different fuels like HFO or MFO, which is very common because of current emission regulations.

4 AIR POLLUTION

The pollution of air and the contemporary increasing amount of emissions are a growing international problem. Normally the air consists of three main components, 78 % nitrogen, 21 % oxygen and 1 % argon. Additionally air contains about 0,038 – 0,039 % carbon dioxide and depending on the area 0,1 – 4 % water vapour.[10] Substances that occur harmful for organisms and the environment naturally in very small amounts. If the harmful substances, so-called emissions, are formed by natural sources, then they are referred to as natural pollution. Possible sources of natural pollution are volcanos, forest fires and swamps. The second category for sources of air pollution is the anthropogenic or man-made pollution. To these belong the agriculture, industries, coal, oil and gas burning power plants, waste incineration plants, landfills and decisively traffic, including shipping. According to Davis and Cornwell [11] comprise combustion processes 96 per cent of the man-made nitrogen oxide pollution.

Emissions that arise global and counted among the greenhouse gases are CO_2, CFC and HCFC, CH_4 and N_2O. Further emissions that are more concentrated on regional areas and cities are NO_x, SO_2, CO, VOC and PM.

As a consequence of intensified shipping in the Baltic Sea the pollution with CO_2 and especially NO_x, SO_2 and PM in the coastal regions and harbour locations is soaring. In contrast to land-based NO_x emissions that are reduced during the 28 years (1980-2008) about 40 %, sea-based emissions are increasing continuously. In general it is estimated that 30 % of the global man-made NO_x emissions are caused by shipping.[12] The transport in the Baltic Sea in the year 2000 was for instance 400 mil tons. During six years a growth of 150 % to 600 mil tons in 2006 can be noticed. This is a percentage share of 8,1 % of the world sea transport.[13] For this reason the sea-based emissions with their ecological consequences become to a more serious and political problem. In 2006 NO_x emissions in the Baltic Sea, caused by ships of any kind, exceed a value about 380.000 tons.[14] Even higher were the NO_x emissions in 2007 with a reached amount of 400.000 tons.[15] This trend shows the imperative necessity for technological approaches to reduce and avoid NO_x emissions

4.1 Effects on health

NO_x and especially NO_2 belong to the most harmful emissions. Like described in chapter 'Development of NO_x', NO is formed in combustion processes and gets outside through exhaust gases where it reacts with oxygen of the air and forms into the more hazardous gas NO_2. In the air, NO_x forms small particles with the help of ammonia, moisture and other substances. These small particles have a size about < 2,5 μm [16] and penetrate through breathing the mucous membranes of the airways and eyes. In the airways they cause several diseases like airway inflammation, pneumonia, (chronic) bronchitis, asthma and emphysema. Furthermore it can get to chronic cough, increase heart diseases and enhance the susceptibility to respiratory infections right up to premature death. Particularly children and youth, elderly and people with lung diseases and asthma are compromised. The average annual natural pollution of nitrogen dioxide amounts to $0{,}4 - 9{,}4\,\frac{\mu g}{m^3}$, referred to the air quality guidelines from the WHO in 2000. Even higher, with an annual range of $20 - 90\,\frac{\mu g}{m^3}$, is the ordinary concentration in cities. According to studies, published by the government of North Rhine-Westphalia exists a huge potential for providing respiratory diseases by decrease the concentration of NO_2 in the breathing air. In the study the population is differed in two groups, children and youth and also adults. As a vivid example the results refer to a population of one million. If the NO_2 pollution would be $20\,\frac{\mu g}{m^3}$ instead of $40\,\frac{\mu g}{m^3}$, 3.000 bronchitis infections by children and youth could be prevented. In case of adults the amount would be even higher, about 3.200.[17]

Another negative aspect of NO_x emissions is their ability to react with VOC into ground-level ozone and also to PM. These effects are known as synergy effects. Necessary for this chemical reaction is the impact of heat and sunlight.[18] Ground-level ozone is also well-known under the common term 'smog'. Through the benefiting conditions in summer, the phenomenon 'smog' can be seen in this season, especially in cities with a high traffic density, quite often.

4.2 Effects on the environment

The environmental effects caused by NO_x emissions are quite serious. NO_2 harms the vegetation and induce necrosis (the yellowing of leaves), prematurely ageing and dwarfism.[19] Dwarfism describes the condition of short stature that is based on atypical slow growth. Furthermore is NO_2 an intermediate product for nitric acid which effects through acid rain the worldwide forest decline and soil acidification. Moreover leads NO_2 to eutrophication that upsets the ecological balance. The consequences of eutrophication could be the growth of several plant species, like stinging nettle and blackberry that prefer high nitrogen containing soil and the contemporary disappearance of more fastidious species and their biocoenosis. Further consequences are the disturbance of the nutrient balance and a changing composition of species.[20] In coastal water eutrophication can contribute to the growth of algae and a deficiency of oxygen. Especially the Baltic Sea is endangered, because it conforms more an inland lake due to its minor fresh water exchange to the North Sea. Hence the nutrients can accumulate in the sea water and a high concentration with the further described consequences follow. How far the Baltic Sea is affected by eutrophication can be seen in figure 6.

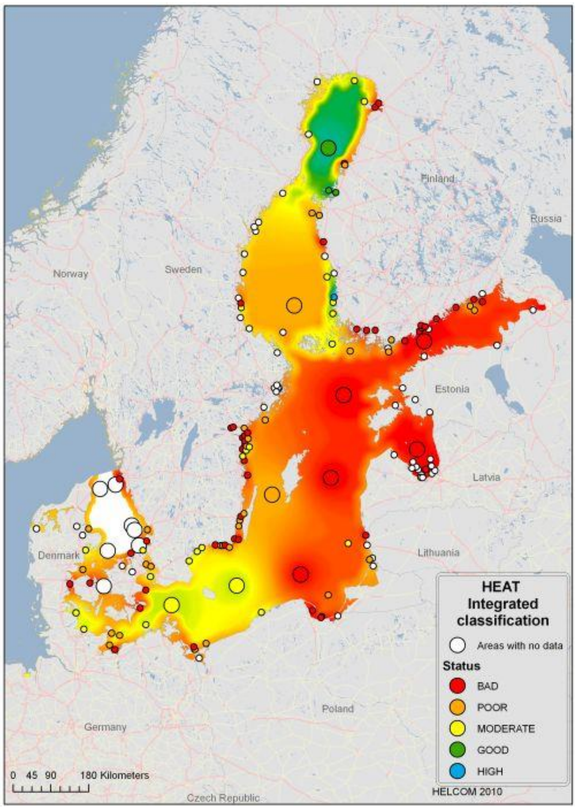

Figure 6: The Baltic Sea affected by eutrophication. The status is based on average data from 2003-2007 and the big circles describe open sea areas and the small ones coast regions.

4.3 Combustion process

During the process of combustion the carbon share of the particular substance will react to CO_2 and the hydrogen share to H_2O. Due to this basic chemical law the chemical equation for a complete combustion is:

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O \text{ [22]}$$

Equation 1: Chemical law for a theoretic complete combustion

For a complete combustion the right amount of supply air is important. This right amount is shown with λ. It describes the ratio of the effectively needed and the theoretical needed air. The theoretical amount of air is the exact amount where no oxygen is left after the combustion. If $\lambda = 1$, the theoretical amount of air is equivalent to the effectively needed amount. If $\lambda < 1$, the amount of air is too small and the fuel will be combusted incompletely. Is, on the other hand $\lambda > 1$, it refers to excess air. Typical values for a Diesel engine are $\lambda \approx 1{,}3$, if the engine is in full load and $\lambda \approx 5$, if the engine is in idle.[21] In case of 1,3 there is 30% more air available for the combustion.

The reasons why additionally emissions originate are the impurities in the fuels. These impurities were not combusted completely and react to some harmful substances. In the figure 7 the occurring emissions of a medium-speed Diesel engine, operating with HFO that has a sulphur content of 4 per cent, is shown.

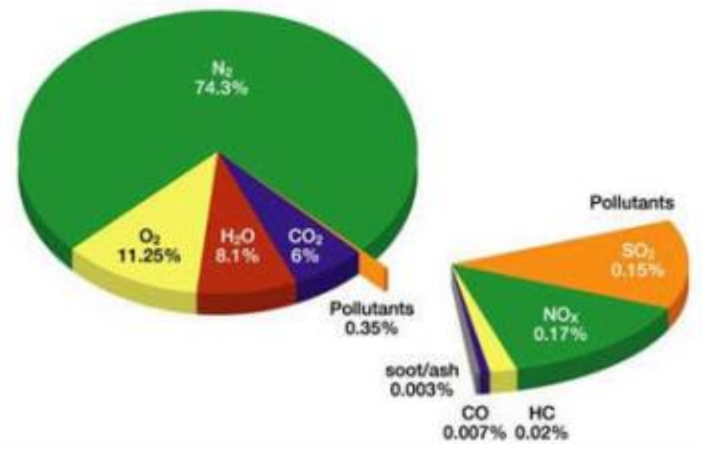

Figure 7: The typical exhaust gas emissions of a medium-speed Diesel engine (HFO with 4 per cent sulphur content)

The incomplete combustion can be caused by an insufficient mixture of fuels and combustion air, sudden cooling of flame gases, a too short period in the specific range of temperature or burning by lifted flames.[22]

4.4 Formation of NO_x

NO_x are produced during the combustion process. The variety of NO_x can be seen in the table below.

Table 1: Overview of the different forms of NO_x

NO	N_2O	N_2O_4
NO_2	N_2O_2	N_2O_5
NO_3	N_2O_3	N_2O_6

Most important in combustion technologies and in the present work are the nitrogen monoxide NO and the nitrogen dioxide NO_2. These two substances occur at high combustion temperatures. During the combustion NO is produced mainly. The conversion to NO_2 happens after the combustion through mixing with oxygen of the exhaust gases or the atmosphere. Generals are NO_x's produced through oxidation of nitrogen by the combustion air or of nitrogen of the fuel.

Furthermore the production is differed in three mechanisms, depending on the origin of nitrogen:

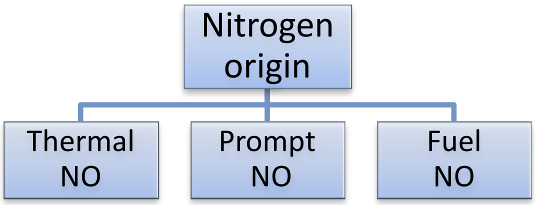

Figure 8: The three types of NO formation

In case of the thermal NO mechanism, also called Zelodovic-mechanism, the nitrogen of the combustion air is used. Due to the high prevailing temperatures an endothermic oxidation of this nitrogen takes place. An endothermic reaction describes the increasing reactivity depended on increasing temperatures. The production of NO starts to increase highly from a temperature on 1570 K.[22] From this temperature on, the dissociation (separation) of oxygen atoms increases rapidly. Consequently are more free oxygen atoms available and a higher amount of NO can be originated. The maximum formation of thermal NO is reached at a temperature from 2.200 to 2.400 K.[23] Due to this fact, peak temperatures that exceed 2.000 K should be prevented to avoid the excessive formation of NO. Chemical reactions in oxygen-rich parts, referred to G. Baumbach, can be seen in the chemical equations below.

$$O + N_2 \leftrightarrow NO + N$$

Equation 2: Chemical reaction of O and N_2

$$N + O_2 \leftrightarrow NO + O$$

Equation 3: Chemical reaction of N and O_2

In fuel-rich parts however, the following chemical equation is quite typical.

$$N + OH \leftrightarrow NO + H \text{ [22]}$$

Equation 4: Chemical reaction of N and OH

Thermal NO can be affected by a few parameters like temperature, oxygen concentration, fuel-air ratio, residence time and pressure.[23] How the three sorts of NO are affected by the incineration temperature can be seen in the figure 9.

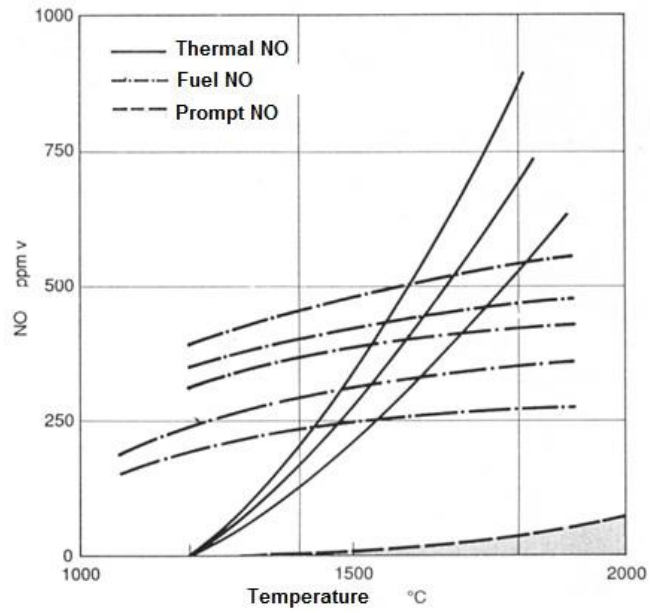

Figure 9: Dependence of the three NO sorts on the incineration temperature

The second mechanism is called prompt NO mechanism, as well known as Fenimore-mechanism. About 5-10 % of NO is produced in this way.[24] The process takes place in the low-oxygen part of the flame. NO is produced through radicals like the intermediate substance CH that reacts with the nitrogen of the air to cyanides like HCN. In the end the chemical equation will be like it is shown below with R is an organic rest.

$$HCN, CN + O \rightarrow NO + R \text{ [22]}$$

Equation 5: Chemical equation for the formation of prompt NO

Prompt NO plays compared with thermal and fuel NO a minor part in the production of NO.

The last mechanism for producing NO is the oxidation of nitrogen of the fuel. So the amount of NO is depended on the nitrogen content of the fuel. Normally it is negligible, but in case of HFO or coal it is not. HFO contains about 0,2 - 0,6 %

nitrogen [25] and that is the reason why such a high amount of NOx emissions are occurring. In contrast to thermal or prompt NO, fuel NO originates already at lower temperatures from approximately 1300 K on.[22] An additional accelerant is the amount of excess air. With a higher concentration of excess air the formation of fuel NO increases. The reason for this principle can be seen on at the chemical equation below, using the example of the ammonium radical NH_2.

$$NH_2 + \frac{1}{2}O_2 \rightarrow NO + H_2 \text{ [22]}$$

Equation 6: Formation of NO due excess air

4.5 Measuring technique

The most common measuring method for determining the sum of NO and NO_2, so-called NO_x, is chemiluminescence. The word 'chemiluminescence' describes rather the luminescence caused by a chemical reaction, but is also used for naming the measuring method that uses the same-named principle. It is used to measure continuously the NO_x concentration near the ground up to a height of 20 kilometres. Further emissions that can be measured with the principle of chemiluminescence are ozone and sulphur oxides. Also the latest available data from M/S Mariella is detected with this method. Basically, the NO_x content is detected through the emitted light of a chemical reaction with ozone. The necessarily needed device is named 'chemiluminescence detector', further abbreviated with CLD. In general the CLD consists of two components, a reaction vessel and a photomultiplier tube. As its name implies, the chemical reaction between ozone and nitrogen monoxide takes place in the reaction vessel. Ozone is produced in a previous step by an electric generator and leads to a reaction with NO like the following chemical equations.

$$NO + O_3 \rightarrow NO_2^* + O_2$$

Equation 7: Reaction of nitrogen monoxide and ozone to oxygen and nitrogen dioxide with an oxygen molecule in an excited state

$$NO_2^* \rightarrow NO_2 + h\nu$$

Equation 8: Reaction from nitrogen dioxide with an oxygen molecule in an excited state to nitrogen dioxide and released energy

Possible existing NO_2 in the gas sample is reduced to NO as a first step. Then O_3 and NO are brought under a continuous flow into the reaction vessel. Through the chemical reaction enough energy is released to bring the NO_2 molecule in an excited state. This is marked in the chemical equation above with a little star. If a molecule is in an excited state, it means that the energy state is higher than in its basic state. The excited state is in general quite unstable and its durability is usually in the range of nanoseconds. Hence the molecule can be return into its basic state it has to emit the additional energy. This original chemical energy is emitted as electromagnetic energy in the form of light, mostly, in a visible range. If energy is emitted in the form of light it is referred to the emission of a photon, which is in everyday language a light particle. For light that can be perceived from human beings, a wavelength range from circa 380 nm, that conforms violet, to 780 nm, that conforms red, takes effect.[26] Below 380 nm the ultraviolet radiation and above 780 nm the infrared radiation can be found. For measuring the occurring radiation a wavelength range from 500 nm up to 3000 nm is used. Also common is the range 600 – 2800 nm, referred to Skoog's and Leary's 'Instrumentelle Analytik'.[27] From traffic exhaust emission measuring experiences a maximum of chemiluminescence was determined at 1200 nm. Also the constant percentage share of NO_2 in an excited state was determined and amounts to 20 per cent.[28] It is further proven that the detected amount of light is proportional to the NO content in the available gas sample, if the measurement is done under defined conditions. One factor in these defined conditions is the abundantly available O_3. Another way to indicate the type of light is to use the frequency instead of the wavelength. For this reason is in the chemical equation above the letter 'ν' used. It symbolizes the frequency of the radiation. The 'h' in turn represents the Planck's constant that is $6{,}6261 \cdot 10^{-34}$ Js and mirrors the ratio between the frequency and energy of a photon, light particle. For measuring and determining the mass of photons a photomultiplier is used. Such a device is shown in the schematic structure below with the number six. Simplified absorbs the photomultiplier the emitted light signals from the chemical reaction and transforms them into an electric impulse. At the same time intensifies the photomultiplier the electrical impulses to get an easy measurable signal to the electronic counter. According to the Karlsruhe institute of technology the intensification factor is about one million.[29] In figure 10 it can also be seen that between the photomultiplier (6) and the reaction vessel (1) a filter (5) is situated.

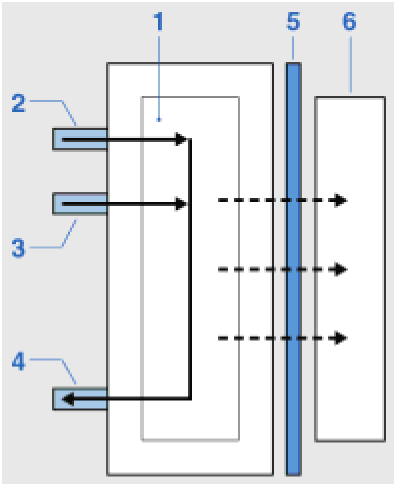

Figure 10: The illustration of the set-up of the measuring principle. 1: reaction vessel 2: inlet ozone 3: inlet gas sample 4: gas outlet 5: filter 6: detector, for example a photomultiplier

This filter prevents the environment of harmful O_3 radiation. The numbers two and three represent the inlets of O_3 and the gas sample, whereas number four stands for the outlet of the gas mixture. Important while using a photomultiplier is the high sensitivity regarding to light. It must be consequently protected from other light sources and daylight.

4.6 Measurements on M/S Mariella

The latest emission measurements on-board were taken from 7th to 9th of March in 2013 by the scientific assistants from Kymenlaakson ammattikorkeakoulu University of Applied Sciences. During those two days NO_x, CO and CO2 emissions of the four main engines, further called ME 1 to 4, were registered. For getting most precisely results the interval of taking values was 60 seconds. The used measurement principle was chemiluminescence which is described in chapter 4.5 in detail and the mess range was 0 – 2500 ppm. At the time of the measurements the main engines were operated at a load of 70 to 80 per cent that mirrors in the engine speed of 315 to 360 RPM. Due to possible occurring inaccuracies during the different working steps, like the taking and preparation of samples, analysis and collection of data a tolerance range of 10 per cent is considered. The results of those measurements are compared to the upcoming NO_x limits of IMO Tier III in figure 11.

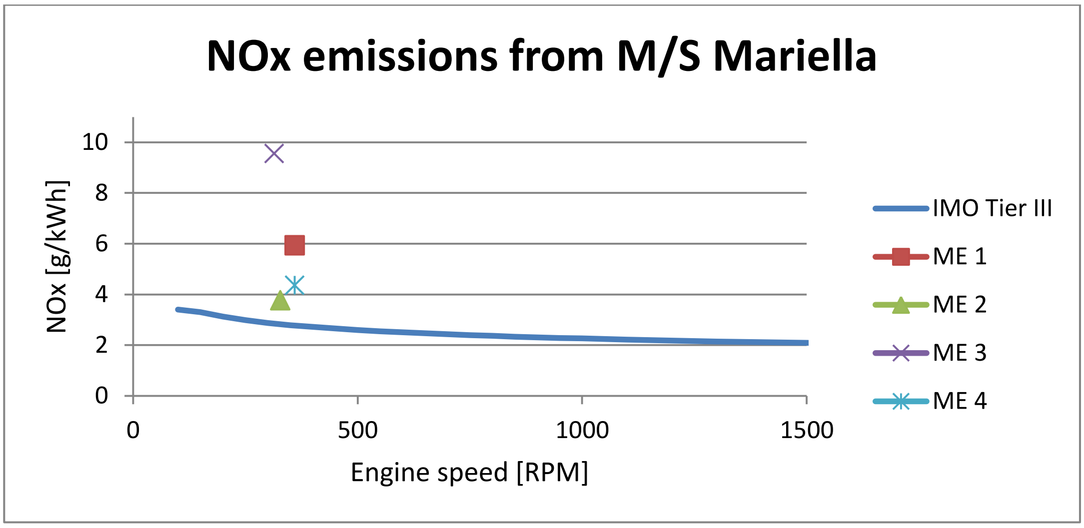

Figure 11: The results of the latest on-board measurement compared to the upcoming NO_x limits of IMO Tier III

There it can be seen that the determined NO_x emissions still exceed the maximum accepted values, but those values are becoming effective not until 2016. During the measurements the ambient conditions can be considered as normal, like the table in appendix 2 shows.

5 EMISSION REGULATIONS

To force the development of new technologies reducing NO_x emissions, there are regulations that reduce regularly the permitted ship emissions. Some of these regulations are initiated by the governments of nations, which are residents of the Baltic Sea. On the other hand there are also attempts to limit the maritime emissions form cross-border organisations like the EU or IMO. The following parts shall give an overview on the different existing emission regulations that affect the Baltic Sea area.

5.1 MARPOL

The NO_x emissions from ships were a long time neglected compared to the laws and limits for greenhouse gases on land. Although the MARPOL 73/78 was established in 1973 as the first regulations about marine exhaust emissions, it took many years before these NO_x limits were implemented. MARPOL is the International Convention for the Prevention of Pollution from ships. The name expresses the short form for Marine Pollution. It was established from the IMO as part of the United Nations that is responsible for guidelines regarding global shipping activities. The MARPOL contains 6 annexes with limits for different pollutions with maritime origin:

Annex I – Oil

Annex II – Noxious Liquid Substances carried in Bulk

Annex III – Harmful Substances carried in Packaged Form

Annex IV – Sewage

Annex V – Garbage

Annex VI – Air Pollution [30]

The last one is the important one for the NO_x reduction and this part came into force in the year 2005 as IMO Tier I. One point of criticism is the rather weak limits to reduce NO_x emissions. Typical NO_x levels of maritime engines vary from 9 to 18 g per kWh. Consequently most ships are not required to reduce their emissions as it can be compared with the Tier I limits in figure 12.

The values for NO_x emissions refer to diesel engines that are built after the 1st January 2000 and have an engine power over 130 kW.[30] The next step of NO_x limits came into force in the year 2011, the IMO Tier II regulations requested a further reduction of 16 - 22 per cent [31] compared to the Tier I limits. IMO Tier III is planned to come into force in the year 2016 and has very strict limits. This can be seen in the figure 12 where the three different NO_x levels depending on the engine speed are shown. In appendix 3, the exact values for the different engine speeds and IMO Tiers can be found.

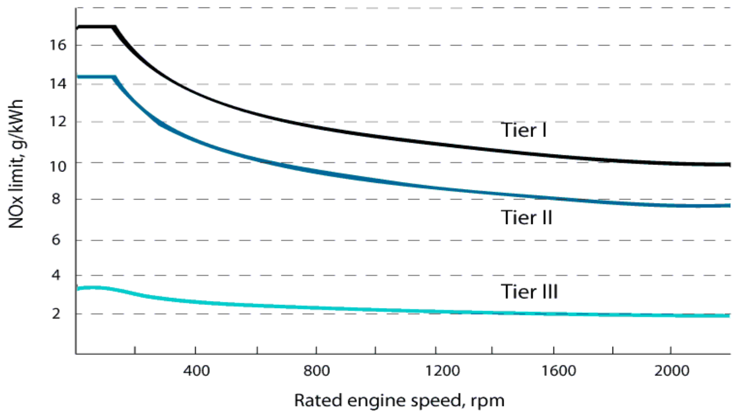

Figure 12: Limits IMO Tier I-III

In comparison to the limits of the Tier I the Tier III NO_x limits are about 80 per cent lower and represent a challenge for the engine manufacturers to meet these regulations. This future regulation is not a global limit, it has its validity for ships operating in the ECAs. The ECAs are divided into areas where the sulphur is controlled respectively the nitrogen oxides. A result of this regional limitation is that the Tier II limits are still obligatory in the rest of the world's seas.

NO_x emissions are mainly influenced by the sulphur content of the used fuel. Hence the IMO restricted also the sulphur content of the fuel oil for maritime diesel engines with the MARPOL Annex VI. For this purpose they created the SECA, which includes the Baltic Sea, the North Sea and the English Channels. Furthermore, since 2011 also the coastal sea area of North America (shown in figure 13).[30]

Figure 13: SECAs in the world

Within this region the sulphur content must be currently less than 1 per cent by weight. Globally the allowed sulphur share is 3,5 per cent by weight. The outlook is a further reduction in the year 2015 to 0,1 per cent in SECA, and worldwide 0,5 per cent by weight from 1st January 2020 on.[30] As an alternative to the expensive low sulphur fuel SO_x treatment technology has to be installed to lower the emission factors.

Ships are a main vehicle to transport goods over a long distance and their share of the freight traffic rose in the last years, which is a still lasting trend. So further steps should involve more countries and sea areas participate in the SECA and NECA to assure a broad maritime emission reduction. Yet the area in which the NO_x emissions are controlled comprises only the coast of North America. The countries of the Baltic Sea and the North Sea are discussing the effects of a denotation as NECA member. Therefor a number of studies are carried out regarding the costs and benefits.

For example in a Dutch and a Danish study they build three different models to compare the costs and monetised health benefits in the year 2030, if the North Sea belongs to the NECA. The result of this study was a factor between 1,6 and 6,8 for the benefits over the costs for the North Sea participating in the NECA.[32] It is questionable how reliable estimations of this kind are, especially the monetarisation of prevented health risks are very difficult. Nevertheless the harms for humans and the environment need to be balanced against the costs of extending the NECA.

5.2 Country specific systems

The amount and the way how fairway dues are charged differ within the resident countries at the Baltic Sea. The port dues vary still more, they even vary within a country from port to port. Up to the present day there are some attempts to implement an environmental differentiated system for fairway and/or port dues such as the schemes in the port of Gotheburg or Mariehamn and the organization of the taxation in Norway. The following chapters provide an outline of systems in different countries.

5.2.1 Norwegian System

In Norway, there are traditionally a lot of regulations regarding the environment. In this country, there exist so-called green taxes which have the purpose to protect the environment against harmful substances and emissions. A great number of them revere to land based emissions. However there are also laws for the sulphur content of vessels' fuels and CO_2 emissions. Since 2007 there is also a tax on NO_x emissions in force.[33] It is about 17,01 NOK/kg (in the year 2013 [34]) approximately 2,2 €/kg NO_x. The NO_x tax is applicable for ships with an installed power of more than 750 kW.[35]

Furthermore there is a different system in the Norwegian taxation. With the tonnage tax the NTG for a vessel under Norwegian flag is taxed, starting with vessels over 1.000 NTG.[36] The net registered tonnage indicates the amount of cargo a ship can carry, it shows the volume of space for cargo. The differentiation part applies to ships with low NO_x emissions and low sulphur content. Environmentally friendly vessels can earn points, which will reduce their tax. They can get a maximum of six points out of ten points in the SEIS by reducing NO_x emissions and using low sulphur fuel. How the points for the sulphur content is staggered can be seen in figure 14. To gain the whole ten points there are five further environmentally related factors. This Norwegian approach of a differentiation model separates the vessels into different types. Tankers, general cargo and passenger ships belong to the above explained system with seven parameters. All other vessels can reach the maximum of ten points by reducing the NO_x emissions and use low sulphur fuel. This leads to different points by reducing the emissions to the same amount.[37]

	Points earned			
	Tankers	General cargo	Passenger ships	Other ships
NOx				
IMO NOx-curve*	0.75	0.75	1.05	1.75
(IMO curve) - 15%	1.50	1.50	2.10	3.50
(IMO curve) - 60%	3.00	3.00	4.20	7.00
Sulphur				
2.5% S	0.75	0.75	0.45	0.75
1.5% S	1.50	1.50	0.90	1.50
0.5% S	3.00	3.00	1.80	3.00
Total points for best emission reduction practice	6.00	6.00	6.00	10.00

* The IMO's NO_x curve is approximately equal to emissions from new ships that do not use any special abatement technique such as SCR or HAM. Any of these techniques will earn a new ship a maximum credit.

Source: Norske Veritas (1999).

Figure 14: Points earned in the Norwegian system

5.2.2 Swedish system

To introduce the Swedish system of fairway dues and port fees there is a diagram below which simplifies the structure (figure 15). This system of duties was firstly introduced in 1996 from the SMA, the Swedish Ship Owners Association and the Swedish Ports' and Stevedores' Association.[38,39] It is called a differentiation system because the path of the fairway dues is further divided and one path of these distinguishes if there are high amounts of NO_x emissions and high sulphur content in the fuel.

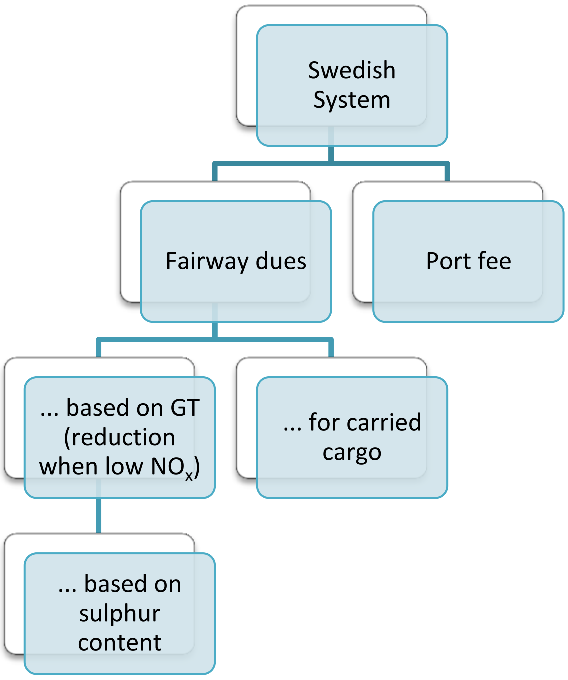

Figure 15: Diagram of the Swedish System

In the year 1998 this scheme came into force with the purpose to reduce the emissions of NO_x and SO_x by 75 per cent in the first years of the new century.[38,39] The above mentioned involved parties decided to create the system with fairway dues and port fees due to a report that showed the requirement of limits for the emissions on the sea. The first part of the differentiation system, the fairway dues, is based on two calculation bases. First of all it is based on the GT of the vessel. This number represents the size of the ship. More precisely the GRT is considered, and this is the total internal volume of a vessel. Secondly the fairway dues depend on the cargo which is carried, meaning the amount of goods which are loaded. For the amount of the cargo fee there is no reduction possibility, it is not the different part of the system. There is just a lower charge of 0,8 SEK/t for low value cargoes, which carry for example sand, stone or gravel. The normal due is 2,90 SEK/t (for 2012), approximately 0,34 €/t.[40]

For the fee per GT there is a reduction possibility. If the NO_x emissions of a ship are below 10 g/kWh at 75 per cent load the fee is reduced by each gram NO_x less.[39,41] Emissions under 0,4 g/kWh exempt from the fee (see appendix 4).[41] The amount of the due differs with the ship type. It is divided into passenger vessels (including railway ferries), cruise ships and other vessels, which may be for instance oil tankers.

Diagrams explaining the different types of ships can be found in appendix 1. To be charged with a lower due it is necessary to prove the emissions from the vessel with a certificate that has to be given to the SMA.

Additionally there is a fee if a ship has a fuel in its bunkers which contains sulphur above 0,2 mass per cent. Between 0,2 and 0,5 mass per cent they have to pay 0,2 SEK per GT and above this level 0,7 SEK per GT (as of 2012).[40] If a shipowner wants to have the lower sulphur fee he is obliged to verify that the ship is running with fuel with a low sulphur level. This has to be done also with a certificate given to the SMA.

The fairway dues are validated for ships regardless the flag on which they are operated on, when they are entering a Swedish harbour. In Sweden the Maritime Administration is partially financed by the fairway dues because it is not funded by the government.[39] It is also funded by other revenues but the fairway payments are a very important part of the economic basis of the SMA. However it is intended to be revenue-neutral. The idea is to compensate the costs for vessels with NO_x reduction technology which is defrayed by higher rates for ships with higher emissions and high sulphur fuel.[37]

On the other side, the port fees are fixed by each Swedish port independently. The SMA is neither involved by levying the port fee nor by the decision if there is a difference or not. As a consequence the 52 commercial ports of Sweden are competitors. In the year 2008 almost 30 ports [39] based their port dues on a differentiation of NO_x emissions from a ships' machinery and the sulphur level of its fuel. Actually there is not a huge difference in the port dues which is visualised in figure 16 with the reduction possibilities in different Swedish harbours.

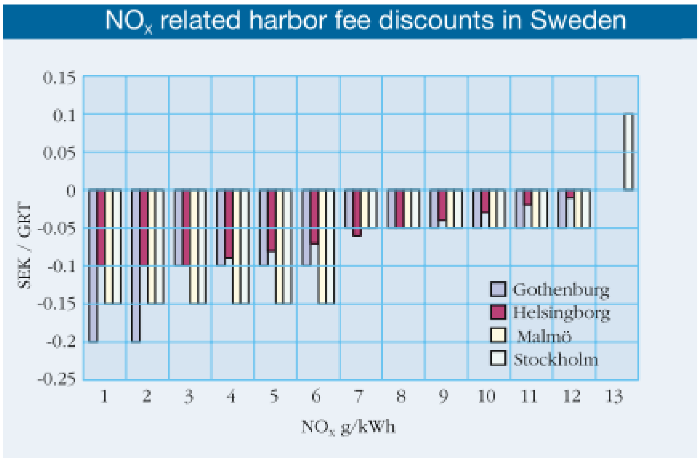

Figure 16: Comparison Swedish port fees

The highest reduction, which can be gained in Gothenburg and the lowest ones for Helsingborg, differ only between 0,1 SEK/GT which is about 0,012 €/GT. For example for the M/S MISIDA with a GT of 15.586 this would mean a price difference of 187 €, which is rather a small difference in the saving. This slight distinction is due to the fact that the ports need to cover their costs and cannot risk losing customers. Although they want to offer some attraction beyond the differentiated fairway dues.[39]

As an example for one of the 52 ports of Sweden it is possible to reduce the port dues in the port of Gothenburg when the NO_x emissions are below 10 g/kWh. Below this level there is a reduction rate of 0,05 SEK/GT. If the emissions are between 6 and 2 g/kWh the reduction rate rises to 0,1 SEK/GT and under 2 g/kWh of NO_x emissions 0,2 SEK/GT.[42]

In the port of Stockholm ships which are reducing their NO_x emissions more than 50 per cent can receive a discount of 450.000 SEK per month (approximately 52.636 €)[43].

As for Finland there are only in the port of Mariehamn on the Åland Islands differentiated dues. Since the beginning of the year 2000 there is a linear reduction system of 1 per cent for NO_x emissions under 10 g/kWh. Emissions less than 1 g/kWh receive a reduction of 8 per cent. In addition the port gives discounts if the sulphur content in the fuel is below 0,5 per cent. A further incentive is an extra deduction of

8 per cent for passenger ships and cargo ships when they emit less than 1 g NO_x/kWh and operate with a fuel containing a maximum of 0,5 per cent sulphur.[44]

In fact in a lot of ports it is necessary to have a proportion of sulphur in the fuel which is below the current limit of 1 per cent from the MARPOL regulations. However these levels are still higher than the limits from the directive 2005/33/EC.

Since January 2010 this directive of the EU has been in force and limits the sulphur content of the ships' fuel to 0,1 per cent by weight while the vessel is at berth in an EU Member State. But this regulation is very complex and due to the many occurring exceptions its realization is rather difficult. [45]

6 NOX REDUCTION TECHNOLOGY

There are different approaches to reduce the emissions and especially the NO_x emissions from marine diesel engines. First of all with internal engine modifications which include for example a different fuel injection valve, called slide valve. With this device it is possible to lower emissions like NO_x and simultaneously VOC and PM. The effect is based on a lower heat release during the combustion because the valve enables an optimized spray distribution in the cylinder. A further fuel related modification is the use of common rail injection systems or the retarded injection as well as the two stage fuel injection. Other ways of reducing emissions from changes on the engine operation are a higher compression ratio or design changes at the combustion chamber. By using a two-stage turbocharger, to get a higher charge pressure and a following charge air cooler, are also good results achieved. The earlier mentioned Miller cycle involves the change of inlet and outlet valve timing.

Bigger changes belong to the strategy of using different fuels like gas or biofuels as well as the strategy to change to propulsion via fuel cells.

These internal engine modifications are sometimes also categorized as dry methods in comparison to wet methods like DWI, HAM or Emulsified fuel. All these methods include the use of water to lower the combustion temperature. A last category of emission reduction measures is the aftertreatment. This is literally rather emission reduction than abatement because here the exhaust gases are treated to fulfil emission regulations. For instance EGR or SCR are instruments to decrease NO_x emissions, where on the contrary the Sea Water Scrubbing is used to clear the exhaust gases from SO_2 emissions. In brief words EGR leads a part of the exhaust gases back to the combustion chamber to lower the O_2 content, which in turn lowers the combustion temperature and hence the emissions. SCR in contrast uses ammonia (NH_3) to neutralise NO_x in the exhaust gas with the help of a catalyst.

6.1 Direct Water Injection (DWI)

One of the wet methods to abate NO_x emissions is DWI, as it uses water to lower the temperature during the combustion. Water can be introduced into the intake air but this technology implies the injection of water directly into the cylinders of the engine.

6.1.1 Construction of various types

Mainly there are three different varieties for the injection. The injection through separate injectors, one for the fuel and one for the water; through separate nozzles in one injector or the so-called, stratified injection.

This type has a common nozzle for fuel and water, but both fluids keep separated until the moment they are injected into the cylinder. Compared to a regular fuel injector, the body of the stratified water injector contains additionally the water supply system. The construction seems similar but this dual injector has a complex and expensive technology. For instance a special nozzle is necessary with high-quality materials that can resist the great risk of corrosion. Furthermore comprehensive adjustments at the cylinder head are necessary for retrofitting this system.

A general order for the injections is first fuel, than water and after that again fuel. In figure 17 is shown with a simplified drawing how a stratified water injection nozzle works. The left picture describes the water loading.

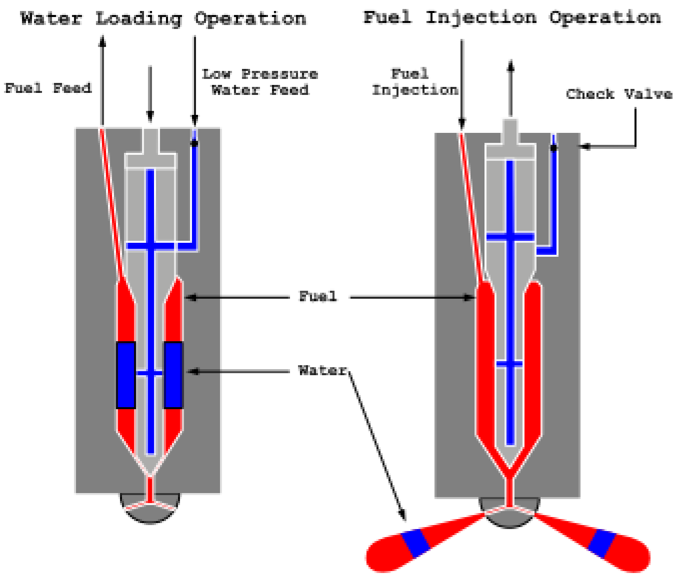

Figure 17: Construction of a stratified injector

The blue line distinguishes the water supply through the needle. In the water supply pipe is a check valve, which provides the water with a low pressure into the hollow part of the injector. The needle has the aim to seal the nozzle. Accordingly the injection takes place when the needle is lifted (visible in the right drawing of figure 17) and apart from this time no droplets are allowed to escape.

The incoming water pushes the fuel back through the pipes. When the fuel injection starts, the pressure rises to dimensions of 1.200 – 1.800 bar or even 2.300 bars when HFO is in use. [6] As a consequence of the pressure the one-way valve closes. This prevents the infiltration of fuel oil into the water supply system. Finally, this high pressure forces the actual injection of the fuel-water-fuel mixture.

With the diesel fuel oil entering at first the cylinder, the ignition can be assured for the stratified water injection. The amount of water which will be injected for one cycle depends on the pre-injected fuel. Typically the share of water to fuel varies from 40 to 70 per cent.

A major benefit of this type, over the injection through separate nozzles, is that the water is sprayed really close to the flame and rather far away from the cylinder wall. Hence it is possible to reach better reduction results. On the other hand, the stratified injection requires expensive retrofitting as a consequence of the complex technology. Therefor more ship owners tend to install the other main type, a twin nozzle.

The second type of DWI injector is also called tandem or combined nozzle.[46] This kind is installed in the case study ship M/S MISIDA. The manufacturer Wärtsilä named this injection system tandem nozzle and a descriptive picture of the construction is shown by figure 18.

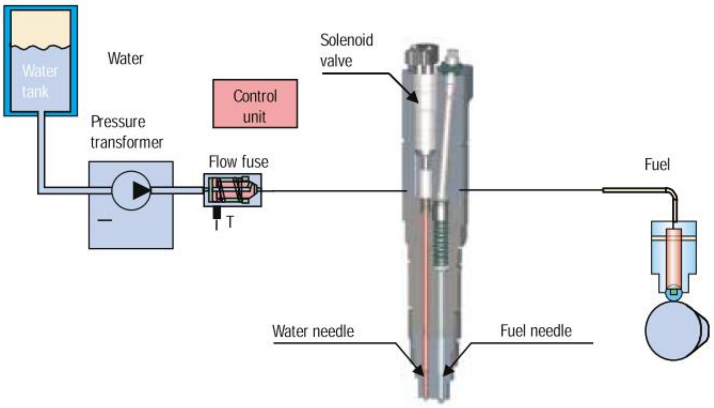

Figure 18: Construction of a tandem nozzle

The name implies the method, because the supply of water and fuel occur separate with two needles and through separate nozzles, but within a single injector body. Consequently it is possible to inject both liquids close to each other which ensures a homogenous mixture in the cylinder. Beyond that, this construction requires less space to be installed and each injector has an own computer control unit to optimize the injection parameters. Likewise it is possible to change the amount of the added water according to the conditions of the engine. For example during the startup or while operating at low loads the water injection can be turned low or completely off.

Not only the nozzle makes the difference between this injection types, it is also the water pressure. The stratified water injection does not need a high pressure for the water spraying. On the contrary, the injection via a twin nozzle needs a pressure of 200 to 400 bars, varying with the engine type. [47] This requirement is assembled with a high pressure water pump module. Additionally a low pressure pump has to be installed before the high pressure pump, which provides constantly 3,5 bars [38], to guarantee a stable water flow in between.

One advantage of the combined nozzle is that higher rates of NO_x reduction (compared to completely separate nozzles) can be achieved with simultaneously no influence on the engine operation. The engine can operate with the water injection on or off due to the separate feed pipes. For marine engines a reliable and failsafe operation is very important, owing to the fact that the whole ship is not maneuverable if the fuel supply collapses and the engine stops. In case of an error in the DWI application, for example a leakage or clogging of the nozzles or pipes, the combined nozzle has a flow fuse as a safety device that stops the water flow. [48]

To achieve a NO_x reduction of 50 - 60 per cent there is a water to fuel ratio, short as w/f-ratio, of 40 - 70 per cent necessary. If more water is fed into the combustion chamber it is possible to reduce the NO_x emissions further, but this involves also a reduction of the engine efficiency.[49]

The last of the three types is the injection of water and fuel through completely separate injectors installed in the cylinder head. An example of the construction can be seen in figure 19. With this application the direction of the water spray can be adjusted quite freely, but still the water is coming into the cylinder rather far away from the flame zone and the fuel spray. There is not a good opportunity for both liquids to build a homogeneous mixture.

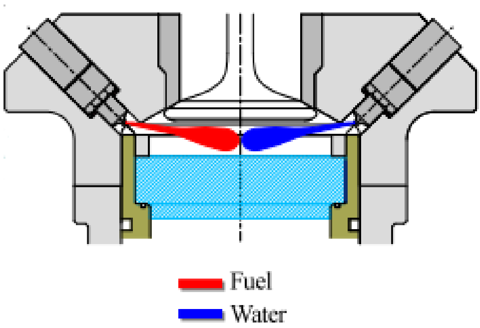

Figure 19: Separate water injection

6.1.2 Process in the cylinder

With the DWI technology it is possible to add a high amount of water to the combustion process, therefore the NO_x reduction can be higher than for other technologies, like water-fuel-emulsions.[3] When emulsified fuel is used to reduce

NO_x emissions the amount of water that can be used is limited to 50 per cent. As for DWI even w/f-ratios exceeding 1:1 can be realized.[50] That means a higher amount of water than of fuel is added to the combustion. Not in any case it is recommended adding such an amount of water, because the w/f-ratio entails some good, but also some undesirable consequences. These will be explained in the further text but firstly it is necessary to understand the effects of the water on the processes proceeding in the cylinder.

How much NO_x emissions are formed during the combustion is depending on different factors. It varies especially with the type of fuel and its premix, the intake air, the duration of the fuel in the cylinder and, of course the temperature during combustion.[3] The phenomenon behind the abatement of NO_x emissions based on water injection is, the immediate vaporisation of the water, when it comes into the hot combustion chamber.

The temperature of the water rises very fast in the cylinder and due to this high temperature the water contains already a high amount of heat. For the phase change an additional amount of heat is required, the so-called heat of vaporization. Accordingly the water vapour has a high heat content. All this heat is taken away from the surroundings, thus the temperature in the combustion chamber and the temperature of the flame is lowered. Further, the water vapour gives the whole gas mixture in the cylinder a higher heating value as usual. Due to the temperature decrease, the very sensitive thermal reaction of NO proceeds slower, so less NO emissions will generate during a combustion that includes water. But from the chemical point of view the water has no impact. All chemical reactions take place, although maybe in a smaller extend or they may proceed slower. A further effect of the added water is the best dilution which causes the flame to enlarge. For the volume of the water vapour is higher and the oxygen is more diluted in the gas mixture the flame has to enlarge.

The size of the water droplet should not be too big, because with smaller droplets it is possible to reach lower temperatures in the cylinder. If they are about 10 µm, the similar size of the fuel droplets, they can vaporize earlier and therefor absorb more heat.[51] A further advantage is the avoidance of wet cylinder walls. If the water vaporizes fast it cannot damp the cylinder walls and damage the lubrication oil film. This is an important matter of the engine maintenance.

The introduction of water into the combustion has a positive influence on the distribution of the pressure and the heat release. Therefor the left part of figure 20 shows the pressure on the ordinate over the crank angle on the abscissa. This diagram compares the normal combustion (without water $\Omega = 0$), signed with a red line, with the combustion with a w/f-ratio of one (drawn with a dashed line). It can be recognised that the pressure difference in the beginning of the combustion process is almost zero. Later, during the main heat release and the actual ignition, there is less pressure when water is injected into the cylinder. More obvious is the decrease of the temperature in the right part of figure 20, where the temperature is shown on the ordinate. The reduction was constantly about 100 K between 100° BTDC and the main injection.[51]

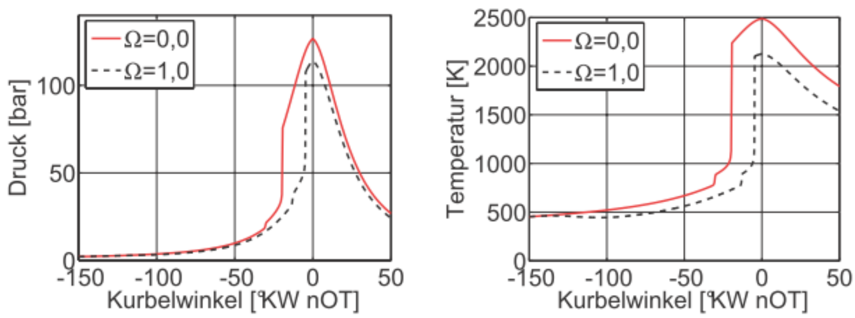

Figure 20: Pressure and temperature distribution

With the water injection into the cylinder there is a lower rate of the pressure rise. This means that the maximum pressure and also the maximum temperature will be reached later. Thus the fuel-air-mixture has a shorter duration in the hottest temperature and fewer emissions will form. Likewise, based on the lower pressure during the combustion, less boundary work needs to be achieved and in this way it is even possible to increase the engine efficiency slightly. Similarly other advantages can be realized when the combustion pressure will be reached in a gently growth. Summarized the slower increase of the pressure leads to less combustion noise, a shorter combustion time, a lower combustion temperature and hence less emissions.[51]

6.1.3 Conditions and requirements

There are many factors which influence the fuel consumption, the power of the engine and the amount and composition of emissions in the exhaust gas. To come to a compromise with these different attributes, key parameters need to be considered carefully. These are for instance the injection timing, including the duration of the water injection and the direction of the water spray.

6.1.3.1 Injection timing, direction and duration

First of all the injection time is an important part of DWI. If the water is introduced too early it could happen that the whole cylinder will cool down instead of a particular area around the flame. This leads to an ignition delay and may cause engine noise. Consequences may be extremely high peak pressures, thus more strain in the material of the cylinder, rod, piston and other components. Another problem is the incomplete combustion process, based on the cooled cylinder. That causes more unburned components, like hydrocarbons or particulate matter, in the exhaust gas, including more soot coming from the chimney.

Secondly, the place where the water is directed at has major influences. Is the water sprayed near the flame, it is possible to reach higher NO_x reduction rates. Due to the precise spraying a more effective cooling of the combustion chamber can be realised. When the water reaches rather the cylinder walls there is less NO_x reduction, as well as higher fuel consumption. In addition more emissions like CO, HC and PM will form.

While it is desirable to reach a high reduction rate, it is necessary to keep in mind, the higher the NO_x reduction, the higher is also the fuel consumption. As more water needs to be injected to achieve a high decrease of emissions.

Adding too much water into the combustion chamber has the adverse effect of an ignition delay, due to the increase of the water volume. In combination with water injection, the main combustion should take place shortly after the TDC. When the main heat is released at that point it is possible to realise the best efficiency. A deviation from this point, results in a not optimal power transmission from the combustion pressure to the piston.[51]

6.1.3.2 Water quality

As a further requirement the installed DWI system needs fresh water. This means drinking water or even distilled water, to prevent any damages of the engine. Otherwise the water in the cylinder may cause clogging of the engine due to the insertion of impurities. An advantage for cruise ships is the possibility to use the drainage water from showers, which can be used after preparation.[3] The water which is injected into the cylinder has to be free of solids, so it needs to be filtered. Furthermore if a water treatment system is installed, seawater can be used. After filtration this water needs to be desalinated to prevent hot corrosion. A greater amount of salts, for instance sodium, may get into contact with the sulphur in the fuel, or other substances like vanadium, form a layer on the surface of the cylinder and pit the cylinder layer during high temperatures.[52]

Regardless the efforts to filtrate and desalinate the water, it is a good benefit that wastewater or seawater can be used. Otherwise huge tanks are necessary for the storage of fresh water on the vessel. These additional tanks mean extra weight and a space loss. In the case of the M/S MISIDA there is a water treatment system installed, which is capable to produce fresh water with a high quality from seawater.

6.1.3.3 Fuel condition

Like for other wet methods to abate NO_x emission a low sulphur content in the fuel is essential. The share in the marine diesel fuels should not exceed 3 per cent. Wärtsilä states for its DWI systems even a level of 1,5 per cent sulphur that should not be overdone.[48] The sulphur can react with the water and oxygen to sulphuric acid (H_2SO_4), which can damage the engine with premature wear due to its highly corrosive nature. During a normal combustion there arises also a small amount of sulphuric acid, but it is important to avoid water in the cylinder liner. If the sulphuric acid and the water get into contact [46], this strong acid will dilute and this can lead to severe problems, for example damage of the lubrication film or contamination of the lubrication oil.

Another restriction is that the reduction of NO_x emissions is greater at higher engine loads. To have an efficient NO_x reduction the DWI system should be used starting by 40 per cent load.[3,53] In lower loads the engine tends to an unsteady operation which may be observed in knocking.

6.1.4 Summary

Summarized there is a need to find a compromise between the rate of emissions (NO_x, PM, soot, C) and an increased fuel consumption, which refers all to the injection timing. The decrease of the NO_x formation happens anyway, at different loads, injection and ignition times, so the injection timing should be optimized. If this is possible low emission levels can be gained as well as no significant increase in the fuel consumption occurs.[54]

The observed ship M/S MISIDA has a DWI technology installed from Wärtsilä that operates with the water injection preceding the fuel injection through a combined nozzle with two needles. With the help of the control unit the injection timing and duration is constantly controlled to find the optimal injection parameters. A further advantage which can be recognized is, for example the reduced heat loss through the cylinder walls. This can be achieved due to the overall lower temperature in the cylinder, as well as the decrease in the duration of the gas mixture in the combustion chamber.[51]

6.2 Humid Air Motor (HAM)

The Humid Air Motor is a further wet method to decrease the NO_x formation during the combustion process. In contrast to DWI the water is injected with the combustion air simultaneously. This is realized by the saturation of the combustion air before it enters the combustion chamber. The following sections should explain the technology HAM with all its particulars. From the definition and used product names via the structure and process through to the reduction potential and advantages and disadvantages.

6.2.1 Terms and definitions

Originally it was invented by the Swedish company Munters Euroform GmbH. In the technical literature it can be found also under the term ‘charge, inlet or intake air humidification’. Furthermore, companies like the Finnish Wärtsilä have their own specific product names. For Wärtsilä it is ‘WetPac’ and ‘STID’ (Steam Injected Diesel Engines) and from cooperation with Marioff Oy it is the ‘Combustion Air Saturation System’, abbreviated with CASS. The German company MAN in turn uses the common term ‘HAM’ for systems that are suitable for 4-stroke engines and SAM (Scavenge Air Moistening) for the systems that work on 2-stroke engines. The technique is already installed on two ships and they are in daily use. One is the Norwegian fishing vessel ‘Kvannoy’ and the other one is the car ferry ‘M/S Mariella’. The latter one serves as a data base for the work in hand.

In the past this technology was already honoured three times. The Euromot 1999, the Seatrade award 2000 and the CIMAC award (International Council on Combustion Engines) 2001.

6.2.2 The structure of the HAM system

First of all is the main principle to humidify the charge air of the engine to avoid high peak temperatures. Due to the explanation of NO_x formation in chapter 4.4, it can be determined that smaller burning temperatures lead to a smaller amount of NO_x emissions.

To humidify the compressed inlet air that comes from the exhaust turbocharger, a humidifier is needed. Further components are a catch tank, a bleed-off system and a heat exchanger. The basic structure can be seen in the schematic figure 21.

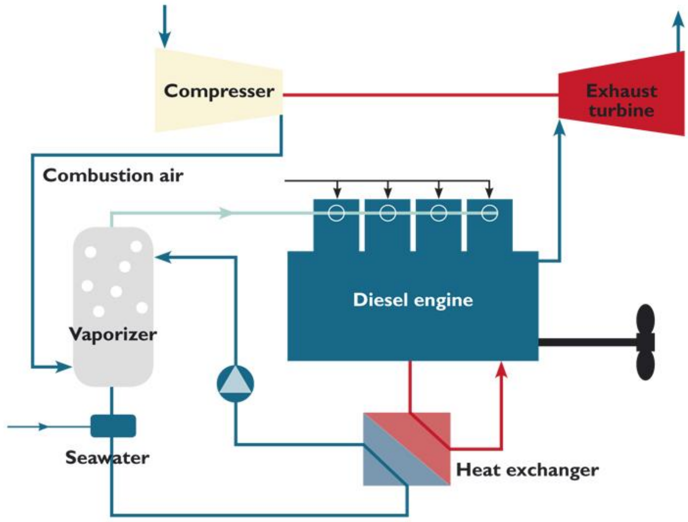

Figure 21: The basic working principle of the HAM system by MAN

The turbocharger of the HAM system works like an ordinary turbocharger. So the principle is that with the help of the exhaust gases from the engine a turbine is operated. This turbine is situated with a compressor on the same shaft. Due to the generated rotation of the turbine, the compressor can compress fresh air for the engine. The known advantages of a turbocharger like the availability of more oxygen for the combustion apply to the HAM system also. A further component is the humidifier, also called HAM unit. This constitutes the core part of the system. As a consequence of the harmful environmental effects the material of the humidifier must meet some requirements. Therefore materials like acid proof steel and reinforced plastics are used to prevent corrosion. Further will the HAM system turn off around 15 minutes before the main engines are stopped to dry the system and prevent corrosion in the engine. Constructed is the humidifier as a cylindrical vessel with three stages of surface enlarging elements. The dimensions based on the engine size and on the considered ship M/S Mariella it has a diameter of 1,3 meter and a length of 4 meter. Important for the planning of the length is the time of the evaporation, for the width it is the avoiding of high flow velocities. Minor flow velocities are required to guarantee the separation of water droplets inside the humidifier. Whereas high flow velocities make it possible for water droplets to enter into the cylinders. The whole humidifier on the M/S Mariella weights around three tons. To prevent condensation of the water droplets between the humidifier and the engine, the pipes are isolated. The next component is the bleed-off system for controlling the salt and mineral concentration in the circular flow. Thus the bleed-off system consists of valves for drain the water back to the sea and conductivity sensors to detect the salt content of the water. The amount of drained water varies between 1 up to 25 per cent of the whole circulating water.

6.2.3 Process in the HAM system

Firstly, water which can be seawater or grey water is pumped into the catch tank. Grey water is minor contaminated waste water from, for example showers and the laundry.

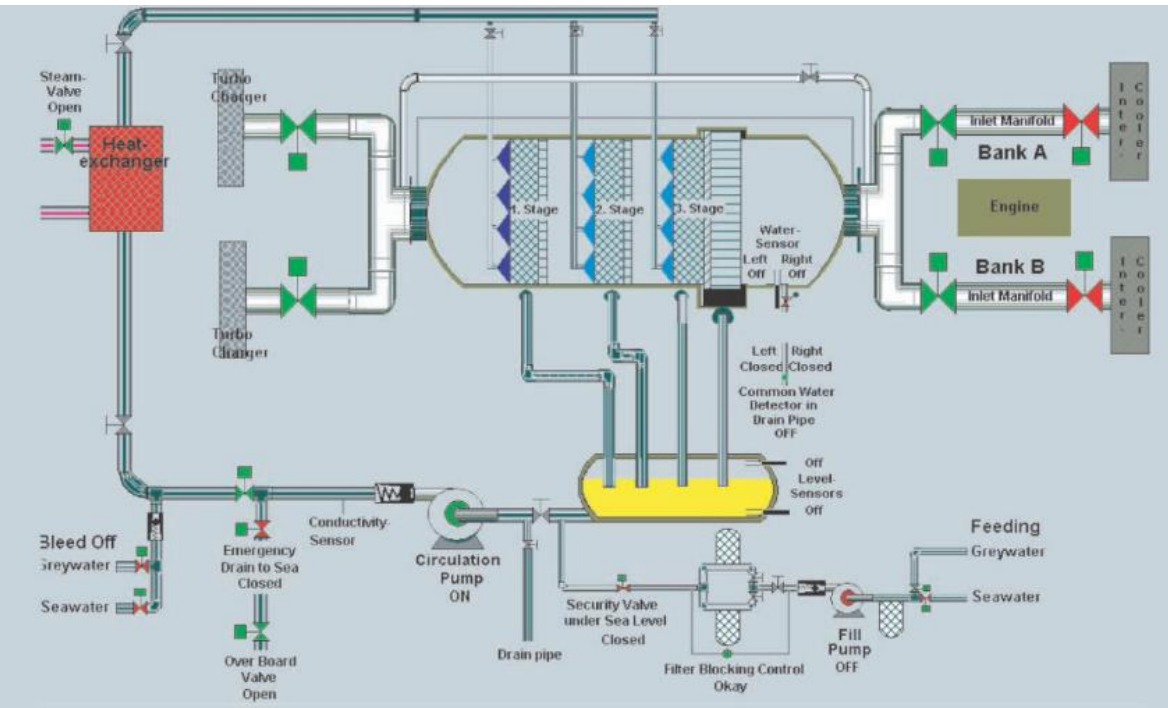

Figure 22: The flow chart diagram of a HAM system, like it can be found on M/S Mariella

Also the drain water that comes from the humidifier as an excess residue is collected in the catch tank. In case of the considered ship M/S Mariella the needed amount of water is about 60 tons [55] on one way from Helsinki via Mariehamn to Stockholm. The distance amounts to circa 250 nautical miles which are about 463 kilometres. Before the sea water reaches the catch tank it has to pass filters for separating algaes and other raw contaminants. Beyond an additive can be fed into the water to prevent the build-up of scale and other deposits. Through a heat exchanger, which is marked in figure 22 in red, the water is then pumped into the humidifier. This heat exchanger operates with the heat of the exhaust gases or with the engines cooling water. The reason for using a heat exchanger is to preheat the sea water to achieve a higher NO_x reduction level. Without the preheating, NO_x emissions of 4,5 $\frac{g}{kWh}$ can be expected, with the preheating even less than 3,5 $\frac{g}{kWh}$ are possible by information from MAN.[56] Therefore the water is preheated to a temperature about 80 °C.[57] In the humidifier the water is sprayed into the hot airflow. According to Pounder's marine diesel engines and gas turbines (2009) a temperature of 200 °C in the humidifier and an airflow velocity of 75 $\frac{m}{s}$ can be assumed. Small water particles, in the size of a few micrometres precipitate the immediate evaporation and best possible mixing with the air. The result of the process is saturated air with a moisture content of 60 $\frac{g}{kg_{dry\ air}}$ [6] in case of CASS. By quoting the contained amount of water the unit grams or kilogram water per kilogram dry air is the standard. This figure is indicated in the literature with the letter X and can be found under the term 'water load'. [58] The state of maximum saturated air is reached if the air contains its maximum amount of water on the specific temperature and pressure. Expressed with the relative humidity it is 100 per cent. If the saturation will exceeds the 100 per cent, the excess water will condense into water droplets. So the relative humidity of the charge air by leaving the humidifier is about 98 per cent. As a general rule the air can contain more moisture the higher the air temperature is. Therefore the air which is heated through compression is quite applicable. This reaction is represented in figure 23, where it is shown that the addition of heat is more profitable than the air in an adiabatic state. It can be also seen that a charge air temperature about 70 °C is required to attain this high saturated state. Normally the charge air is tempered about 40 °C to 50 °C. Possible sources of heat for the charge air preheating are the engine coolant and exhaust gases that are lead into the charge air.

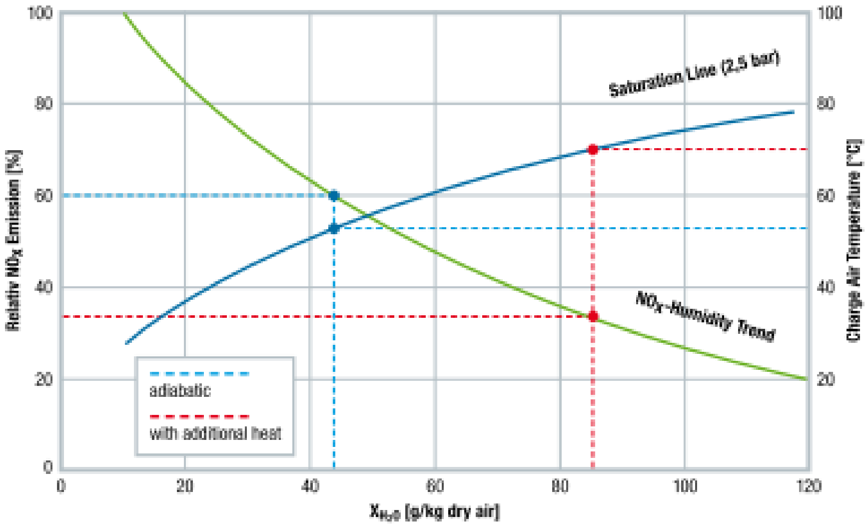

Figure 23: NO_x emissions with and without additional heating of the charge air

During the humidification two main reactions can be determined. On the one hand an increase of the specific heat capacity of the air-water-mixture. This enables the charge air to contain a higher amount of heat. On the other hand, water will replace the oxygen in the air what leads to lower peak temperatures in the combustion chamber.

Mainly is the feasible amount of injected water dependent on the pressure and temperature of the charge air. So a higher air temperature has a favourable effect on the humidification, an increasing pressure in turn not. Through a rising pressure, the intake air can contain smaller amounts of water what is adverse to the process. The cooling of the hot compressed charge air by water has the side benefit of almost obviating the need for a charge air cooler (CAC). Without a humidification system the CAC would regulate i.e. lower the temperature of the compressed charge air. So the humidification system replaces the CAC. In the interest of safety a CAC can be bypassed for the case of a failure in the HAM system. To cool the charge air is essential, because through a higher temperature the density of the air will decrease. Consequently the air will contain less oxygen. As a result the engine has a minor power and a greater thermal load. However, the water will evaporate in the humidifier with the help of so-called surface enlarging elements. The humidifier on board of the M/S Mariella is made up of three surface enlarging elements, so it has three injection stages where the preheated water is sprayed into the air flow. Through the evaporation process the sea water will be distilled. Consequently no harmful substances like salt or other pollutants of the sea water can get into the cylinders of the engine. Another protection device for the engine is the, from MAN named, high-performance mist catcher. This mist catcher is situated at the end of the humidifier and, like its name hints at, separates the water droplets out of the saturated charge air. For the reason that the humidification system operates with higher excess water, the water that does not evaporate is led back into the catch tank. Generally it is considered that the amount of injected water is three times the fuel consumption. So the water to fuel ratio is 3. This generalization can be particularized by the field experience on-board, where a water to fuel ratio of 2,5 [3] was determined. Accorded is this to the amount of water that is effectively injected into the cylinders. It does not mirror the whole used amount of water. To guarantee a continuous low salt and mineral content in the circle a 'bleed-off' system is used. Furthermore a safety drain to the sea is available, so the water can be bled off anytime. According to Lövblad and Fridell [55] 95 per cent of the water is used in the cycle again and 5 per cent are bled off. Another important adjustment that must be considered by installing a HAM system is the adaption of the turbocharger. Through the usage of such a humidification system the temperature of the exhaust gases will decrease. This in contrast leads to an increase of the density, what enables the air to absorb more water vapour. Consequently the turbocharger has a higher intake and must be adjusted to handle the additional mass. For this reason an adaption in the form of raising the speed is necessary.

6.2.4 Reduction potential

Generally differs the potential of saved NO_x emissions on the manufacturer's declarations. Normally a reduction rate of up to 70 – 80 per cent is assumed. According to Wärtsilä, an abatement of 50 % to approximately 7 $\frac{g}{kWh}$ is achievable with its humidification system 'WetPac'.[48] MAN indicates a reduction rate of 65 per cent if the charge air is preheated and 40 per cent if it is not. As detected on M/S Mariella the NO_x emissions before the installation were 16,70 $\frac{g}{kWh}$. The latest measurements however revealed NO_x emissions of 3,76 $\frac{g}{kWh}$ at a load of 73 per cent, 9,55 $\frac{g}{kWh}$ at a load of 70 per cent and 4,36 $\frac{g}{kWh}$ respectively 5,93 $\frac{g}{kWh}$ at a load of 80 per cent. The measurements were done from 07. to 09.03.2013 by an engineer and technician from Kymenlaakson ammattikorkeakoulu University of Applied Sciences. Consequently a reduction rate of 42,80 up to 77,50 per cent was realized. On the Norwegian fishing vessel Kvannoy that uses the HAM system as well, 61,3 per cent

NO_x emissions could be saved . So they had emissions of 9,3 $\frac{g}{kWh}$ before the installation and 3,6 $\frac{g}{kWh}$ after.[59] For two stroke engines the SAM system from MAN was invented. By general information of MAN may a reduction rate of 30 – 40 % be realistic.[55]

6.2.5 Pros and cons

Due to the previous chapter it can be seen that the HAM system is a quite convenient and efficient method to reduce NO_x emissions. In the following lines the advantages and disadvantages of this technology should be summarized.
The HAM system distinguishes itself positively through the fact that it can be operated with simple sea water. Consequently are the operational costs far smaller compared to other NO_x reduction methods that need fresh, distilled or water with specific additives or substances like urea. Further is the HAM system a relatively light and compact system and 15 to 30 tons lighter than SCR for instance. No huge storage tanks for fresh water or additives are needed. The only requirement is the physical closeness of the system to the engine, to avoid heat losses on the one hand and to prevent condensation of the saturated air on the other hand. Moreover the HAM system can be installed vertically or horizontally and due to the fact that it replaces the CAC, it can be integrated as a part of the engine. A further benefit is the far less lube oil consumption. This is caused by the much cleaner piston crowns. In general is the engine cleaner and a turbocharger cleaning is redundant. Also the TBO has increased to 12 to 15 per cent what affect the maintenance costs in a positive way. Another advantage of the engine is the minor thermal load that can affect the lifetime of engine components positively. Furthermore, no significant increase in the fuel oil consumption could be noticed either on the M/S Kvannoy or on the M/S Mariella. In fact decreased the fuel consumption on the M/S Mariella about five per cent [39]. Also there are no requirements for low-sulphur fuels.

7 COST-EFFICIENCY CALCULATIONS

To find reliable values for the calculation of the cost-effectiveness of DWI and HAM systems, several publications were consulted, like for instance from the Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments, Task 2b – NO_x Abatement. Furthermore brochures and product data sheets of the manufacturers Wärtsilä and MAN served as a basis. Also attempts to get into contact with the ship owners and suppliers of the engines and technologies were made, but ended without any great achievements. But some information from manufacturers and other experts could be gained with the help of Jouni-Juhani Häkkinen. He is one partner of the BSR Innoship project and acts as an adviser and customer of this thesis.

One of those given information is the trend history of a vessel's operation, like it is shown in figure 24. It is an example of the ship M/S MISIDA. The higher amplitudes indicate the operation on the open sea at about 80 – 85 per cent load. In the following calculations the assumption is a load of 80 per cent at open sea operation for the half of the ship running hours. The other half of the time is assumed with operation at 11 percent load for maneuvering in harbours. This corresponds with the given speed of 2 knots for M/S Mariella in the harbour.

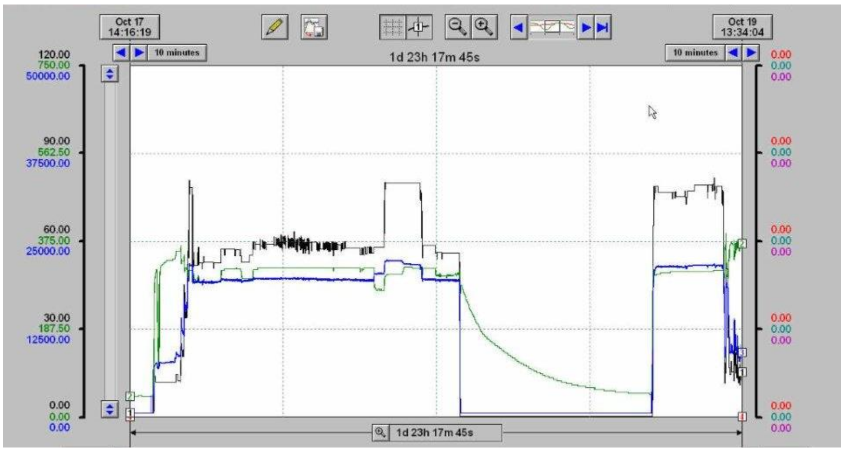

Figure 24: Trend history M/S MISIDA

All cost-efficiency calculations were made for three options – new build, retrofitted and a specific ship. In case of HAM it is the M/S Mariella and for DWI M/S MISIDA.

The procedure started with the detailed consideration of the costs for the systems. First of all there is the CapEx that contains the costs for the technology itself with all the equipment, and also the costs for the installation. For both abatement measures the whole installation can be done during operation. As a consequence there are no downtime costs, because there is no additionally time for the ship at berth needed. As a second part there are running expenses. They include costs for maintenance and operation of the systems. Towards the cost calculations are the emission calculations. As a result on the one hand the reduced NO_x emissions and on the other hand the cost for one abated ton of NO_x were received. At last the net present value and the dynamic payback period were determined with an assumed interest rate of five per cent. The main purpose of the thesis is the occurring costs per saved ton NO_x. The financial mathematical calculations only support the effectiveness.

All of the estimations were made with the best efforts, but to compensate possible upcoming defaults a tolerance of 10 per cent was chosen.

7.1 DWI

For DWI calculations the observed ship is the M/S MISIDA a Ro-Ro Ship, which is shown in figure 25.

Figure 25: M/S MISIDA

It has two main engines of the type Wärtsilä 6L46F which are 4-stroke diesel engines, each with a power output of 7.500 kW and 600 RPM. For the fuel injection these medium speed engines are equipped with a common rail injection system. Additionally all main engines are equipped with DWI since the ship was built in the year 2007. When the emission measurements for this report were taken the ship was running with heavy fuel oil and a sulphur content of 0,89 per cent.

The amount of water used onboard was also measured. For 57 per cent load it was 1.000 l/h and at 78 per cent load it was 1.300 l/h. These values are for both engines. With the fuel consumption [9] it is possible to calculate the used w/f-ratio. In appendix 5 the complete calculations can be seen. The result is 1.021 litres fuel per hour for the higher load, which is close to the typical operation load. Compared to the water consumption, it gives a w/f-ratio of 0,64. This value is well within the scope. The typical range of water to fuel is 0,4 – 0,7, so the used ratio gives hope for great reductions. On the contrary are first of all the costs for the DWI system.

7.1.1 CapEx

According to different sources for the capital costs a value of 20,00 €/kW was used for the calculation of this case study. It can be found greatly varying values, even from the manufacturer of the DWI system Wärtsilä. Starting from 10 – 15 €/kW,[47, 38] until a range of 40 – 60 €/kW are usual statements.

Considering the equipment price for the installation of DWI components like a low-pressure pump (3,5 bar) and a high pressure pump (200 - 400 bar) need to be installed. Like mentioned earlier further parts are injection valves and a flow fuse. Both have to be built into each cylinder, as well as cables, pipelines and the control unit for each cylinder. All this parts cost 234.00 € and have a lifespan of 25 years. The required injector on the contrary, has a relatively short lifespan of four years.[3] This is based on the exposed position of the injector in the cylinder where it has to endure high pressures and temperatures. At the same time a major part of the whole installation price belongs to this device. About 22 per cent of the capital costs need to be spent for the injectors in each cylinder. In fact that were 66.000 € for the considered vessel. It follows a sum of 300.000 € for the investment (shown in appendix 7). In this case study the CapEx include also the costs for the water treatment system.

7.1.2 Operational expenditure

The operation costs of this system include the costs for fresh water. In case of M/S MISIDA there is a freshwater production on board. The water treatment system is powered by energy generated by the ship. Due to this the ship has increased fuel consumption. Owing to the fact that the size of the water treatment system installed on the ship is unknown, the amount of additionally required fuel was calculated for both available sizes. The values are based on the Wärtsilä product information [61] and result in 3.443 tons respectively 6.057 tons extra fuel per year. In appendix 8 are the detailed figures to this calculation. The DWI technology has low operation costs of about 2.634 €/a (appendix 9). A further factor which needs to be considered is the maintenance. Even if it is possible to reduce the expenses for maintenance due to less thermal stress, there is some effort necessary for trouble-free operation. In this case study the maintenance costs include the expenses for replacing the water injectors every fourth year. This leads to annual maintenance costs of about 48.022 €. In sum there are costs of 50.665,80 € for maintenance and operation of the system. This fits well with the statement of 2 $/MWh from the Project Clean North Sea Shipping.[49]

7.1.3 Emission reduction calculation

To calculate the costs per abated ton NO_x of the technology all the above mentioned costs need to be considered and converted to annual costs. In the case of the ship M/S MISIDA the emissions without water injection are also low. Therefor there are only 82,46 tons of abated NO_x per year, as it can be seen in table 2. The main engines are new and they emit 9,27 g/kWh in normal operation. According to the low reduction the costs per abated ton NO_x are 928,08 €. In comparison, usual stated emissions range between 14-16 g/kWh.[62] Typical values for ships with DWI injection are 4 - 6 g/kWh for MDO or 5 – 7 g/kWh for operation on HFO.[53] With these values a reduction of 314,59 tons NO_x per year are feasible. As a consequence for a ship with DWI installed from the beginning the costs per abated ton NO_x are 243,25 € (shown in table 3 Emission calculation case 2).

Table 2: Emission calculation case 1

Emission calculation Case 1		
case study M/S MISIDA		
without DWI	9,27	g/kWh
with DWI	6,31 - 7,69	g/kWh
Ø with DWI	6,78	g/kWh
abated Nox	**2,49**	**g/kWh**
annual performed work	33.114,90	MWh/a
abated NOx	**82,46**	**t/a**
new build		
costs	76.525,80	€/a
abated NOx	82,46	t/a
costs per abated ton NOx	**928,08**	**€/t**
tolerance		
+10%	1.020,89	€/t
-10%	835,27	€/t

Retrofitting is more complicated for DWI. If the injector is integrated in the injection system this system needs to be modified. Though it is more expensive if the nozzle is separate from the injection system, then the cylinder head needs to be changed. In any case retrofitting is assumed to be 25 per cent more expensive than installing DWI on new ships. This was taken into account with costs of 292.500 € for the equipment and installation (details appendix 10 Cost calculation DWI – Case 2). Like it can be seen in table 3 the final figure is with 250,69 €/t slightly higher than for a new build ship, although below the value for M/S MISIDA.

Table 3: Emission calculation case 2

Emission calculation Case 2			
without DWI	14-16	g/kWh	
Ø without DWI	15,00	g/kWh	
with DWI	5,50	g/kWh	
abated NOx	9,50	g/kWh	
annual performed work	33.114,90	MWh/a	
abated NOx	**314,59**	**t/a**	

new build				***retrofit***			
costs		76.525,80	€/a	costs		78.865,80	€/a
Abated NOX		314,59	t/a	Abated NOX		314,59	t/a
costs per abated ton NOx		**243,25**	**€/t**	**costs per abated ton NOx**		**250,69**	**€/t**
tolerance				tolerance			
	+10%	267,58	€/t		+10%	275,76	€/t
	-10%	218,93	€/t		-10%	225,62	€/t

7.1.4 Financial mathematic calculations

As mentioned before the expenses for maintenance can be reduced about 25 per cent due to the DWI installation. The reason for this is the lower combustion temperature which implies less stress for the cylinder walls, piston and other parts. This leads to a saving of 16.007€/a. The table with the exact values is shown in appendix 13.

The ship M/S MISIDA and the rest of the fleet of the Godby Shipping company mainly carry forest products, like paper and pulp, from Finland to European countries. In fact the ship berths regularly in countries like Spain, Poland and Russia. It is not often calling ports with differentiated fee and due systems. For this reason there are no possibilities to save money by reduced fees.

Finally, with the lower expenses for maintenance as earnings, the net present value for the DWI system on the M/S MISIDA could be calculated as it is shown in table 4. For this particular case study it is not economical to install this abatement technology. The annual revenues are negative due to the small earnings.

Table 4: Net present value DWI

Net present value DWI				
Interest		5%		1,05
Capex	-	300.000,00	€	
Expenses		50.665,80	€/a	
Earnings		16.007,25	€/a	
Revenue	-	34.658,55	€/a	
Years		25		
Present value factor		14,09		
Net present value	**-**	**1.166.463,75**	€	

7.2 HAM

For determining the cost-efficiency of a HAM system the data of the passenger ferry M/S Mariella that is operating for the Finnish company Viking Line, is served as a basis. A passenger ferry is defined as a ship that can carry more than 120 passengers and has additionally one or more decks for cargo. Further calculations are for installing during the new build and the retrofit in general.

Figure 26: The passenger ferry M/S Mariella from Viking Line

The M/S Mariella has space for around 2200 passengers and 540 vehicles and can be seen above in figure 26. It covers the distance from Helsinki to Stockholm every day in turn with the M/S Gabriella. For the propulsion the ferry is equipped with four main engines (ME) and two auxiliary engines (AM). The used MEs are of the type Wärtsilä S.E.M.T Pielstick 12 PC2-6.2 with a power of 5.750 kW each at 500 RPM. These engines were all retrofitted by a HAM system. Primarily in the year 1999, where for a start only one engine was retrofitted. After two years, in 2001, also the three other

MEs were equipped with the HAM system. Until March 2013 the system had, depending on the ME, from 113.092 up to 132.887 working hours.

7.2.1 Capex

The assumed CaPex include the costs for the needed equipment and for the installation. To the needed equipment belong mainly the humidifier, the catch tank and the heat exchanger for preheating the water. Further components are the pumps, filters, pipes and valves, as well as the control and monitoring system. The advantage of the system is that the most expensive components like the humidifier, the heat exchanger, the catch tank and the circulation pump are only needed once. It is not necessary to install these devices for each engine, only once for all. To enable the comparability the lifespan for the three options is assumed with 15 years.

For new build ships the CaPex can be assumed with 2.530.000 €. If the CaPex are stated per kW, the average would be 110 $\frac{€}{kW}$, referred to C. Hugi.[47] Will the system be installed afterwards, the CaPex will increase. Fortunately it is possible to install the system while the engines are in daily operation, but for such an action an immense planning effort is necessary. This is mirrored in the higher capital costs compared to the costs of a system on a new build ship. So the capital costs for a retrofitted system are 2.760.000 €, which results an average of 120 $\frac{€}{kW}$.[47] In case of the retrofitted system on the M/S Mariella the capital costs amounted to 500.000 € for one engine. Consequently 2.000.000 € were necessary to install the system for all four main engines. Per installed kW the CaPex is about 87 $\frac{€}{kW}$. The first installation was done while the ship was in its daily operation and the three following during its usual dry dock time.

7.2.2 Operational expenditure

For the calculations the expenditure for the operation and maintenance were summarized. According to the given values from M/S Mariella an expenditure of 4000 € per engine was assumed. As a result it was calculated that 16.000 € per ship were necessary every year. The operational expenditure is in comparison to DWI for instance significantly low. This is due to the ability of the HAM system to use sea water and grey water, which would be otherwise just drained off.

7.2.3 Emission reduction calculation

Due to the latest measurements on the M/S Mariella it is possible to calculate the actual costs for the emissions. At a load of 80 per cent emission values of 4,36 $\frac{g}{kWh}$ up to 5,93 $\frac{g}{kWh}$ were determined. The revealed average is then 5,15 $\frac{g}{kWh}$. Compared is this value with the emission value for an identically constructed engine that is operated without a HAM system. This is the reference value 16,70 $\frac{g}{kWh}$. With the help of the difference and the annual performed work of the engines it was possible to calculate the abated NO_x amount in tons per year, which are 528,46 $\frac{t}{a}$. The value is valid for the whole ship M/S Mariella with its four MEs.

Table 5: Emission calculation of the HAM system

Emission calculation		
without HAM	16,70	g/kWh
with HAM	5,93 - 4,36	g/kWh
Ø with HAM	5,15	g/kWh
abated NOx	**11,56**	**g/kWh**
annual performed work	45.734,20	MWh/a
abated NOx	**528,46**	**t/a**

new			***retrofit***			***case study M/S Mariella***		
costs	184.666,67	€/a	costs	200.000,00	€/a	costs	149.333,33	€/a
abated NOx	528,46	t/a	abated NOx	528,46	t/a	abated NOx	528,46	t/a
costs per abated ton NOx	**349,44 €/t**		**costs per abated ton NOx**	**378,46 €/t**		**costs per abated ton NOx**	**282,58 €/t**	
tolerance			tolerance			tolerance		
+10%	384,39 €/t		+10%	416,31 €/t		+10%	310,84 €/t	
-10%	314,50 €/t		-10%	340,61 €/t		-10%	254,32 €/t	

Further could the value for the amount of abated NO_x per year be adapted to determine the annual costs per abated ton NO_x for the three cases ‘new’, ‘retrofit’ and ‘M/S Mariella’.

7.2.4 Financial mathematic calculations

The financial mathematical calculations like the net present value and the payback period are shown exemplarily on the basis of the M/S Mariella. To get earnings, the saved money from the port fees and the decreased fuel consumption were considered. The concerned ports are Mariehamn and Stockholm, because they have on emission based port fees. For Mariehamn a discount of 4,8 per cent of the basic fee is determined. This was figured out with the help of a linear scale and the two limits: One per cent discount with 10 $\frac{g}{kWh}$ emissions and eight per cent discount with 1 $\frac{g}{kWh}$.[44] For the port fees in Stockholm the table in appendix 4 must be consulted.[43] Secondly, the decreased fuel consumption about five per cent can be noticed as a the main saving. Details can be looked up in appendix 19. The expenses are the annual expenditures for operation and maintenance and the lifespan is, like it is mentioned previously, 15 years.

As it can be seen in table 6 and table 7 the HAM system with a net present value of 653.139 € and a payback period of 10 years is worth its purchase.

Table 6: Calculation of the net present value

Net present value HAM				
Interest		5%		1,05
Capex	-	2.000.000,00	€	
Expenses		16.000,00	€/a	
Earnings		271.613,79	€/a	
Revenue		255.613,79	€/a	
Years		15		
Present value factor		10,38		
Net present value		**653.183,71**	**€**	

Table 7: Calculation of the payback period

Payback period HAM		
Capex	2.000.000,00	
Revenues	255.613,79	
Interest	5%	1,05
Life span	15	
t	**10,17**	

8 CONCLUSION

After having a look at facts about air pollution and the rising demand of freight traffic by sea it is clear why there are many attempts to abate marine emissions.

The measures to abate NO_x emissions, observed in this report are capable to reduce these pollutants of about 50 to 70 per cent. This value is quite high but not enough to meet the IMO Tier III limits. As it is shown in figure 27 these wet methods achieve better reduction rates than in-engine modifications like optimized fuel equipment or the Miller cycle. They were options in the past to meet IMO Tier I limits (blue part). At the present they are still an important part as they are a foundation for the recent methods. Therefor the wet methods are able to meet IMO Tier II restrictions (orange part). Technologies belonging to the aftertreatment measures are more likely to meet the challenging restrictions starting from 2016. SCR is capable to reduce NO_x emissions below 80 per cent compared to Tier I limits.[60]

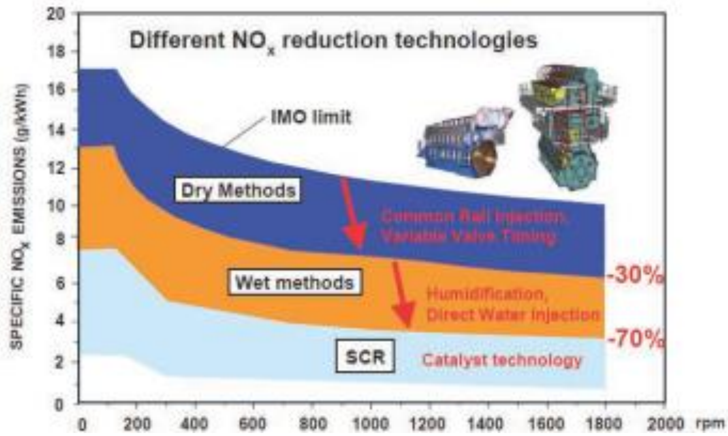

Figure 27: Different NO_X reduction technologies meeting IMO TIERs

A strategy to reduce the emissions in the range of the new limits with the wet methods is to combine it with the aftertreatment measures. This provides for example the possibility to use cheaper fuel (with high sulphur content) by installing the HAM technology combined with an additional aftertreatment system. So low emission levels can be reached. In this way it can be realised to combine advantages of different abatement technologies.

The water based measures DWI and HAM have some crucial advantages, but also drawbacks. Both techniques involve low operation costs compared to other abatement methods, as for instance there are no additives necessary. Furthermore they have a positive effect on the whole engine, like a cleaner piston in case of HAM and less thermal stress caused by DWI. That leads to lower maintenance efforts. On the other hand there are technical drawbacks like the risk of corrosion, technical feasibility or the need of changes – for DWI for the installation and for HAM the adjustment of the turbocharger speed. Just as it is for all the abatement technologies, they have to face also financially drawbacks. For instance the HAM system has high investment costs and the DWI system may cause increased fuel consumption. In the part regarding the financial calculations the cost-efficiency of the HAM system could be proven. Opposed is the situation of the DWI installation. In these precise case studies the cruise ferry could benefit from good earnings based on the daily calls in the port of Stockholm. With the emission reduction of 15 g/kWh to 5,9 g/kWh there is a noticeable difference in the fee system for M/S Mariella. Together with the decreased fuel consumption great revenue was estimated. The distinct less frequent calls of M/S MISIDA in Swedish ports give no possibility for equivalent revenues for the investment. The ship owner still has to spend the money for the installation because the vessel is operating in the Baltic Sea. This leads to a further drawback, the lack of appropriate incentives. The ship owners have to invest a lot for installing abatement measures to meet the new regulations but except for some countries and ports there are now financial compensations. Similarly the existing discounts for fees and port dues are scarcely perceptible as it can be seen in the calculations for M/S Mariella.

Aside from these calculations the cost estimations per abated ton of NO_x are assertive. In table 8 the different results from the two water-based measures are shown.

Table 8: Costs per abated ton NOx

costs per abated ton NOx		
case study M/S MISIDA	*new*	*retrofit*
928,08 €/t	**243,25 €/t**	**250,69 €/t**
case study M/S Mariella	*new*	*retrofit*
282,58 €/t	**349,44 €/t**	**378,46 €/t**

In summary, it can be stated that there is still a huge potential in abating emissions from the maritime traffic, but with these technologies a step in the right direction was made.

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Figure 20 Steinhilber T., Einfluss der Wasser- oder Emulsionseinspritzung auf die homogene Dieselverbrennung, December 2007, Page 124, https://www.google.de/search?q=Einfluss+der+Wasser-+oder+Emulsionseinspritzung+auf+die+homogene+Dieselverbrennung&ie=utf-8&oe=utf-8&aq=t&rls=org.mozilla:de:official&client=firefox-a#client=firefox-a&hs=7UW&rls=org.mozilla:de:official&q=Einfluss+der+Wasser-+oder+Emulsion+Einspritzung+auf+die+homogene+Dieselverbrennung&spell=1&sa=X&ei=GWerUevkCYXVswbsjoCwBg&ved=0CCwQBSgA&bav=on.2,or.r_qf.&bvm=bv.47244034,d.Yms&fp=4581f8b41541bdb8&biw=1525&bih=685 [25. April 2013]

Figure 21 Viking Line, Energy consumption and atmospheric emissions, http://www.vikingline.com/en/Investors-and-the-Group/Safety--environment/Environment/Energy-consumption-and-atmospheric-emissions/ [15. May 2013]

Figure 22 Coquillaud P., Graf K., The MAN B&W V 40/50 Diesel engine, 2002, Page 11, http://www.mandieselturbo.com/1001265/Press/Publications/Technical-Papers/Marine-Power/Medium-Speed/Medium-Speed-Archive/The-MAN-BandW-V40%2F50-Diesel-engine.html [20 May 2013]

Figure 23 MAN Diesel SE, Humid Air Motor – Technology for Green Profits, Page 4, http://mandieselturbo.com/files/news/filesof15316/HAM_PS_Brochure_May2011.pdf [21. May 2013]

Figure 24 Real time record from M/S MISIDA provided by Jouni-Juhani Häkkinen

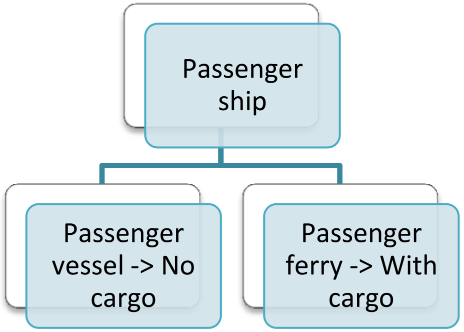
Figure 25 Godby Shipping Ab, mv MISIDA, Page 1, http://www.godbyshipping.fi/english/company.php, [03. June 2013]

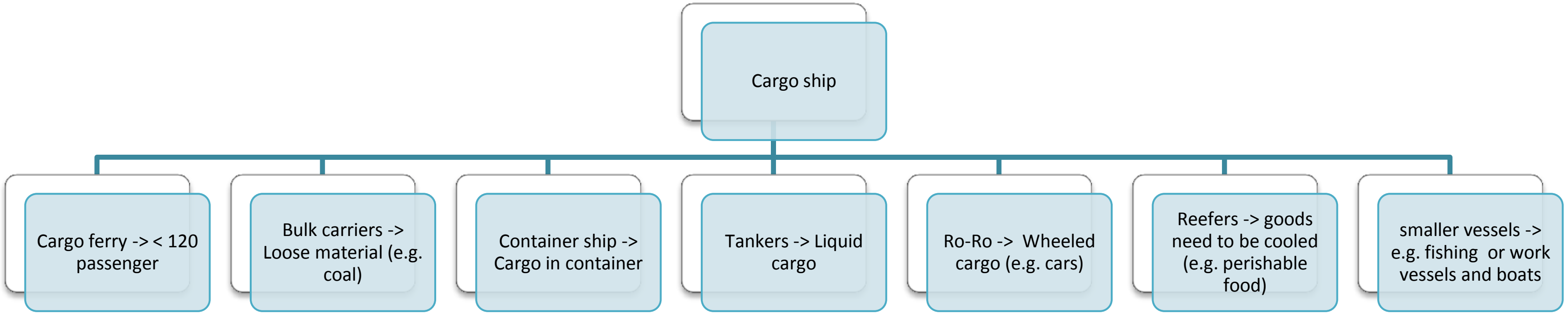
Figure 26 Viking Line – Mariella, 2007, http://www.shippax.se/page/page.asp?id=57 [25. May 2013]

Figure 27 Wärtsilä, Wärtsilä – Energy and Environmental Efficient Sea Transport, Aug.2009, Page 6, http://snu.as/files/Ingve_Sorfonn.pdf [18. May 2013]

APPENDICES

Appendix 1. Different ship types





Appendix 2. The ambient conditions during the measurements on the M/S Mariella

	ME 1	ME 2	ME 3	ME 4
Temperature [°C]	31,0	31,0	31,0	31,0
Pressure [kPa]	101,7	101,7	101,7	101,7
Humidity [%]	31,0	31,0	31,0	31,0

Appendix 3. NOx limits for IMO Tier I - III

NOx limits for IMO Tier I-III			
	Validity for engines installed on or after…	**Speed (n) [rpm]**	**Maximum allowed NOX emissions [g/kWh]**
Tier I	1st January 2000 to 1st January 2011	< 130	17
		130 ≤ n < 2.000	$45{,}0 * n^{-0{,}2}$
		n ≥ 2.000	9,8
Tier II	1st January 2011	< 130	14,4
		130 ≤ n < 2.000	$44{,}0 * n^{-0{,}23}$
		n ≥ 2.000	7,7
Tier III	1st January 2016 when operating in ECAs	< 130	3,4
		130 ≤ n < 2.000	$9{,}0 * n^{-0{,}2}$
		n ≥ 2.000	2

Appendix 4. Swedish fairway dues – Dues per gross tonnage

Swedish dues per gross tonnage			
Fairway dues with NOX reduction			
NOX emissions [g/kWh]	Due in SEK/GT Passenger vessels	Due in SEK/GT Cruising vessels	Due in SEK/GT other vessels (e.g. oil tanker)
0 - 0,5	-	-	-
0,51 - 1,00	0,15	0,03	0,25
1,01 - 2,00	0,40	0,08	0,61
2,01 - 3,00	0,63	0,16	0,77
3,01 - 4,00	0,77	0,24	0,93
4,01 - 5,00	0,91	0,32	1,09
5,01 - 6,00	1,05	0,40	1,25
6,01 - 7,00	1,19	0,48	1,41
7,01 - 8,00	1,33	0,56	1,57
8,01 - 9,00	1,47	0,64	1,73
9,01 - 10,00	1,61	0,72	1,89
>10,01	1,80	0,80	2,05

Appendix 5. Water/fuel ratio calculation DWI

w/f-ratio M/S MISIDA					
per engine:			**per engine:**		
installed power	7.500,00	kW	installed power	7.500,00	kW
load	**0,57**		**load**	**0,78**	
operation power	4.275,00	kW	operation power	5.850,00	kW
fuel consumption	171,00	g/kWh	fuel consumption	171,00	g/kWh
	731,03	kg/h		1.000,35	kg/h
density of fuel	980,00	kg/m³	density of fuel	980,00	kg/m³
fuel amount	0,75	m³/h	fuel amount	1,02	m³/h
	745,94	l/h		1.020,77	l/h
fuel volume	**3.619,32**	**m³/a**	**fuel volume**	**4.952,75**	**m³/a**
Per ship:			**Per ship:**		
fuel volume	**7.238,64**	**m³/a**	**fuel volume**	**9.905,51**	**m³/a**
water amount	500,00	l/h	water amount	650,00	l/h
fuel amount	745,94	l/h	fuel amount	1.020,77	l/h
w/f-ratio	**0,67**		**w/f-ratio**	**0,64**	
Ø running hours MEs	24.259	h			
Years of operation	5	a			
running hours per a	4.852	h/a			

Appendix 6. Cost calculation DWI – Case 1

Cost calculation		
new build - M/S MISIDA		
CapEx:		
injector	66.000,00	€
lifespan	4	a
	16.500,00	**€/a**
equipment & installation	234.000,00	€
lifespan	25	a
	9.360,00	**€/a**
∑ CapEx	**300.000,00**	**€**
∑ annual costs	**25.860,00**	**€/a**
Operation & Maintenance costs	50.665,80	€/a
∑ annual costs	**76.525,80**	**€/a**
tolerance		
+10%	84.178,38	€/a
-10%	68.873,22	€/a

Appendix 7. CaPex DWI – Case 1

CapEx		
chosen	20,00	€/kW
installed power	15.000,00	kW
CapEx	**300.000,00**	**€**
injector	**66.000,00**	**€**
equipment	**234.000,00**	**€**

Appendix 8. Additional fuel for water treatment

Additional fuel for water treatment					
small installation			**big installation**		
installed power	4,15	kW	installed power	7,30	kW
fuel consumption	171,00	g/kWh	fuel consumption	171,00	g/kWh
	0,71	kg/h		1,25	kg/h
density of fuel	980,00	kg/m³	density of HFO	980,00	kg/m³
fuel amount	0,001	m³/h	fuel amount	0,001	m³/h
	0,72	l/h		1,27	l/h
Ø running hours MEs	4.852,00	h/a	Ø running hours MEs	4.852,00	h/a
Fuel volume	3,51	m³/a	Fuel volume	6,18	m³/a
Fuel mass	3.443,22	t/a	Fuel mass	6.056,75	t/a
Costs for water treatment					
fuel price	543,45	€/t	fuel price	543,45	€/t
costs	1.909,40	€/a	costs	3.358,71	€/a
costs for water treatment			**2.634,05**	**€/a**	

Appendix 9. OpEx DWI – Case 1

Operation & maintenance		
new build - M/S MISIDA		
annual performed work:		
Ø running hours	24.259,00	h
years of operation	5	a
running hours	4.852,00	h/a
with 80% load:	12,00	MW
hours sea operation	2.426,00	h/a
	29.112,00	**MWh/a**
with 11% load:	1,65	MW
hours harbour operation	2.426,00	h/a
	4.002,90	**MWh/a**
∑ performed work	**33.114,90**	**MWh/a**
	1,53	€/MWh
O&M costs	**50.665,80**	**€/a**

Appendix 10. Cost calculation DWI – Case 2

Cost calculation							
new build				***retrofit***			
CapEx:				**CapEx:**			
injector		66.000,00	€	injector		66.000,00	€
lifespan		4	a	lifespan		4	a
		16.500,00	**€/a**			**16.500,00**	**€/a**
equipment & installation		234.000,00	€	equipment & installation		292.500,00	€
lifespan		25	a	lifespan		25	a
		9.360,00	**€/a**			**11.700,00**	**€/a**
∑ CapEx		**300.000,00**	**€**	**∑ CapEx**		**358.500,00**	**€**
∑ annual costs		**25.860,00**	**€/a**	**∑ annual costs**		**28.200,00**	**€/a**
Operation & Maintenance costs		50.665,80	€/a	Operation & Maintenance costs		50.665,80	€/a
∑ annual costs		**76.525,80**	**€/a**	**∑ annual costs**		**78.865,80**	**€/a**
tolerance				tolerance			
	+10%	84.178,38	€/a		+10%	86.752,38	€/a
	-10%	68.873,22	€/a		-10%	70.979,22	€/a

Appendix 11. CaPex DWI – Case 2

CapEx - new build			CapEx - retrofit		
new build			***retrofit***		
	20,00	€/kW		20,00	€/kW
installed power	15.000,00	kW	installed power	15.000,00	kW
CapEx	**300.000,00**	**€**	**CapEx**	**358.500,00**	**€**
injector	**66.000,00**	**€**	**injector**	**66.000,00**	**€**
equipment	**234.000,00**	**€**	**equipment**	**292.500,00**	**€**

Appendix 12. OpEx DWI – Case 2

Operation & maintenance		
annual performed work:		
Ø running hours	24.259,00	h
years of operation	5	a
running hours	4.852,00	h/a
with 80% load:	12,00	MW
hours sea operation	2.426,00	h/a
	29.112,00	**MWh/a**
with 11% load:	1,65	MW
hours harbour operation	2.426,00	h/a
	4.002,90	**MWh/a**
∑ performed work	**33.114,90**	**MWh/a**
	1,53	€/MWh
O&M costs	**50.665,80**	**€/a**

Appendix 13. Savings maintenance

Savings maintenance		
O&M	50.655,80	€/a
operation costs	2.634,05	€/a
maintenance with DWI	48.021,75	€/a
maintenance before	64.029,00	€/a
saving	**16.007,25**	**€/a**

Appendix 14. Earnings DWI

Earnings DWI		
Savings from maintenance	16.007,25	€/a
	16.007,25	**€/a**

Appendix 15. Cost calculation HAM

Cost calculation								
new			***retrofit***			**case study M/S Mariella**		
CapEx	2.530.000,00	€	CapEx	2.760.000,00	€	CapEx	2.000.000,00	€
lifespan	15	a	lifespan	15	a	lifespan	15	a
	168.666,67	€/a		184.000,00	€/a		133.333,33	€/a
CapEx per KW installed	110,00	€/kW	CapEx per KW installed	120,00	€/kW	CapEx per KW installed	86,96	€/kW
Operation & Maintenance costs	16.000,00	€/a	Operation & Maintenance costs	16.000,00	€/a	Operation & Maintenance costs	16.000,00	€/a
∑ annual costs	**184.666,67**	**€/a**	**∑ annual costs**	**200.000,00**	**€/a**	**∑ annual costs**	**149.333,33**	**€/a**
tolerance			tolerance			tolerance		
+10%	203.133,33	€/a	+10%	220.000,00	€/a	+10%	164.266,67	€/a
-10%	166.200,00	€/a	-10%	180.000,00	€/a	-10%	134.400,00	€/a

Appendix 16. CaPex HAM

CapEx				
	new		*retrofit*	
range	90 - 130	€/kW	110 - 130	€/kW
average	110	€/kW	120	€/kW
installed power	23.000	kW	23.000	kW
	2.530.000	**€**	**2.760.000**	**€**

Appendix 17. Annual performed work of all four engines on M/S Mariella

Annual performed work		
Ø running hours	122.365,75	h
time of operation	28	a
Ø running hours per year	4.370,21	h/a
80 % load	18,40	MW
hours sea operation	2.185,10	h/a
	40.205,89	**MWh/a**
11 % load	2,53	MW
hours harbour operat	2.185,10	h/a
	5.528,31	**MWh/a**
Σ performed work	**45.734,20**	**MWh/a**

Appendix 18. Savings from dues

Savings from dues				
Port fee Mariehamn				
basic fee = 5,79*(Length over all)+0,011*NT				
basic fee	1.277,39 €			
discount	4,80%			
	per call		**per year**	
			max. 350 times	
with HAM:	**1.216,07**	**€**	**425.625,35**	**€/a**
without HAM:	**1.277,39**	**€**	**447.085,45**	**€/a**
Savings	**61,31**	**€**	**21.460,10**	**€/a**
Port fee Stockholm				
with HAM:	**per call**		**per year**	
Passenger 5,15g/kWh	1,05	SEK/GT	max. 18 times	
	39.690,00	SEK		
	37.800	GT		
0,1163€ = 1SEK (31.05.13)	**4.615,95**	**€**	**83.087,05**	**€/a**
without HAM:	1,08	SEK/GT		
	40.824,00	SEK		
	4.747,83	**€**	**85.460,96**	**€/a**
Savings	**131,88**	**€/a**	**2.373,92**	**€/a**

Appendix 19. Savings from the decreased fuel consumption HAM

Savings from fuel				
M/S Mariella				
Per engine:				
Installed power	5.750,00	kW	5.750,00	kW
Load	0,80		0,11	
Operation power	4.600,00	kW	632,50	kW
Fuel consumption	200,00	g/kWh	195,00	g/kWh
	920,00	kg/h	123,34	kg/h
Density of fuel	980,00	kg/m³	980,00	kg/m³
Fuel amount	0,94	m³/h	0,13	m³/h
	938,78	l/h	125,85	l/h
Running hours per a	2.185	h/a	2.185	h/a
Per engine:				
Fuel volume	2.051,22	m³/a	274,99	m³/a
Fuel mass	2.010,20	t/a	269,49	t/a
Per ship:				
Fuel volume	8.204,90	m³/a	1.099,97	m³/a
Fuel mass	8.040,80	t/a	1.077,97	t/a
Ø running hours MEs	122.366	h		
Years of operation	28	a		
Running hours per a	4.370	h/a		

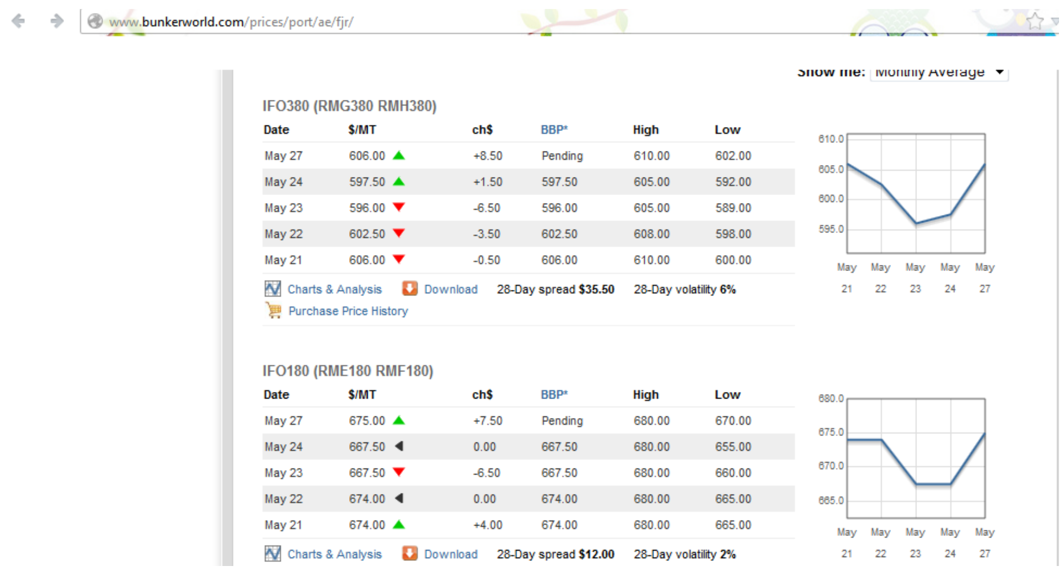
Saved fuel ***per engine***		
Fuel mass	2.279,69	t/a
Consumption reduction	5%	
	113,98	**t/a**
Fuel price	543,45	€/t
Savings	**61.944,94**	**€/a**

Saved fuel ***per ship***		
Fuel mass	9.118,77	t/a
Consumption reduction	5%	
	455,94	**t/a**
Fuel price	543,45	€/t
Savings	**247.779,77**	**€/a**

Appendix 20. Earnings HAM

Earnings HAM		
Savings Mariehamn	21.460,10	€/a
Savings Stockholm	2.373,92	€/a
Savings from fuel	247.779,77	€/a
	271.613,79	**€/a**

Appendix 21. Fuel price


www.bunkerworld.com/prices/port/ae/fjr/

Show me: Monthly Average

IFO380 (RMG380 RMH380)

Date	$/MT	ch$	BBP*	High	Low
May 27	606.00 ▲	+8.50	Pending	610.00	602.00
May 24	597.50 ▲	+1.50	597.50	605.00	592.00
May 23	596.00 ▼	-6.50	596.00	605.00	589.00
May 22	602.50 ▼	-3.50	602.50	608.00	598.00
May 21	606.00 ▼	-0.50	606.00	610.00	600.00

Charts & Analysis Download 28-Day spread $35.50 28-Day volatility 6%

Purchase Price History

IFO180 (RME180 RMF180)

Date	$/MT	ch$	BBP*	High	Low
May 27	675.00 ▲	+7.50	Pending	680.00	670.00
May 24	667.50 ◄	0.00	667.50	680.00	655.00
May 23	667.50 ▼	-6.50	667.50	680.00	660.00
May 22	674.00 ◄	0.00	674.00	680.00	665.00
May 21	674.00 ▲	+4.00	674.00	680.00	665.00

Charts & Analysis Download 28-Day spread $12.00 28-Day volatility 2%